Best-Practices for Per- and Polyfluoroalkyl Substances (PFAS) Biomonitoring in Firefighters




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1 BACKGROUND

This report presents actionable guidance on best-practice methodologies and standardized protocols for biomonitoring of per- and polyfluoroalkyl substances (PFAS) in firefighter populations. It was developed in direct response to appropriations by the Minnesota Legislature in 2023 to investigate PFAS exposure risks among firefighters. Specifically, Laws of Minnesota 2023, Chapter 60, Article 1, Section 2, Subdivision 2(r), and Article 3, Section 32 allocated funding and directed the Minnesota Pollution Control Agency (MPCA) and the Minnesota Department of Health (MDH) to develop "recommendations and protocols for PFAS biomonitoring in firefighters." An additional goal is to provide a scientific foundation for any future biomonitoring programs that would allow Minnesota "firefighters to voluntarily register for biomonitoring." MDH contracted with Eastern Research Group, Inc. (ERG) to develop this report.

1.1 PFAS and General Population Exposure

PFAS are a large class of synthetic chemicals used in a wide range of consumer products and industrial applications due to their oil-, stain-, and water-resistant properties (MDH, 2025). They are also valued for their thermal stability and resistance to chemical degradation. These characteristics make PFAS common ingredients in products such as nonstick cookware, water-repellent fabrics, food packaging, and firefighting materials. However, the same properties that make PFAS useful also contribute to their environmental persistence, widespread distribution, and potential for bioaccumulation.

Health Effects

Most PFAS are not metabolized in the body and can accumulate in human blood over time (MDH, 2024a). Some PFAS can remain in the body for years, particularly long-chain compounds that have been phased out of production like perfluorooctanoic acid (PFOA), perfluorooctanesulfonic acid (PFOS), perfluorohexanesulfonic acid (PFHxS), perfluorononanoic acid (PFNA), and perfluorodecanoic acid (PFDA). These 'legacy' PFAS have been associated with select adverse health effects, including increased cholesterol level, small decreases in birth weight, decreased antibody response to vaccines, kidney and testicular cancer, pregnancy-induced preeclampsia/hypertension, and changes to liver enzymes (ATSDR, 2024; NASEM, 2022). While legacy PFAS are among the most studied, they represent only a small fraction of the thousands in use. Many newer substitute PFAS are smaller compounds that are expected to have shorter half-lives in the body, but far less is known about their environmental behavior, bioaccumulation potential, and toxicity (ITRC, 2023).

General Population Exposures

People can be exposed to PFAS in many ways including drinking water where the source has been impacted by PFAS contamination. The most common exposure pathways are dietary intake and PFAS-treated consumer product usage (MDH, 2025). Dietary intake can include consumption of food packaged in PFAS-treated materials (e.g., fast food wrappers, microwave popcorn bags), fish from contaminated water bodies, and food grown or raised near areas with known PFAS exposure. Exposure through PFAS-treated consumer products can occur through contact with or use of stain- or water-repellant consumer products such as carpets, upholstery, nonstick cookware, outdoor gear, and some personal care products (MDH, 2025). Inhalation of indoor air or ingestion of house dust may also contribute to exposures, particularly for infants and young children.

For most Minnesotans, the majority of PFOS exposure comes from non-drinking water sources. MDH has identified PFAS-contaminated drinking water in several communities across the state where manufacturing, waste disposal sites, and other PFAS releases have resulted in environmental

contamination of PFAS (MDH, 2024b). PFAS has been found in industrial air emissions, industrial and municipal wastewater, soil and water in and around firefighter training sites, and in groundwater of areas surrounding landfills (MPCA, 2021).

Due to the widespread use and persistence of PFAS, national biomonitoring programs, such as the Centers for Disease Control and Prevention's (CDC's) National Health and Nutritional Examination Survey (NHANES), have found that nearly all people in the United States have detectable levels of PFAS in their blood (ATSDR, 2024). The sources of PFAS exposures continue to change as product phase-outs are implemented. For example, on January 1, 2024, Minnesota banned intentionally added PFAS in food packaging, and on January 1, 2025, it banned intentionally added PFAS in selected consumer products (MPCA, 2025).

1.2 PFAS and Firefighter Exposure

Firefighters face heightened occupational exposure to PFAS through multiple sources that go beyond those experienced by the general public. Two of the most significant are the historic and ongoing use of AFFF and the routine wearing and handling of PFAS-treated personal protective equipment (PPE), commonly referred to as turnout gear (Mazumder et al., 2023). These exposures are of particular concern given the repeated and prolonged contact firefighters have with these materials throughout their careers, often under high-heat and high-stress conditions that may increase chemical mobility and uptake (van der Veen et al. 2020).

AFFF Exposures

AFFF has been widely used in firefighting, particularly for suppressing Class B flammable liquid fires, and in fire training exercises and emergency responses at airports, military installations, and industrial facilities. Historically, AFFF formulations contained high concentrations of PFOS, PFOA, and their precursors. Newer AFFF no longer contain intentionally added long-chain PFAS but still contain short-chained PFAS that are less studied. AFFF can be broadly grouped into the following categories based on their manufacturing history and chemical composition (ITRC, 2023; MPCA, 2024a):

- **Legacy PFOS-based AFFF.** Consists of PFOS and PFHxS, as well as other related precursors. This AFFF can also contain trace amounts of PFOA and precursors that can degrade to PFOA and related PFAS.
- **Legacy fluorotelomer-based AFFF.** Consists of short- and long-chain fluorotelomer PFAS, i.e., polyfluorinated precursors that will degrade to PFOA and its related compounds but will not transform to PFOS or its related compounds. This AFFF can also contain trace amounts of PFOA.
- **Modern fluorotelomer-based AFFF**. Consists almost only of short-chain fluorotelomer PFAS that cannot transform to long-chain PFAS, such as PFOA and PFOS. This AFFF may also contain trace amounts of PFOA and its precursors.
- **Fluorine-free Foams (F3).** Does not contain PFAS and have only recently been approved for fighting Class B fires. May not be available in sufficient quantities to meet current demand.

Although production and use of PFOS- and PFOA-based formulations have declined due to regulatory restrictions and voluntary phase-outs, stockpiles of legacy foams still exist and may be used in some jurisdictions, particularly at airports, Department of Defense (DoD) sites, and certain industrial locations. Only very recently have the DoD and the Federal Aviation Administration (FAA) approved F3 foams, but PFAS containing AFFF can still be used in certain contexts (DoD, 2023)

In Minnesota, state law (Minn. Stat. § 325F.072) prohibited the use of AFFF in training exercises as of July 1, 2020. And as of January 1, 2025, PFAS-containing AFFF is also limited in incident responses with some exceptions. At the time of publication of this report, PFAS-containing foams are still allowed for use at airports (DoD, 2023), and in Minnesota, airports may use legacy Class B firefighting foams until the state fire marshal determines that fluorine-free foams have suitable quantities available for sale (MPCA, 2025).

Turnout Gear Exposures

Turnout gear is another potential source of PFAS exposure among firefighters. A 2024 report by MPCA and MDH found that PFAS are incorporated into all three layers of turnout gear: the outer shell, moisture barrier, and thermal liner (MPCA, 2024b; Peaslee et al., 2020). PFAS are often intentionally added during manufacturing or applied as coatings to provide protection against water, chemicals, and bloodborne pathogens (Maizel et al., 2023). Firefighters can be exposed to PFAS in turnout gear through dermal absorption, ingestion of particles, or inhalation of volatile or semi-volatile PFAS. Older turnout gear might contain higher concentrations of phased-out PFAS such as PFOS, while newer gear contains alternative compounds that are less studied but still persistent (Maizel et al., 2023). For example, a study by the National Institute of Standards and Technology (NIST) identified 26 distinct PFAS compounds in newly manufactured turnout gear textiles, including both legacy long-chain compounds and newer short-chain replacement compounds (Maizel et al., 2023). The PFAS detected at the highest concentrations were 6:2 fluorotelomer alcohol (6:2 FTOH) and 6:2 fluorotelomer methacrylate (6:2 FTMAC), which are both replacement compounds not typically measured in standard biomonitoring panels (Maizel et al., 2023).

Minnesota fire departments universally (or nearly so) are in accordance with the 2018 version of NFPA 1971 ‘Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting’.

Other Sources of Occupational Exposures

In addition to AFFF and turnout gear, other potential sources of PFAS exposure for firefighters include fire station dust and air; smoke, debris, and air from structural fires; contaminated equipment; and residues from prior foam use (Mazumder et al., 2023). For example, PFAS was detected in 92% of dust samples taken from living rooms, apparatus bays, and turnout gear locker areas across 15 career fire stations in Massachusetts (Young et al., 2021). And increased smoke and dust exposure has been found to contribute to higher PFAS blood levels of first responders (Mazumder et al., 2023). These varied and overlapping exposure sources make it difficult to isolate individual contributors to PFAS body burden and emphasize the need for firefighter-specific biomonitoring efforts.

Occupational Factors that Contribute to Exposure

PFAS exposure among firefighters can vary by occupational and organizational factors. For example, the frequency and duration of turnout gear use, the age and type of gear issued, and cleaning decontamination behaviors might affect potential exposure levels (Maizel et al., 2023). Occupational factors can include years of experience, firefighting calls per year, and duration of fire runs (Goodrich et al., 2021; Graber et al., 2021; Hooker et al., 2025; Nematollahi et al., 2024). MPCA’s Report to the Legislature on *Perfluoroalkyl and Polyfluoroalkyl Substances (PFAS) in Firefighting Turnout Gear* determined that fire departments in Minnesota make every effort to replace their turnout gear and other protective gear every 10 years (MPCA, 2024b). Departments with limited resources may reuse older gear for longer periods or lack specialized laundering services. In an NFPA survey, 36% of fire departments indicated complete compliance with this 10-year limit (MPCA, 2024b). Firefighters who

regularly engage in suppression of chemical or fuel-based fires, or who respond to incidents at airports or military sites, may also be in more frequent contact with AFFF.

Minnesota Firefighter Population

Minnesota's firefighter workforce includes a mix of career, volunteer, paid-on-call, and combination departments, with a strong reliance on non-career staffing. An MPCA report notes that Minnesota has the second highest proportion of volunteer and paid-on-call firefighters among all 50 states (MPCA, 2024b). On average, firefighters in these smaller departments would be expected to wear turnout gear for fewer hours and respond to fewer fires than full-time firefighters in larger urban departments, which may influence patterns of PFAS exposure (MPCA, 2024b).

Table 1. Number and percentage of fire departments by type and geographic designation in Minnesota[1]

Departments	Volunteer	Paid on call	Combination[2]	Career	Total
Metropolitan[3]	92 (12%)	158 (21%)	72 (9.4%)	16 (2.1%)	338 (44%)
Micropolitan[3]	74 (9.6%)	68 (8.8%)	15 (2.0%)	0	157 (20%)
Rural[3]	130 (17%)	138 (18%)	5 (0.65%)	1 (0.13%)	274 (36%)
Total	296 (38%)	364 (47%)	92 (12%)	17 (2.2%)	769 (100%)

[1]Source = Data provided to ERG by MnFIRE in May 2025
[2]A combination department refers to a fire department with both full-time career firefighters and paid on call firefighters.
[3] Metropolitan, micropolitan, and rural distinctions were taken from MPCA, 2017.

Table 2. Number and percentage of firefighters by department type and geographic designation in Minnesota[1]

Firefighters	Volunteer	Paid on call	Combination[2]	Career	Total
Metropolitan[3]	1,860 (9.3%)	3,930 (20%)	3,018 (15%)	1,618 (8.1%)	10,426 (52%)
Micropolitan[3]	1,621 (8.1%)	1,583 (7.9%)	544 (2.7%)	0	3,748 (19%)
Rural[3]	2,635 (13%)	3,061 (15%)	154 (0.77%)	18 (0.09%)	5,868 (29%)
Total	6,116 (31%)	8,574 (43%)	3,716 (19%)	1,636 (8.2%)	20,042 (100%)

[1] Source = Data provided to ERG by MnFIRE in May 2025
[2]A combination department refers to a fire department with both full-time career firefighters and paid on call firefighters.
[3] Metropolitan, micropolitan, and rural distinctions were taken from MPCA, 2017.

1.3 The Role of Biomonitoring

Biomonitoring refers to the measurement of chemicals or their metabolites in human tissues (e.g., blood, urine, hair) with the goal of assessing exposures. Biomonitoring is not intended to identify health effects, though it can be coupled with health measurements in a health study. For PFAS, blood is generally the preferred biological tissue because many PFAS preferentially accumulate in the serum fraction of blood over time. Several well-studied PFAS, including PFOA, PFOS, and PFHxS, have biological half-lives (the amount of time a chemical remains in the body) of several years allowing them to persist in the bloodstream and reach detectable levels even after exposures have ended. While the half-lives of many replacement PFAS are not well characterized, they are generally expected to be shorter than those of legacy compounds such as PFOA and PFOS, which may affect how long these substances remain detectable in the bloodstream. As a result, PFAS measurements in blood can reflect a combination of

both recent and historical exposures depending on the compounds, although the measurements cannot distinguish between the timing or specific sources of those exposures (ATSDR, 2024; ITRC, 2023).

Biomonitoring can be used to understand how, and to what extent, firefighters are uniquely exposed to PFAS. Firefighter exposures likely include both legacy PFAS and newer replacement chemicals that are less understood and more difficult to detect. For instance, the emerging PFAS that have been detected in newly manufactured turnout gear may not be captured by standard laboratory analytical methods. The growing diversity of PFAS used in firefighting materials, along with limited data on the behavior and biological half-lives of newer compounds, highlights the importance of ensuring that laboratory capabilities align with goals of the biomonitoring project.

In addition to unique occupational exposures, firefighters are also subject to background PFAS exposure from sources common in the general population, such as contaminated food, drinking water, and consumer products. This overlap makes it challenging to attribute PFAS exposures solely to occupational sources. To meaningfully characterize firefighter-specific exposures, biomonitoring studies generally incorporate detailed exposure histories, including information on AFFF use, turnout gear handling practices, departmental protocols, and job roles. This context is essential for interpreting results, identifying exposure patterns, and guiding targeted exposure reduction strategies.

Standardized sampling, laboratory analysis, and data interpretation methods are essential to ensure consistency across studies, improve comparability between populations, and track changes over time. Agencies such as the CDC, the Council for State and Territorial Epidemiologists (CSTE), and the Association of Public Health Laboratories (APHL), have developed best practice guidance for population-based biomonitoring efforts, and these guidelines are incorporated in this report as appropriate (CDC, 2023; APHL, 2019; CSTE, 2012).

Biomonitoring data, when collected and interpreted appropriately, can play a critical role in guiding public health action. For example, in its East Metro Biomonitoring Project, MDH found that residents in areas impacted by PFAS contamination had elevated blood levels of PFOA, PFOS, and PFHxS compared to national averages (MDH, 2010). In follow-up studies, MDH used biomonitoring to show that interventions to reduce PFAS drinking water exposures in this area were successful (MDH, 2015). Biomonitoring studies like this one can be used to prioritize exposure reduction strategies, inform occupational safety guidelines, and support communication with firefighters and other interested parties about potential risks and trends.

2 APPROACH

ERG's approach to developing this report consisted of an environmental scan of PFAS biomonitoring methodologies including leveraging ERG's internal expertise and experience conducting biomonitoring programs across the country, a literature review of scientific studies and protocols, as well as structured interviews with principal investigators from other biomonitoring programs and with Minnesota firefighter organizations. Each of these components is described in more detail below.

2.1 Review of Internal Resources

ERG began by gathering and organizing relevant internal resources to inform the report structure and content. ERG first compiled all PFAS biomonitoring protocols, standard operating procedures (SOPs), quality assurance/quality control (QA/QC) documents, exposure history questionnaires, participant communications, and data analysis tools that we have used in the past 5 years. These resources have been refined through ERG's experience supporting PFAS biomonitoring in more than 11 communities across the country on behalf of federal and state agencies.

ERG also requested internal guidance documents and protocols from MDH that would be relevant for conducting a state-led biomonitoring program. This included past reports, protocols, or data analysis templates. We also requested internal policies that MDH might have on human subjects research and interviewed the state public health laboratory. This step was to ensure that recommended protocols to conduct a state-led biomonitoring program would align with the department's priorities.

2.2 Review of Published and Grey Literature

In addition to compiling relevant internal assets, ERG identified external government reports, white papers, and peer-reviewed publications related to PFAS exposure and biomonitoring among firefighters. The goal was to gather published evidence on biomonitoring study designs, data collection protocols, laboratory methods, exposure assessment strategies, and data analysis procedures. To do this, ERG conducted a literature review in PubMed® and ad-hoc targeted searches in Google Scholar to ensure broad coverage of both peer-reviewed and government-sponsored studies. Search terms were designed to capture research relevant to the United States firefighter workforce and focused on 1) studies reporting PFAS blood biomonitoring results and methods among firefighters, and 2) biomonitoring activities among Minnesota-based firefighter populations (including for non-PFAS exposures). Articles were screened for relevance and categorized by their applicability to major sections of this report.

A summary of databases queried, search terms, and inclusion criteria is provided in Appendix A – Literature Review Strategy.

2.3 Structured Interviews with Other State Agencies

To supplement findings from the literature review and ensure that the expert report reflects not just theoretical best practices but also real-world experience, ERG also identified existing state-led PFAS biomonitoring programs focused on firefighters. The goal was to find programs most applicable to a potential Minnesota-led initiative and to gather insights on best practices and common challenges. ERG then conducted structured interviews with principal investigators or program leads from selected states to learn from their on-the-ground experiences. Specifically, ERG spoke with representatives from biomonitoring programs conducted by the Michigan Department of Health and Human Services, the California Department of Public Health, and the Indiana Department of Homeland Security. These conversations provided practical insights into:

- Effectiveness of different recruitment and retention strategies.
- Challenges and solutions encountered during field implementation.
- Laboratory coordination logistics.
- Data analysis challenges.
- Result communication practices.

These details are not always fully described in published literature, and some of the interviewed programs were still in progress, allowing ERG to access preliminary materials and learnings before final reports were released. Insights from these interviews are incorporated throughout the report.

The questions asked during the structured interviews are included in Appendix B – Structured Interview Questions.

2.4 Structured Interviews with Firefighter Organizations

To ensure the recommendations in this report reflect the practical realities, concerns, and priorities of Minnesota's firefighter community, ERG conducted structured interviews with representatives from firefighter associations across Minnesota. These interviews were designed to gather perspectives on how best to design a firefighter-focused biomonitoring program that is responsive to the needs of participants. The discussion focused on better understanding perspectives related to:

- Perceived benefits and risks of biomonitoring participation.
- Preferences around timing, location, and format of biomonitoring events.
- Ideas for incentives or motivations to encourage participation.
- Barriers to participation.
- Recommendations for trusted messengers or channels for recruitment.
- Preferences for outreach and communication.
- Experiences with previous health monitoring or research initiatives.

The input received from these interviews directly informed the recommendations throughout this report, especially those related to recruitment, consent, result communication, and community engagement. The questions used to guide these structured interviews are included in Appendix B – Structured Interview Questions.

2.5 Report Organization

This report synthesizes findings from all the above data sources into a set of best-practice recommendations, organized around the core components of a PFAS biomonitoring program. Table 3 outlines the focus of each section and how it contributes to the overall design and implementation of a potential firefighter biomonitoring program in Minnesota. Each section describes relevant methodologies drawn from prior firefighter and occupational biomonitoring studies and offers tailored considerations for the Minnesota context. The structure is designed to reflect the practical decisions MDH and its partners would need to make when planning and conducting a future study.

Table 3. Report structure organized by key elements of a biomonitoring program

Section	Topics Discussed
3. Study Design	General study design choices and objectives, sampling frame, IRB and eligibility
4. Recruitment and Consent	Engagement strategies, informed consent approaches, participation barriers
5. Exposure Assessment	Collection of contextual exposure data (e.g., AFFF use, gear practices)
6. Sample Collection	Biological matrices, field logistics, participant experience
7. Laboratory Analysis	Laboratory partnerships, analyte selection, QA/QC practices
8. Data Analysis	Statistical methods, stratification, comparison populations
9. Reporting Results	Approaches for individual and aggregate result communication
10. Conclusions	Summary of key findings, cross-cutting themes, and considerations for future biomonitoring efforts in Minnesota

3 BIOMONITORING STUDY DESIGN

The design of a PFAS biomonitoring project in firefighters will depend on its goals, which might include estimating PFAS exposure levels in a defined population, exploring differences across subgroups (e.g., by job role, geographic region, or gear use), or guiding public health policies and exposure reduction strategies. Study design decisions have implications for data quality, generalizability of results, budget, logistical complexity, and ethical oversight by an Institutional Review Board (IRB).

Key elements of study design involve defining a target population, determining eligibility criteria, and selecting a sampling strategy that balances scientific rigor with feasibility. As emphasized in guidance provide by the CDC, CSTE, APHL, these study design choices impact all downstream aspects of the biomonitoring project (CDC, 2023; CSTE, 2012; APHL, 2019).

3.1 Overview of Types of Study Designs

Several types of study designs are used in biomonitoring. Here we describe three key considerations in the choice of study design including the purpose of the study, sampling approach, and study timeline.

Purpose: Surveillance vs. Research

Depending on the purpose, a biomonitoring project may be classified as research or public health surveillance. Research is "a systematic investigation designed to develop or contribute to generalizable knowledge" (45 CFR § 46.102(l)). Research studies require IRB involvement and adherence to federal human subjects research protections requirements. Surveillance studies are led by public health authorities "to identify, monitor, assess, or investigate potential public health signals, onsets of disease outbreaks, or conditions of public health importance" (45 CFR § 46.102(l)(2)). Surveillance activities typically aim to collect data to inform short-term or immediate public health action. A biomonitoring project that is designated as a surveillance activity is excluded from the definition of research; meaning it does not require IRB involvement under federal regulations (OHRP, 2018). Because the line between public health surveillance and research can be difficult to draw, the MDH IRB should be consulted to determine whether a study requires IRB oversight. Biomonitoring projects that are deemed public health surveillance or classified as research exempt from IRB review (45 CFR § 46.104) should still follow best practices for human subjects protections and applicable laws governing data privacy.

Sampling Approach: Representative vs. Convenience Sampling

Another key consideration when designing a biomonitoring project is whether the sample is intended to be representative of a broader population. Representative sampling incorporates some element of randomness and is often probability-based. When properly conducted with a sufficient sample size, this type of sampling design allows results to be generalized to the larger target population and minimizes potential bias. Probability-based sampling can also be used to make sure certain subgroups are included in a study by applying stratifications and weights. For example, a stratified random sampling might randomly select participants from firefighter departments across the state while guaranteeing that both rural and urban departments are included. CDC provides more detailed guidance on conducting probability-based sampling for a biomonitoring project (CDC, 2023). A representative sampling approach is preferred for surveillance studies; however, it is often more logistically challenging due to greater time and resource demands to recruit and enroll participants in a manner that ensures statistical validity.

In contrast, convenience sampling selects participants based on accessibility or willingness to participate, such as firefighters from departments with existing PFAS concerns or those recruited through word-of-mouth. While the results of this type of study may not be generalizable, they can still

provide valuable insight into exposure patterns (APHL, 2019). In addition, a convenience sample can still provide a public health service to those most concerned about their individual exposures. This approach can also help pilot the protocols ahead of a larger effort rollout or collect preliminary data to determine whether and how a larger study should be conducted.

Study Timeline: Cross-sectional vs. Longitudinal Designs

A cross-sectional study measures exposure levels in participants at a single point in time. This design is useful for establishing baseline exposure levels, comparing subgroups, and identifying general exposure patterns all at a specific point in time. Most existing firefighter biomonitoring projects have used cross-sectional designs to characterize exposure across regions or occupational roles.

In contrast, longitudinal studies involve repeated measurements in the same individual or population over time. This design can be used to assess changes in PFAS levels following interventions (e.g., gear changes, AFFF phase-outs) or to track exposure trends. However, while longitudinal designs offer greater insight into exposure dynamics, they are generally logistically more complicated and more resource-intensive than cross-sectional designs. Longitudinal studies require greater investment in participant follow-up, ongoing consent, IRB oversight, and long-term data management. However, longitudinal studies may offer more insight into how firefighter PFAS exposures evolve over time or respond to interventions. MDH's East Metro PFAS Biomonitoring project began as a cross-section study and became longitudinal when MDH asked that the same participants return for blood testing (MDH, 2024d).

3.2 Selection of Target Population and Sampling Frame

Another key step in designing the study is clearly defining the target population and the sampling frame. The target population are the people the study focuses on and which the results are meant to reflect. In a PFAS biomonitoring study of Minnesota firefighters, the target population could range from all firefighters statewide to more narrowly defined groups such as:

- Only professional (career) firefighters in Minnesota.
- Firefighters who have used or trained with AFFF.
- Firefighters employed at or near airports.
- A combination of these.

The specific population chosen should be guided by the study's goals, whether the aim is broad surveillance, targeted exposure assessment, or hypothesis testing. Within that population, clear eligibility criteria should be defined. These may include minimum years of service, type of fire response (e.g., structural, wildland, aircraft), exposure history (e.g., documented AFFF use), or department characteristics. Eligibility criteria help ensure consistency in who is included, promote transparency, and support reproducibility.

Once the target population and eligibility are defined, the next step is to construct a sampling frame. The sampling frame is the actual list or other source material from which participants are selected. The target population and sampling frame influences who is eligible to participate, the generalizability of findings, and the methods for recruitment. A well-defined sampling frame is essential for minimizing selection bias and enabling the use of probability-based sampling methods (APHL, 2019; CDC, 2023). If participants are self-selected, the findings are unlikely to be generalizable to the broader target population (APHL, 2019). The sampling frame should closely align with the target population and contain

sufficient detail to allow stratification or oversampling if subgroup comparisons are a part of the study design.

Usually no single, centralized roster exists that includes complete contact information and demographic details for all individuals in a target population. This presents challenges for drawing a fully representative sampling frame. Constructing a high-quality sampling frame can often require creative data integration from multiple sources (CDC, 2023). For example, potential data sources for building the sampling frame for a firefighter biomonitoring study may include:

- State fire marshal or licensing agency records.
- Department rosters obtained through direct outreach.
- Union or professional association membership lists.
- Training program rosters or firefighter certification databases.

Each data source might have advantages and limitations with respect to completeness, accuracy, and accessibility. For example, state-level firefighter databases may be more complete for career departments but undercount volunteers. Union lists may include detailed contact information but exclude non-members. A combination of data sources, along with collaboration from local departments and associations, may be necessary to create a usable sampling frame that reflects the target population.

When a complete sampling frame is not feasible, investigators should clearly document the limitations of the available sampling frame, the rationale for its use, and any potential implications for generalizability. Finally, the sampling frame should include or allow for the collection of information that supports stratified sampling or oversampling of underrepresented groups or higher-risk groups. For example, a study might stratify by urban versus rural department, or oversample departments known to have used AFFF extensively. In some cases, hybrid models combining probability and convenience sampling may offer a practical compromise between representativeness and feasibility.

3.3 Examples from Other PFAS Biomonitoring Projects

Minnesota's East Metro Biomonitoring Project provides an important precedent for state-led PFAS biomonitoring (MDH, 2024d). Conducted by MDH in response to drinking water contamination in Washington County, the study assessed serum PFAS concentrations in residents whose private wells or municipal supplies were contaminated. Although not designed to be representative of the statewide population, the study aimed to characterize exposures among a clearly defined, high-risk community. Initially launched in 2008 as a cross-sectional study, it transitioned into a longitudinal design when participants were resampled in 2010 and 2014 to assess the effectiveness of water treatment interventions. This design allowed MDH to evaluate both baseline exposure and the impact of public health actions over time.

Several other states have recently implemented PFAS biomonitoring studies specifically focused on firefighters. These efforts illustrate a range of study designs, target populations, and sampling strategies that are relevant to Minnesota's context:

- **Michigan's PFAS in Firefighters of Michigan Surveillance (PFOMS)** project is a statewide public health surveillance study led by the Michigan Department of Health and Human Services (MDHHS, 2025a). Its goal was to determine average PFAS serum levels among both career and volunteer firefighters across the state. It used a stratified sampling strategy, inviting all fire departments that support airports, the largest fire departments, and a random sample of the

remaining departments stratified by rural and urban classification. All firefighters in the selected departments were eligible to participate. A total of 1,023 participants completed exposure history questionnaires and provided blood samples for laboratory analysis. Because the study was classified as a public health surveillance effort, it was not subject to IRB oversight.

- **California's Firefighter Occupational Exposures (FOX) project** was an early firefighter biomonitoring effort led by Biomonitoring California, a joint program between California Department of Public Health, Office of Environmental Health Hazard Assessment (OEHHA), and the Department of Toxic Substances Control (DTSC) (Biomonitoring California, 2025; Dobraca et al., 2015). Conducted in Southern California, the study aimed to assess blood concentrations of PFAS and flame retardants among full-duty firefighters. It used a convenience sample of 101 active firefighters scheduled for their voluntary annual or biannual wellness exams. The study was not designed to be representative and limited participation to individuals who had been in active service for at least 12 months. The study protocol and informed consent process were approved by both the state IRB and the university IRB.[1]
- **Indiana's PFAS Testing Pilot Program** is a statewide biomonitoring initiative led by the Indiana Department of Homeland Security (IDHS). The pilot program offered free PFAS blood testing to active and retired firefighters across the state. Firefighters from across the state were encouraged to apply and a subset was randomly selected from the pool of volunteers using a stratified sampling approach based on 10 IDHS districts that cover the entire state. Enrolled participants (N=380) completed a questionnaire on firefighting activities and submitted blood samples using self-administered home collection kits. As a public health surveillance effort, the project was not subject to IRB oversight (IDHS, 2024).

These examples demonstrate different approaches to state-led firefighter biomonitoring projects. They illustrate key considerations related to sampling design, participant recruitment, and IRB oversight. The programs also varied in scale from statewide surveillance initiatives with over 1,000 participants to smaller, localized pilot efforts of 100 people demonstrating that biomonitoring can be adapted to different levels of resources and public health priorities. Table 4 describes the study design of these studies and additional studies on PFAS biomonitoring in firefighters identified in the literature review, including study design, target population, and sampling approach.

[1] Since the time of this study, updates to the Common Rule (45 CFR § 46) have introduced requirements for the use of a single IRB of record in many multi-institutional studies involving human subjects.

Table 4. Study designs for PFAS biomonitoring studies of firefighters in the United States

Study	Study Design	Target Population	Sampling Approach	IRB	Sample Size
MDHHS' PFOMS Project	Cross-sectional surveillance	Career and volunteer FF statewide in MI	Stratified by department type and region	Non-research (surveillance)	~1,000+
Biomonitoring California's FOX Study	Cross-sectional research	Active-duty FF in Southern CA	Convenience sample (scheduled wellness exams)	IRB-approved (state + university)	~100
IDHS' PFAS Testing Pilot Program	Cross-sectional surveillance	Active-duty and retired FF statewide in IN	Stratified by district, participation	Non-research (surveillance)	380
Burgess et al., 2025	Cross-sectional research	Career FF	Convenience sample	IRB (university)	290
Furlong et al., 2025	Cross-sectional research	Active-duty career municipal (TFD) or airport FF	Convenience sample	IRB (university)	303
Mitchell et al., 2025	Longitudinal research	Frontline essential workers in AZ (FF within)	Convenience sample	IRB (federal + university)	280 (FF) 1960 (total)
Nematollahi et al., 2024	Cross-sectional and longitudinal research	Active-duty career FF recruits or incumbents within TFD	Convenience sample	IRB (university)	154
Quaid et al., 2024	Cross-sectional research	Career FF (TFD and other)	Convenience sample	IRB (university)	440
Goodrich et al., 2021	Cross-sectional research	Active-duty career FF from AZ (TFD), MA or CA	Convenience sample	IRB (university)	197
Graber et al., 2021	Cross-sectional research	Recruits and incumbent volunteer FF in a department in NJ	Convenience sample	IRB (university)	135
Khalil et al., 2020	Cross-sectional research	Phoenix and TFD (active-duty career) male FF with 5+ years of experience	Convenience sample	IRB (university)	38
Leary et al., 2020	Cross-sectional research	Active-duty FF at airport (career) and mostly volunteer department in Ohio	Convenience sample	IRB (university)	47
Trowbridge et al., 2020	Cross-sectional research	5+ years' experience, active-duty female FF, nonsmoker in SFFD	Convenience sample	IRB (university)	86 (FF) 170 (total)
Shaw et al., 2013	Cross-sectional research	FF in SF with 5+ years of experience	Convenience sample	IRB (unspecified)	12
Jin et al., 2011	Cross-sectional surveillance	Class-action claimants (male FF within)	Class-action lawsuit	Non-research (surveillance)	36 (FF) 8,826 (total)

FF = Firefighters, TFD=Tucson Fire Department, SFFD=San Francisco Fire Department

4 RECRUITMENT AND INFORMED CONSENT

Recruitment and informed consent are essential to any biomonitoring project. For a firefighter-focused PFAS biomonitoring program in Minnesota, these components should be tailored to the unique needs, concerns, and organizational structure of the state's fire service. Minnesota's firefighter population is geographically and organizationally diverse encompassing career, volunteer, paid-on-call, and combination departments across urban and rural communities.

This diversity presents both opportunities and challenges for equitable and representative recruitment. For example, unlike career firefighters, volunteers are not regularly stationed at firehouses, making them harder to reach through traditional recruitment channels and less available for in-person appointments. These structural characteristics require flexible recruitment strategies and consent procedures that accommodate various schedules and communication preferences.

This section outlines strategies for recruiting firefighters across Minnesota and obtaining their consent in ways that supports study participation, protects participant rights, and fosters community confidence in the program. Recommendations draw from CDC, APHL, and CSTE guidance, results of the literature review (e.g., Nilsson et al., 2022), and lessons learned from previous firefighter biomonitoring studies.

4.1 Recruitment and Enrollment Strategies

Recruitment strategies for biomonitoring projects should align with the goals, design, and scope of each project. Some biomonitoring projects aim for broad statewide participation, while others focus on specific exposures or targeted populations. In either case, a successful recruitment strategy often combines top-down approaches initiated by state or department leadership with bottom-up approaches like direct outreach at the individual level. Using both methods can help ensure broad awareness and maximize participation.

Engagement with Firefighter Organizations and Leadership

Firefighter organizations should play a central role in helping to promote any PFAS biomonitoring project. Their endorsement can also help legitimize the study and they can greatly improve recruitment outcomes. Therefore, as a first step, the project leads should engage with trusted firefighter organizations. In Minnesota, state-level associations that could support recruitment and enrollment include:

- Minnesota State Fire Chiefs Association (MSFCA).
- Minnesota State Fire Department Association (MSFDA).
- Minnesota Professional Fire Fighters (MPFF).
- Minnesota Firefighter Initiative (MnFIRE).
- Minnesota State Fire Marshall.
- Minnesota Fire Service Foundation.
- Minnesota Board of Firefighter Training and Education (MBFTE).

Direct communication with fire chiefs, department leadership, and other association leadership can also facilitate obtaining firefighter rosters, understanding scheduling details, and disseminating study materials. These leaders can also help identify other local champions to promote the study and help coordinate logistics.

Multichannel Recruitment and Enrollment

Providing multiple enrollment pathways improves accessibility and helps accommodate the needs of different firefighter groups, including volunteers and paid-on-call staff who may not have regular firehouse shifts. Recruitment and enrollment should leverage communication platforms that firefighters already trust and use including:

- Statewide association communications.
- Firefighter union bulletins or listservs.
- Department-wide emails, newsletters, or briefing sessions.
- Social media pages managed by fire departments or associations.
- Announcements at firefighter conferences.
- Materials distributed at training events or licensing exams.

Recruitment messages should clearly explain the purpose of the study, how data will be used, and the steps taken to protect confidentiality. Messaging should be concise, written in plain language, and answer common questions. Recruitment materials may include:

- Project overview and timeline.
- Enrollment instructions.
- Frequently Asked Questions (FAQ).
- Contact information.
- Factsheets/infographics about PFAS and the situation in Minnesota from authoritative sources (e.g., CDC, MDH).
- Visual materials such as infographics on PFAS and biomonitoring.

Depending on the study design, recruitment materials may need to be tailored to different levels. For example, messages for department leadership may differ from those sent to individual firefighters. Messaging should address the specific concerns of each group, which may differ.

Flexible enrollments options can increase participation by accommodating varying schedules and levels of comfort with technology. A wide range of options have been used by biomonitoring projects to bring enroll participants including:

- Online sign-up portals accessible by computer or smartphone.
- In-person enrollment at fire stations or during fire service events.
- On-site registration at annual health exams, wellness checks, training sessions, departmental meetings, or conferences.
- Mailed consent packets with pre-paid return envelopes.
- Telephone-based enrollment support.

Conferences may offer a concentrated opportunity to raise awareness and recruit from across departments in the state. In Minnesota, many of the firefighter associations will have annual conferences.

Incentives and Participant Engagement

Offering incentives can support recruitment and demonstrate appreciation for participants' time. While compensation is not always necessary, small gestures can improve participation rates and foster goodwill. Most studies did not offer monetary compensation. However, when they did they were relatively small amounts. For example, in Michigan's PFOMS project, firefighters received a $25 gift card. Other programs have provided snacks, certificates of participation, or other small tokens of appreciation. These approaches can be particularly helpful in engaging volunteers and paid-on-call firefighters who may participate outside of regular work hours.

4.2 Informed Consent Procedures

The informed consent process is a critical component of ethical biomonitoring projects. If classified as human subjects research, the informed consent process must comply with legal requirements (listed in 40 CFR § 26.116). Regardless of classification, the project should follow best practices that respect participants' choices, clearly explain what's involved (e.g., benefits and risk), and build trust. While this section does not list all elements required under federal human subjects regulations, it summarizes key considerations and recommended practices for biomonitoring in firefighters.

Consent materials should be provided in clear, plain language and be available in multiple formats (e.g., paper and electronic) and languages to ensure accessibility. Using an electronic consent platform can streamline enrollment, particularly for participants in remote or volunteer departments. However, participants should also be given opportunities to ask questions and should be clearly informed that participation is voluntary, that they may withdraw at any time, and that declining participation will not affect their employment or standing in any way. Materials should also describe how blood samples and questionnaire data will be stored, how long they will be retained, and who will have access. Any relevant agency or state data privacy policies should be followed, and participants should be informed of these protections as part of the consent process.

Given the occupational context, it is especially important to address concerns about confidentiality and potential employment implications. The consent process should include explicit language about how data will be de-identified, who will have access to individual-level results, and the limits of data sharing. These assurances can reduce fears related to data misuse, impacts on employment, or implications for health insurance.

4.3 Addressing Recruitment Barriers

Recruitment and consent are the first steps when potential firefighters are directly involved in the project. However, several logistical, organizational, and cultural challenges can make it hard for them to participate. It is important to identify and address these barriers to make sure enough firefighters from across Minnesota will participate. The rest of this section describes common challenges and ways to address them. Below are common challenges and strategies for overcoming them:

- **Leadership Buy-In and Departmental Approval.** Participation in biomonitoring programs may require approval or support from department leadership. Not having departmental approval or encouragement can limit access to personnel and slow recruitment efforts. In Minnesota's decentralized fire service, reaching and coordinating with hundreds of independent departments may be time intensive. Reaching out to leadership early can help build support and encourage more people to take part.
- **Operational and Scheduling Constraints.** Firefighters often work irregular, rotating shifts that can include overnight hours or on-call schedules. These schedules can make it difficult

to identify specific time when a wide range of people would be available to participate in biomonitoring events. To address these constraints, project staff could offer flexible, off-hours scheduling opportunities.

- **Privacy and Data Security Concerns.** Firefighters might feel hesitant to participate in studies or initiatives due to concerns surrounding the handling of their personal data and biospecimens. Specifically, they may worry about how their information will be used in research, whether it will be securely stored to protect their privacy, whether their samples will be tested for anything else (e.g., drugs), and how or if their data will be shared with third parties. Recruitment and consent materials should describe how personal data and results will be protected and kept confidential, and not shared with employers or regulatory bodies. Strong safeguards can minimize risk and build trust. In some instances, individual results could be sought in legal proceedings. However, the Department of Health and Human Services can provide a Certificate of Confidentiality, which protects identifiable, sensitive biomedical research data from compelled disclosure.
- **Resource and Budget Limitations.** Limited funding can restrict the scope and scale of recruitment efforts, reduce access to participant incentives, and constrain staffing for outreach and coordination. Projects operating on tight budgets may need to rely heavily on existing infrastructure or collaborative partnerships, which can lead to uneven access and increased burdens on participating departments.
- **Accessibility to Participants.** Volunteer and rural departments may be geographically isolated or less connected to centralized communication systems, making them harder to reach. Without intentional strategies to ensure inclusion, certain firefighter groups may be excluded from participation, which could weaken the validity and applicability of the findings. Accessibility can be improved by offering flexible scheduling options, translated materials, virtual appointments, and regional collection sites.
- **Unclear Program Purpose or Benefits**. If firefighters do not understand the goals of the program or how it relates to their health and safety, they may not prioritize participation. Firefighters are more likely to take part when they understand how the program supports their health, contributes to occupational safety policies, and benefits the wider fire service community.

4.4 Examples from Other PFAS Biomonitoring Projects

Understanding how different states approach firefighter biomonitoring recruitment offers valuable insight into effective and common challenges. While each state approached and tailored its strategy to local needs, leadership structures and available resources, these models reveal key themes around communication, consent, and participation engagement. The following highlights recruitment efforts and engagement techniques conducted in biomonitoring studies in three states: Michigan, California, and Indiana.

- **Michigan's PFOMS project** enrolled 1,026 participants from 64 fire departments across the state, with support from the State Fire Marshal, firefighter unions, and support organizations. An interdisciplinary project team reached out to fire departments and firefighters through 2,200+ mailed recruitment packets, 1,900+ phone calls, 180+ posters distributed to fire departments, and monitoring of an email address and toll-free hotline (MDHHS, 2024). Fire departments were randomly selected based on a stratified sampling plan, and eligible participants from those selected departments were screened via phone. A detailed list of frequently asked questions were provided to potential enrollees (MDHHS, 2025b). Appointments were scheduled at the time of the phone screening and survey and appointment

reminders were sent through email or text. Participants were allowed to complete the questionnaire on their own time with up to 10 days to complete following their blood draw. Participants received a $25 gift card once the blood draw and questionnaire were completed (MDHHS, 2025a).

- **California's FOX Project** recruited 101 full-duty firefighters from a Southern California fire department in partnership with the University of California Irvine. Recruitment followed a top-down model, with department fire chiefs approving participation before individuals were invited. Eligible participants were enrolled during their scheduled wellness exams, where paper-based consent was obtained (Biomonitoring California, 2025; Dobraca et al., 2015).
- **Indiana's PFAS Testing Pilot Program** recruited both career and volunteer firefighters through an online sign-up portal, which initially drew over 1,000 applicants on the first day. Due to a communication error, the recruitment process had to be restarted, but interest remained high. A total of 180 participants who applied were randomly selected from across the 10 IDHS districts. The program was supported by the Indiana State Firefighters Association, which helped promote participation and had previously advocated for the program's creation. No financial incentives were offered to participants (IDHS, 2024).

These examples highlight a range of successful strategies, such as integrating recruitment into wellness exams, leveraging partnerships with firefighter associations, and offering flexible enrollment options. Each program shared examples of recruitment materials that can be used to inform a Minnesota specific project.

5 EXPOSURE ASSESSMENT

Understanding how firefighters are exposed to PFAS is essential for interpreting biomonitoring results and identifying opportunities for exposure reduction. PFAS exposure in the fire service is complex and can occur through multiple occupational sources, including firefighting foams, turnout gear, and contaminated fire station environments. This section describes common exposure pathways, strategies for collecting exposure data, and examples of how other PFAS biomonitoring programs have assessed firefighter exposures.

5.1 Occupational PFAS Exposure Pathways in Firefighters

As discussed in Section 1.2, firefighters are occupationally exposed to PFAS through several pathways, many of which are unique to the fire service. The primary routes of exposure include:

- **Dermal absorption.** PFAS can be present in the outer and inner layers of turnout gear and may also be encountered through direct contact with AFFF. Exposure may be elevated when gear is worn for extended periods, damaged, or contaminated.
- **Inhalation.** Firefighters may inhale PFAS from volatilization on turnout, use or proximity to AFFF, or combustion of PFAS-containing materials. Although self-contained breathing apparatus (SCBA) provides protection during active firefighting, inhalation exposure can occur during overhaul, cleaning, or when SCBA use is inconsistent.
- **Ingestion.** Indirect ingestion of PFAS can happen through hand-to-mouth behaviors after handling contaminated gear, eating or drinking in contaminated environments, or ingesting indoor dust. Studies have shown that dust in fire stations, particularly in gear storage areas, can contain elevated levels of PFAS (Mazumder et al., 2023).

The degree of PFAS exposure may also vary by job role (e.g., firefighter, officer, driver/operator), frequency of AFFF use, cleaning habits, and adherence to safety protocols. Understanding these occupational pathways helps inform exposure assessment strategies and supports more accurate interpretation of biomonitoring results.

5.2 Approaches to Capturing Exposure Information

Most biomonitoring studies assess PFAS exposure in firefighters through a combination of exposure history questionnaires and environmental sampling, which together help identify patterns, sources, and risk factors for PFAS exposure.

Exposure History Questionnaires

Exposure history questionnaires contain individual-level information that can help interpret biomonitoring data and identify patterns of occupational exposure. These questionnaires are typically administered alongside biospecimen collection and allow researchers to explore how PFAS levels vary with job duties, protective practices, and other factors. Questionnaires can also help identify high-risk subgroups within the firefighter population. Most firefighter-focused questionnaires include the following types of information:

- **Demographics, particularly those that may affect PFAS pharmacokinetics (e.g., age, sex).** Demographic factors can influence how PFAS is absorbed, distributed, and eliminated from the body. For example, older individuals may have higher PFAS levels due to longer cumulative exposure and slower elimination. Women may have lower PFAS levels due to elimination through menstruation, pregnancy, and lactation.

- **Lifestyle and environmental factors (e.g., diet, water source).** PFAS exposure can occur outside of the workplace through drinking water, food, and consumer products. Individuals who consume locally sourced fish or game, or who rely on contaminated private wells, may have higher non-occupational PFAS exposures. Tracking these factors helps distinguish occupational from environmental exposure pathways.
- **Work history (e.g., years of service, department type, primary roles).** Years of service can serve as a proxy for cumulative occupational exposure. Department characteristics, such as being a career vs. volunteer, may influence frequency of fire calls, use of PFAS-containing AFFF, and exposure control practices. Specific job roles (e.g., firefighter, engineer, chief) can reflect differing levels of exposure based on duties and time spent at fire scenes.
- **Occupational risk factors (e.g., frequency of AFFF use, turnout gear cleaning practices, use of SCBA during overhaul).** These questions assess specific behaviors linked to known PFAS exposure pathways. Frequent use of AFFF (aqueous film-forming foam), infrequent gear cleaning, and failure to wear respiratory protection during overhaul can all be associated with increased PFAS exposure. Capturing these practices helps identify modifiable risk factors.
- **Relevant health information (e.g., blood donation frequency, kidney disease).** Health conditions can influence PFAS retention. For example, individuals who donate blood regularly may have lower PFAS levels due to its removal during donation. Conversely, kidney disease may impair PFAS excretion, leading to higher body burdens. Understanding these factors improves interpretation of biomonitoring results.

While exposure questionnaires are a practical and cost-effective way to assess potential PFAS exposures, they also have limitations. Responses rely on participant recall and self-report, which can introduce recall bias or inaccuracies, especially when asking about long-term habits or past events. In addition, standardized and validated exposure assessment instruments specific to PFAS are still under development. However, several studies have published their survey tools, which can serve as a starting point for future efforts. Despite these limitations, well-designed questionnaires are essential for identifying high-risk subgroups within the firefighter population and can guide both statistical analyses and occupational health recommendations.

Environmental Sampling

Environmental sampling can complement exposure questionnaires by providing objective measurements of PFAS contamination in firefighters' work environments. These data help validate self-reported information and highlight potential exposure sources that may not be evident from questionnaires alone. Although not always included due to cost and logistical constraints, environmental sampling can be a valuable component of a comprehensive exposure assessment when resources allow. Key environmental sampling approaches include:

- **Fire station dust sampling.** Dust samples collected from gear locker rooms, living areas, or apparatus bays can be analyzed for PFAS (Young et al., 2021). Elevated PFAS levels in dust may indicate ongoing sources of contamination within the station and offer insight into indirect exposure pathways, including inhalation and incidental ingestion. Dust sampling can also help identify high-exposure areas and support targeted mitigation strategies (e.g., improving cleaning protocols or ventilation).
- **Turnout gear sampling.** Surface wipe tests or fabric extractions from turnout gear can detect PFAS residues accumulated from fire response activities or manufacturing treatments. These samples provide direct evidence of potential dermal and inhalation exposure risks associated

with wearing contaminated gear. Sampling can be done before and after cleaning to assess decontamination effectiveness and inform replacement policies (Benner et al., 2024; Young et al., 2021).

- **Other environmental samples.** Some programs may also collect additional environmental samples (drinking water, air, and household dust). For example, testing drinking water sources at fire stations or households would allow distinguishing between occupational and environmental exposures. Other less common approaches include air sampling to evaluate inhalation risks, and household dust sampling to assess the potential for take-home exposures. Emerging tools such as silicone wristbands or other wearable passive samplers have also shown promise in characterizing personal PFAS exposures across environments (Hoxie et al., 2024).

Environmental sampling may be conducted at various times to assess changes in contamination levels, such as before and after gear cleaning, after fire calls involving AFFF, or during different seasons. These timing decisions should align with the study's exposure assessment goals.

5.3 Examples from Other PFAS Biomonitoring Projects

This section summarizes findings from ERG's literature review and interviews with principal investigators from state-led biomonitoring programs. The examples below highlight different strategies used to assess occupational PFAS exposure in firefighters and lessons learned related to questionnaire design, follow-up methods, and environmental sampling.

Timing of Questionnaire Administration

Firefighter biomonitoring programs vary in when participants are asked to complete exposure questionnaires. Most studies administered the survey on-site during the appointment, often alongside blood collection (Dobraca et al., 2015; Leary et al., 2020). Some studies ask participants to complete the questionnaire during enrollment before their appointment and data were available for review during the visit (Burgess et al., 2025). Michigan's PFOMS study also allowed participants the option to complete the survey after their blood draw, allowing for greater scheduling flexibility and participant convenience. Each approach offers tradeoffs between data availability, completion rates, and logistical complexity.

Mode of Administration

Questionnaires may be self-administered or conducted through interviews. Virtual or online questionnaires are convenient and scalable but can lead to quality issues due to skipped questions or misinterpretation (Burgess et al., 2023; Graber et al., 2021). Often virtual platforms are used such as REDCap or Qualtrics surveys. The Michigan PFOMS study implemented an online system with built-in checks to reduce missing data. In-person or interviewer-administered formats allow for real-time clarification and can help build rapport, though they require more resources (Dobraca et al., 2015; Shaw et al., 2013). Survey length varied across studies, ranging from approximately 15 minutes (Dobraca et al., 2015) to about 45 minutes (Graber et al., 2021).

Longitudinal Follow-Up

Some studies have adopted longitudinal designs to capture evolving occupational exposures. For example, Burgess et al. (2025) and Nematollahi et al. (2024) used follow-up questionnaires to track changes in job roles and PFAS-related activities. Navarro et al. (2022) surveyed wildland firefighters before and after fire seasons to understand changes in exposure. While this approach enhances the ability to study exposure trends over time, it also introduces challenges such as participant attrition and the need to maintain consistency across survey rounds.

Environmental Sampling Practices

While environmental sampling can provide objective data to complement self-reported exposures, its use in firefighter PFAS biomonitoring studies has been limited. Among the studies reviewed, only Michigan's PFOMS study incorporated environmental sampling, which involved testing drinking water at participating fire stations to assess potential ingestion exposures. None of the other biomonitoring projects reviewed included environmental sampling such as station dust collection or turnout gear testing. As discussed above, these approaches have been used in related PFAS exposure research.

6 SAMPLE COLLECTION

Biomonitoring studies rely on the careful collection, handling, and documentation of biological samples to ensure valid and interpretable results. Standardized protocols are used to maintain sample integrity during every step—from selecting appropriate specimen containers to storing and shipping samples to the laboratory. This section outlines best practices for sample collection, handling, storage, and transport.

6.1 Sample Type and Collection Protocols

In PFAS biomonitoring studies, blood is the most commonly collected sample type, typically processed as serum or plasma. Some studies also collect urine, although PFAS concentrations in urine are generally much lower than in blood. The optimal biological matrix may vary depending on the specific PFAS of interest and the exposure window of interest. For example, urine or whole blood may be more suitable for detecting PFAS with shorter biological half-lives, though this approach is not yet widely used (NASEM, 2022). The following best practices highlight key considerations for specimen collection protocols, container selection, labeling, and shipping procedures for on-site blood sample collection. At-home PFAS test kits are also available from commercial laboratories but these are not discussed here because they are not widely used for biomonitoring.

Specimen Collection Protocols

Collection protocols should be developed in collaboration with laboratory staff and state public health officials. These protocols should include detailed procedures for:

- Selecting and preparing PFAS-free sample containers (container volume specified by the laboratory/analytical method).
- Preventing cross-contamination during sample collection and processing.
- Labeling specimens and ensuring proper chain of custody.
- Instructing participants on pre-sampling guidance (e.g., adequate hydration).
- Serum processing procedures.
- Ensuring timely storage, temperature control, and shipping.

Each step in the process should be clearly documented in a written standard operating procedure (SOP), and staff should be trained accordingly. Consistent implementation of the SOP across all collection sites helps maintain data integrity and comparability.

PFAS-free Specimen Collection Containers

Because PFAS are widely used in consumer and industrial products, including some plastics, careful attention must be paid to the materials used in specimen collection and processing. PFAS can leach from collection devices and contaminate samples if appropriate materials are not used. Supplies such as collection tubes, transfer pipettes, and cryogenic vials for serum that will come into contact with samples should be certified PFAS-free or lot-tested for PFAS contamination prior to use (APHL, 2019; ITRC, 2023). Commonly used materials include polypropylene or polyethylene vials and powder-free nitrile gloves. Broadly speaking, avoid use of Teflon®, polytetrafluoroethylene (PTFE), polyvinylidene fluoride (PVDF), low-density polyethylene (LDPE), ethylene tetrafluoroethylene (ETFE), and other fluoropolymer-coated materials. Laboratories can assist in selecting approved materials or performing

testing to confirm they are free from PFAS contamination. Staff should be trained on PFAS-avoidance during field procedures.

Specimen Identification and Documentation

All specimens should be labeled with unique study IDs, not participant names. Labels should be compatible with freezing temperatures and moisture exposure. A secure key linking participant names to study IDs should be retained only by the principal investigator or an authorized data manager. Where possible, specimens should be tracked using a laboratory information management system (LIMS) that captures:

- Date and time of collection.
- Sample type.
- Collection site.
- Chain of custody information.

Proper documentation reduces the risk of sample mix-ups and supports regulatory and quality assurance compliance.

Serum Processing

Most methods analyze the serum portion of blood for PFAS analysis; standard best practices for separating and aliquoting serum must be followed. Primary steps include:

- Allowing blood samples to clot in the tubes collected from each participant (30 to 120 minutes).
- Spinning tubes in a calibrated, balanced centrifuge for 15 minutes at a minimum speed of 2,400 revolutions per minute.
- Transferring clear serum from the collection tube to storage vials (e.g., cryovials). The size and target volume of serum will be dictated by the analytical method, but the goal is to collect as much serum as possible from each sample.

Preservation and Shipping to the Laboratory

Serum samples should be immediately frozen at temperatures and within the timeframe specified by the receiving laboratory. Samples must remain frozen during transport, requiring reliable cold chain logistics and minimal transit time. All specimens must be shipped in accordance with applicable state and federal regulations (e.g., U.S. Department of Transportation guidelines). Packaging should be selected based on the specimen's hazard classification and mode of transport, and must be clearly labeled. To ensure sample integrity and regulatory compliance, best practices include:

- Using cold packs or dry ice to maintain sample integrity.
- Including temperature monitors if needed to confirm cold chain integrity.
- Completing a chain-of-custody form for each batch of samples.
- Coordinating with the receiving laboratory to confirm readiness and chain-of-custody procedures upon receipt.

6.2 Logistics, Timing, and Feasibility Considerations

Successful sample collection requires careful logistical planning to maintain data quality, minimize participant burden, and use resources efficiently. This section outlines practical considerations for field scheduling, field logistics, and overall feasibility.

Participant Scheduling

Projects should offer flexible scheduling options to encourage participation and reduce disruption to firefighters' routines. Appointments can be scheduled after shifts, on weekends, or during periods of downtime. In some cases, collecting samples while firefighters are on duty or on call, if approved by department leadership, can be both efficient and convenient for participants. Coordination with department leadership can also help identify optimal days and times based on shift calendars, training schedules, or call volumes.

To make appointment setting and rescheduling easy, scheduling processes should provide multiple methods of communication, such as phone, email, or text. Providing advance notice and sending appointment reminders 24 to 48 hours in advance can reduce no-shows and improve sample completion rates. Some projects find it helpful to define a dedicated sample collection window (e.g., over 2 to 3 weeks) across all sites to consolidate staffing needs and lab coordination.

It is also important to maintain privacy and confidentiality during scheduling and sample collection. This may involve staggering appointments or ensuring private spaces are available for sample collection. Finally, contingency planning (e.g., backup appointments or extra sample supplies) can help mitigate missed appointments, walk-in appointments, or unexpected logistical issues.

Site Selection and Field Operations

The choice of collection site is another important factor. Options include conducting sample collection at fire stations, in medical clinics, or using mobile laboratories. Each approach has tradeoffs:

- **Fire station collection** is convenient for participants and may increase participation by minimizing travel and time burden. However, it may present privacy concerns in shared spaces and require careful coordination to avoid interfering with emergency operations or shift changes.
- **Medical center collection**, as used in Shaw et al. (2013), provides a controlled clinical environment with trained staff and established infrastructure for sample handling and storage. However, it may be less accessible for participants from volunteer or rural departments who may not be able to take time off or travel easily to centralized facilities.
- **Mobile laboratory setups** offer the advantage of bringing professional-grade collection equipment and trained staff directly to participants, increasing accessibility and convenience. However, they can be resource-intensive to deploy.

Regardless of the location of the site selected, it is important to ensure that a private space is available for both sample collection and administering any accompanying questionnaires, so participants feel comfortable and can respond candidly to questions about occupational exposure behaviors. All biological samples should be collected by experienced phlebotomists who have been trained on PFAS-specific contamination risks, including avoiding PFAS-containing materials. Sites should also be equipped with appropriate infrastructure for on-site processing of the blood, such as a centrifuge for separating serum. Finally, all hazardous biological waste and sharps should be disposed of according to applicable regulations to protect both staff and the environment.

Cost and Resource Allocation

Sample collection can be resource-intensive. Required elements may include trained phlebotomists, travel expenses, participant incentives, specimen collection supplies or kits, on-site processing equipment (e.g., centrifuges), and appropriate sample processing and storage materials (e.g., cryovials, coolers, dry ice). Projects should also account for staff time needed for scheduling, administrative coordination, and field quality assurance/quality control (QA/QC) procedures.

6.3 Examples from Other PFAS Biomonitoring Projects

Sample collection methods vary across state-led PFAS biomonitoring efforts, depending on local infrastructure, staffing models, and participant needs. Below are examples from recent programs that highlight different logistical approaches and considerations:

- **Michigan's PFOMS Project** collected blood samples from firefighters at departments across the state. Although the original plan was to use the state's mobile laboratory to streamline statewide sample collection, the mobile lab was unavailable due to competing demands. Instead, in-house staff were dispatched to fire stations, where phlebotomists conducted sample collection and in-house laboratory technicians handled on-site processing. Because exposure assessment surveys were completed online prior to the appointment, the sample collection process was efficient with most participants only spending about 10 minutes having their blood drawn.
- **California's FOX Study** collected blood and urine samples from firefighters during their annual or biannual wellness exams. Conducting sample collection at fire stations was logistically efficient; however, project staff noted certain limitations. Specifically, because firefighters were on duty, there was limited time to administer the exposure assessment questionnaire. Additionally, some biospecimens were collected immediately after participants returned from off-duty periods, which could have reduced measured exposures.
- **Indiana's Pilot Study** was one of the few projects to use a self-administered finger-prick blood collection method, with analysis conducted by a commercial laboratory. Participants were mailed at home testing kits, which were required to be returned within 14 days. This approach offered a logistically simple way to collect samples statewide without the need for on-site staff or field logistics. However, potential drawbacks included the inability to observe quality control procedures during collection and some participants failing to return their kits.

7 LABORATORY ANALYSIS

High quality, reliable laboratory data are central to the success of any biomonitoring project. This section reviews attributes of current and evolving PFAS analytical methods and considerations for partnering with analytical laboratories.

7.1 Key Considerations for Method and Laboratory Selection

Selecting the analytical method and laboratory for PFAS analysis in biological samples is determined by a number of factors including study design, available measurement methods, laboratory capacity, resources, among others. Key questions include:

- What are the analytes of greatest interest (as determined by the exposure sources, exposure timeframe, analyte half-lives)?
- Can the method measure target analytes at the level of specificity to answer the study or research question?
- What is the anticipated number and cadence of samples to be collected?
- Does the laboratory have the capacity to process and run the samples within the desired turnaround period?
- How do proposed methods compare to those used to test reference or comparison populations (e.g., CDC NHANES)?

When selecting an analytical method and laboratory partner for a biomonitoring project, focus should be on understanding the differences across available methods and the capabilities of various laboratories to implement the selected method (see Section 7.2). Reviewing documentation of laboratory certifications, method capabilities, quality assurance/quality control (QA/QC) protocols, and data deliverables can help inform and guide the decision-making process.

Laboratory Documentation and Protocol Review

In its guidance for laboratory biomonitoring programs, APHL (2019) describes overall laboratory best practices. To support protocol development, at minimum, lab-specific analytical protocols and procedural documents should be available for review and should detail the following (APHL, 2019):

- Procedures for collecting, labeling, storing, and processing specimens.
- Criteria for rejecting or flagging specimens (e.g., hemolysis).
- Method description, including analyte list, detection limits, and minimum sample volume.
- Method limitations (including possible interferences).
- Equipment and instrumentation.
- Step-by-step procedures for running analyses.
- Preparation of calibration and quality control samples.
- Calibration, calibration curves, acceptance criteria, verification procedures.
- Calculations (e.g., adjustments dictated by the method).

- Quality control procedures, such as blank samples, batch sampling, laboratory control samples, etc.
- External proficiency testing (measurement standardization).
- Data management and reporting systems that can facilitate data analysis and reporting (e.g., electronic data deliverables versus PDF reports).

Quality Assurance and Method Sensitivity

The National Academy of Sciences, Engineering, and Medicine (NASEM), in its guidance on PFAS exposure, testing, and clinical follow-up, emphasizes the importance of robust QA/QC procedures, reporting data traceable to the National Institute of Standards and Technology Standard Reference Material (NIST-SRM), and using methods with limits of detection (LOD) that are comparable to those used by the CDC and academic laboratories (NASEM, 2022).

Non-clinical laboratories that test for PFAS are not always subject to external proficiency programs or clinical certification such as Clinical Laboratory Improvement Amendments (CLIA), which apply to laboratories that return results to patients (NASEM, 2022). For example, CLIA has an exception for "research laboratories that test human specimens but do not report patient specific results for the diagnosis, prevention or treatment of any disease or impairment of, or the assessment of the health of individual patients" (42 CFR § 493.3(b)(2)). Even so, when returning results to individual participants, using a CLIA-certified laboratory is generally considered best practice to ensure analytical quality and regulatory compliance (ATSDR, 2024).

7.2 Analytical Methods and Laboratory Capabilities

Methods to measure PFAS in biological specimens (and across media) continue to evolve, and no universally accepted methods currently exist for PFAS biomonitoring (NASEM, 2022). While many laboratories use methods modeled after those developed by the CDC, variations remain in extraction techniques, instrumentation, and the PFAS analyzed. In contrast, methods for PFAS analysis in environmental media are published and multi-laboratory validated (EPA, 2024). However, adaptations of these methods for human biospecimens are not yet standardized and can vary across laboratories (ITRC, 2023).

Overview of Laboratory Types and Capabilities

As highlighted below, various federal, state, university/research, and commercial laboratories offer analytical services for measuring PFAS in environmental and biological samples, including blood and serum. Most use "targeted" analytical methods involving isotope dilution liquid chromatography tandem mass spectrometry (LC-MS/MS) techniques to quantify a defined subset of the thousands of PFAS. However, some academic and research laboratories are beginning to explore more novel methods, such as non-targeted methods to identify emerging PFAS or "total" PFAS.

- **CDC's Division of Laboratory Systems (DLS)** has been analyzing PFAS in blood for over two decades supporting its National Biomonitoring Program and NHANES. CDC's method currently measures 17 PFAS (including PFOA and PFOS linear and branched isomers) using online solid-phase extraction and analysis by high performance LC (turbo ion spray)-MS/MS (online SPE-HPLC-TISMS/MS) (CDC, 2019). Many PFAS studies funded through CDC grants or cooperative agreements partner with CDC's laboratory for sample analysis.
- **State public health laboratories**, particularly those participating in CDC's National Biomonitoring Program cooperative agreements, have established capabilities for PFAS

analysis. Analytical methods are generally based on or expand on CDC methods. In such instances, PFAS exposure assessment and biomonitoring teams have successfully partnered with their state laboratories for PFAS analysis. In Minnesota, MDH's Public Health Laboratory Division has developed a PFAS analytical method, performed through protein precipitation and analysis via LC-MS/MS using electrospray ionization. The lab is also CLIA-certified and participates in an established proficiency testing program—"CTQ AMAP Ring Test for Persistent Organic Pollutants in Human Serum," which includes PFAS (INSPQ, 2024).

- **University/academic laboratories** can also support PFAS analysis but generally as part of independent or collaborative research initiatives. Many are at the forefront of developing and testing advanced technologies, including non-targeted analytical approaches and methods for measuring total organofluorine or extractable organic fluorine. Non-target mass spectroscopy techniques can detect a broader range of PFAS including novel compounds that lack available analytical standards. However, these methods are not yet standardized, and no reference values are available, making results difficult to interpret (NASEM, 2022). Total organofluorine and extractable organic fluorine are methods for estimating the overall level of PFAS in a sample without identifying or quantifying individual compound.
- **Several commercial laboratories** offer PFAS analysis of human blood and serum, largely using a modified EPA Method 1633, which reports 40 PFAS. The method measures PFAS via solid-phase extraction followed by LC-MS/MS. However, the analytical methods and modifications from these validated laboratory protocols may not be consistent across vendors (ITRC, 2023). Some commercial laboratories offer fingerprick kits (e.g., Eurofins/EmpowerDX) that measure up to 45 PFAS in whole (capillary) blood. Research is ongoing to evaluate whether capillary blood (which unlike venous blood contains interstitial fluid) concentrations are comparable to serum measurements; conversions may be needed (NASEM, 2022; PFAS-REACH, 2022). Commercial laboratories are also starting to use non-targeted approaches (NASEM, 2022).

As a general guide, Appendix C – Comparison of Target Analytes Across Methods, provides a snapshot of targeted analytes reported by selected methods. Currently reported LODs or limits of quantification across these methods generally range from 0.025 to 0.1 nanograms per milliliter (ng/mL) across PFAS. Pricing across laboratories for serum PFAS analysis ranges from $400 to $700 per sample. Turnaround times will vary by laboratory but may take 1 to 4 weeks or longer (PFAS-REACH, 2022).

Broadly speaking, Table 5 outlines key questions to consider when selecting a laboratory partner for PFAS biomonitoring. These questions are designed to help project teams evaluate the specific capabilities, logistical compatibility, and quality standards of candidate laboratories. Often, pre-existing partnerships with laboratories exist (e.g., state health department), which may offer advantages in coordination and data integration. Of note, MDH's Public Health Laboratory has biomonitoring experience, PFAS analysis capabilities, well-documented QA/QC procedures, external proficiency testing, and sufficient capacity for supporting PFAS exposure assessments and biomonitoring programs.

Ultimately, the analytical method selected to support biomonitoring should align with the project's specific objectives—in this case to understand firefighter exposures to a range of PFAS. The choice of laboratory partner will be informed by the laboratory's ability to implement the selected method reliably. In practice, the selected method will be based on available methods at the time of protocol development and should be aligned with CDC methods to enable comparisons with NHANES reference data. Ideally, the selected method should provide data on as many analytes as possible associated with the known or suspected exposure sources, while acknowledging that available methods detect only a

small fraction of the thousands of known PFAS. Depending on the project's aims, there may be some benefit in pursuing non-targeted methods to assess total exposure levels in individual firefighters in addition to targeted analyses. However, this approach could require partnerships with more than one laboratory.

Table 5. Key considerations when evaluating a laboratory partner

Category	***Questions to Ask When Evaluating a Laboratory***
Analytical methods	• Does the lab offer a validated method for the PFAS of interest? • Are methods compatible with CDC/NHANES for comparability? • Is the lab capable of both targeted and/or non-targeted analysis if needed?
Quality assurance (QA/QC)	• Does the lab participate in external proficiency testing? • Are they CLIA-certified or accredited by a relevant body? • Are QA/QC procedures clearly documented and shared with project staff?
Detection limits	• Are the reported limits of detection (LODs) low enough to capture relevant PFAS levels (e.g., ≤0.1 ng/mL)?
Turnaround time	• What is the average time from sample receipt to result delivery? • Can the lab meet the project's required turnaround time for processing and reporting results?
Sample volume and matrix	• Can the lab analyze serum or whole blood using available sample volumes? • Does the lab have experience with matrix-matched calibration?
Capacity and throughput	• Does the lab have sufficient staffing and equipment to handle the expected number of samples within the desired timeframe?
Cost and budget	• What is the cost per sample, including shipping and data reporting? • Are discounts available for public health or academic projects?
Logistical support	• How are samples shipped to the lab? • Are temperature control and chain-of-custody protocols well established?
Materials and contamination control	• Can the lab supply sample collection materials (e.g., vials, gloves)? • Can they verify that materials are PFAS-free? • Have materials been lot-tested for PFAS contamination?
Data management	• Can the lab support electronic data deliverables? • Will the lab provide electronic data files in a format that is compatible with existing data systems? • Can the lab deliver results in formats suitable for individual reporting and statistical analysis?
Communication and collaboration	• Is the lab responsive to questions? • Are they willing to work with project staff to adjust protocols or accommodate special needs (e.g., re-runs, custom analytes)?

7.3 Examples from Other PFAS Biomonitoring Projects

Here we describe the methods and laboratories supporting various firefighter biomonitoring programs. The examples show consistency in choosing similar targeted methods. Methods and laboratories used in these studies were dictated by study aims, funding source and conditions, and what was considered the best available methods at the time of study implementation.

The methods used by state-run firefighter biomonitoring programs are summarized below.

- **Michigan's** PFOMS project partnered with the MDHHS Bureau of Laboratories for the PFAS analysis (MDHHS, 2025a). The effort promoted MDHHS's CDC cooperative agreement biomonitoring aim to increase state laboratory capacity. MDHHS method adhered to CDC-based guidelines with an expanded analyte list of 39 unique PFAS (45 if linear and branched isomers counted). PFAS methods employed are highlighted in another publication (Noyes et al., 2025). Validated methods were used for preparing samples (isotope dilution with addition of acetonitrile to precipitate proteins) and analysis by LC-MS/MS, with strict QA/QC in accordance with the College of American Pathologist and CLIA.
- **California's Firefighter Occupational Exposures (FOX) Project.** Partnering with the state laboratory, FOX measured 12 legacy PFAS using an on-line solid phase extraction high-performance liquid chromatography tandem (LC-MS/MS) with seven-point external calibration curves were processed together with each batch of serum samples to measure 12 PFAS. The method was validated by analyzing blank bovine serum spiked with unlabeled PFC standards. Each batch of participant samples were also processed with blank samples (bovine serum) (Dobraca et al., 2015). "Biomonitoring California's" list of designated PFAS and methods align with those measured in CDC's National Biomonitoring Program (Biomonitoring California, 2025; Dobraca et al., 2015).
- **Indiana's PFAS Testing Pilot Program**. IDHS partnered with Eurofins, a commercial laboratory, to implement an at-home blood sampling strategy using self-administered finger-prick kits. These kits allowed participants to collect small-volume capillary blood samples and mail them back to the laboratory for analysis. Eurofins uses a targeted PFAS method based on LC-MS/MS that quantifies up to 45 PFAS (Carignan et al., 2023). The method was specifically validated for use with dried blood spot microsamples and demonstrated good reproducibility and sensitivity, with most PFAS showing limits of detection between 0.1 and 0.5 ng/mL. The comparability of PFAS concentrations in capillary vs venous blood are still under investigation.

Scanning the published literature for PFAS laboratory analysis methods used for other firefighter biomonitoring projects generally revealed the use of similar targeted methods, again reflecting established methods at the time of the studies. Approaches were also tied to principal investigator affiliations and study funding entity. Examples follow.

- Several studies examining various firefighter cohorts shipped samples to the CDC's laboratory for analysis (Burgess et al., 2023; Furlong et al., 2025; Goodrich et al., 2021; Khalil et al., 2020; Quaid et al., 2024). Papers cited CDC's on-line solid-phase extraction LC-MS/MS methods, several referencing Kato et al., 2018.
- For a New Jersey firefighter study, the New Jersey Department of Health Public Health and Environmental Laboratories (NJDOH-PHEL) were close collaborators guiding biospecimen collection, processing, and analysis (Graber et al., 2021). NJDOH-PHEL analyzed PFAS serum levels using a high-throughput online solid phase extraction system and tandem mass

spectrometer (MS/MS). The method was optimized from CDC Method 6304.04 for 12 target PFAS. As part of the New Jersey State Biomonitoring Program, the laboratory participates in CDC's quality assurance programs and has passed all proficiency tests.

- A study of Ohio firefighters sent serum samples to the Wadsworth Center, New York State Department of Health for PFAS analysis, testing for a total of 21 PFAS (Leary et al., 2020). The samples were eluted through a cartridge and analyzed via LC-MS/MS. Method details are available in Honda et al. 2018.
- For a recent study in Arizona firefighters, the New Jersey Department of Health conducted the PFAS analysis, testing 18 PFAS based on availability of assays (Mitchell et al., 2025). The paper cites CDC Method #6304.09 for PFAS analysis.
- The University of California San Francisco laboratory analyzed samples for a study of San Francisco female firefighters and office workers. This university lab analyzed samples using LC-MS/MS for 12 PFAS, selected to enable comparison to available NHANES data (Trowbridge et al., 2020).

8 DATA INTERPRETATION AND ANALYSIS

The approach to analyzing and interpreting biomonitoring data should align with the study's objectives, which could include estimating average exposure levels, identifying occupational risk factors, or informing potential public health interventions. Decisions about how to process and interpret data affect the accuracy, comparability, and usefulness of the findings. This section outlines how previous biomonitoring studies have analyzed their data and highlights best practices for data preparation, statistical analysis, and contextualization of results.

8.1 Data Preparation and Cleaning

Preparing and cleaning data is a critical first step once biomonitoring results become available. This process typically involves cleaning, organizing, and validating the data. Data are typically drawn from multiple sources, including laboratory results and questionnaires. In some cases, additional datasets are also incorporated, such as environmental data linked to residential addresses. Ensuring the integrity of these data is crucial for producing reliable results. Common practices for processing laboratory data and analyzing the results are discussed below.

Quality Control and Data Cleaning

Before any statistical analysis can take place, it is important to conduct thorough quality control (QC) and data cleaning. This process helps ensure the accuracy, consistency, and completeness of the dataset. QC steps typically include:

- Checking for missing or implausible values (e.g., PFAS concentrations outside expected biological ranges, unreasonable drinking water consumption values).
- Verifying that variables are coded correctly.
- Confirming consistency across datasets (e.g., matching questionnaire responses with lab results for each participant).
- Removing duplicate records.
- Standardizing variable labels, units, and formats to facilitate analysis.

Project staff should keep a clear record of how they clean and prepare the data so that others can understand and repeat the process if needed. When combining data from different sources—like lab results, survey answers, or location data—it's important to double-check that each participant's information is correctly matched using ID keys. The original raw data should always be saved, and any changes should be made to a separate copy.

Handling non-detects

Frequently, biomonitoring data of PFAS will include results reported as below the LOD. These data present a challenge for statistical analysis, especially when a substantial portion of the dataset consists of non-detects.

The most common and simplest approach is to substitute non-detects with a fraction of the LOD, typically the LOD divided by the square root of 2. This method is straightforward and minimizes bias when the proportion of non-detects is relatively low (Hornung and Reed, 1990). In such cases, results are unlikely to differ significantly from those obtained using more advanced methods. Nearly all of the studies reviewed used this approach (e.g., Burgess et al., 2023; Dobraca et al., 2015). One exception was

Shaw et al., (2013) which used half of the LOD for substitutions and assigned a value of zero for compounds detected in fewer than 50% of samples.

While substitution methods are still commonly applied, they are increasingly viewed as limited. When feasible, more robust statistical techniques (e.g., multiple imputation, maximum likelihood estimation) should be used, particularly for inferential analyses. The choice of method should reflect the analysis objective and the distribution of the data. Sensitivity analyses can also be conducted to evaluate whether alternative approaches to handling non-detects would alter the conclusions being drawn.

To avoid distortion of summary statistics (e.g., means), many studies excluded PFAS compounds from certain analyses with detection frequencies below 50-70%. In these cases, when analyzing data, compounds detected in more than a certain percentage of samples were treated as continuous, while those with detection frequencies lower than that percentage were analyzed as categorical (detect vs. non-detect). Detection thresholds varied by study, but ranged between 50% (Burgess et al., 2023; Mitchell et al., 2025; Nematollahi et al., 2024) and 70% (Goodrich et al., 2021; Quaid et al., 2024; Trowbridge et al., 2020).

Log-transformation of skewed data

PFAS concentrations in biomonitoring studies are typically right-skewed, meaning most participants have relatively low levels while a few have much higher values. This skew can distort statistical analyses and make it harder to compare subgroups or detect patterns. To address this, PFAS data are often log-transformed before visualization or analysis. Log transformation makes the distribution more symmetrical and improves the validity of statistical tests that assume normality. This approach is commonly used when reporting geometric means or conducting regression modeling and group comparisons on log-transformed values (Burgess et al., 2023; Goodrich et al., 2021; Trowbridge et al., 2020).

8.2 Statistical Analysis

Different types of statistical methods can be used to summarize PFAS levels and explore patterns across firefighter groups. The methods chosen should match the study's goals, which can include estimating average levels, comparing subgroups, or identifying what factors may be linked to higher exposure.

Descriptive statistics

Descriptive statistics are used to summarize PFAS levels in the study group and look for patterns across different types of firefighters. These summaries help describe the data and should be interpreted in the context of the population being studied, including factors that may affect PFAS levels in the body, such as age or sex. Commonly reported values include:

- Number of participants tested by different subgroups.
- Percentage of results above or below the detection limit.
- Measures of central tendency such as the arithmetic, median or geometric mean.
- Minimum, maximum, and percentiles (e.g., 10th, 25th, 75th, 90th) to describe the range and distribution of concentrations.
- Confidence intervals around each of these statistics when possible.

Because PFAS levels are typically right-skewed, geometric means or medians are generally the preferred measure of central tendency. When a large percent of data fall below the detection limit, detection

frequencies and percentiles can still be used to describe the data. For example, reporting the 90th or 95th percentile can still provide valuable insight into higher exposure levels.

These descriptive statistics are often presented for the overall population as well as subgroups (such as by job role or region). Small sample sizes can make it difficult to draw reliable conclusions, especially when comparing subgroups. For example, stratified analyses may not be meaningful if each subgroup has only a few participants. As a general rule, descriptive statistics like averages or percentiles should only be reported when there are at least 10 participants in a group (Talih et al., 2023). Some public health agencies may also have their own privacy protection rules about what results can be shared when sample sizes are small.

Inferential statistics

Inferential statistics are used to identify trends in PFAS levels, differences among subgroups, or predictors of exposure within the study population. Statistical tests help to draw broader conclusions about exposure patterns among firefighters. These methods help answer questions like:

- Are PFAS levels higher in certain groups?
- Do exposures increase with years of service?
- What workplace factors are linked to higher PFAS blood levels?

The choice of statistical method depends on the type of outcome (e.g., continuous vs. categorical), how many groups are being compared, and the distribution of the data. If the data follow a certain distribution (usually 'normal') then parametric tests can be applied. Because PFAS concentrations are usually right-skewed, log transformation is often needed before applying parametric tests. If the data do not follow a specific distribution than non-parametric tests may be more appropriate.

Key considerations when applying inferential statistics include:

- **Group comparisons:** Comparing PFAS levels by job status (e.g., current vs. former), department type, or years of service.
- **Correlations**: Exploring whether PFAS levels increase with certain characteristics or behaviors, such as year of service, frequency of foam use, or gear cleaning.
- **Regression modeling:** Estimating the combined effect of multiple variables, or adjusting for confounders such as age, sex, or smoking.

While there are many different types of regression models, the most common are some form of linear regression which can include continuous predictors (e.g., years of service) and categorical covariates (e.g., job duty), and are usually adjusted for confounding variables like sex, race/ethnicity, and smoking status (Burgess et al., 2023; Graber et al., 2021; Jin et al., 2011; Mitchell et al., 2025; Nematollahi et al., 2024; Quaid et al., 2024). Logistic regressions are less commonly used in biomonitoring studies but can be used when modeling PFAS analytes with low detection frequency (i.e., detected vs. non-detected outcome) (Jin et al., 2011; Mitchell et al., 2025; Nematollahi et al., 2024).

The tools described here are useful for answering policy-relevant questions and identifying risk factors. However, researchers should be cautious with small sample sizes or low detection frequencies, which can limit statistical power or interpretability. Table 6 summarizes common statistical approaches used in firefighter biomonitoring studies. The assumptions underlying the specific method should be understood and validated before applying the method.

Table 6. Statistical methods for analyzing biomonitoring data

Objective	Example research questions	Continuous, parametric	Continuous, non-parametric	Categorical or binomial
Compare two groups	Are PFAS concentrations significantly higher in Minnesotan firefighters compared to the general U.S. population?	Equal or unequal variance t-test	Mann-Whitney U test	Chi-square test, Fisher's exact test
Compare three or more groups	Do PFAS concentrations vary significantly across fire departments within the state?	ANOVA	Kruskall-Wallis test	Chi-square test, Log-linear models
Describe strength and direction of relationship between two variables	Are PFAS concentrations correlated with years of service?	Pearson correlation	Spearman correlation, Kendall's tau	Contingency coefficient, Cramer's V
Model PFAS levels using multiple variables	What factors best predict PFAS levels among firefighters: years of service, foam use, or gear cleaning habits?	Linear regression	Generalized additive models, Quantile regressions	Logistic regression

Sample Weights in Probability-Based Designs

If the study uses a probability-based sampling design, such as stratified or cluster sampling, sample weights should be calculated and applied prior to analysis. These weights account for the differing probabilities of selection across subgroups and help ensure that estimates are representative of the broader target population. For example, if firefighters from rural departments were oversampled to enable subgroup analysis, applying appropriate weights would adjust for this and prevent bias in statewide estimates.

While not commonly applied in the biomonitoring studies of firefighters reviewed for this work, the use of sample weights is a standard approach in large national studies like the National Health and Nutrition Examination Survey (NHANES). It is also recommended in the CDC's *Guidance, Examples And Tools For Probability Sampling When Designing A Population-Based Biomonitoring Study* (CDC, 2023). According to this guidance, weights should be calculated based on the sampling design and adjusted, when needed, for nonresponse (discussed below). These adjustments allow for representative estimates and supports valid statistical inferences at the population level.

Sampling Weights and Post-Hoc Adjustments

In biomonitoring studies based on convenience samples, traditional sample weights, such as those used in NHANES, are generally not applicable because the study sample is not drawn using probability-based methods. However, when the goal is to generalize findings to a broader population (e.g., all Minnesotan

firefighters), it is still important to account for potential bias if those who enroll differ meaningfully from the overall target population.

This type of bias can result from both the recruitment process and from non-response. For example, some firefighter groups may be more likely to be contacted or may be more willing to participate. In both cases, the final sample may differ in important ways from the full population, which can skew results and limit their generalizability. For example, if older or more experienced firefighters are more likely to participate in a biomonitoring study, perhaps because they are more familiar with PFAS issues, the study sample may end up overrepresenting individuals with longer service histories. Since PFAS levels can accumulate over time, this could lead to an overestimation of average PFAS concentrations compared to the broader firefighter population, which includes younger and less exposed individuals.

Post-stratification adjustment is a method for correcting these types of biases. It involves applying weights to participants' data so that the sample more closely reflects the known characteristics of the target population, such as age, sex, or department type. To perform this adjustment, researchers need to know the distribution of a characteristic in the total population (e.g., the proportion of firefighters in each age group statewide) and compare it to the distribution in the study sample. They then assign weights to individual responses so that underrepresented groups count more and overrepresented groups count less in the final analysis.

The following section provides more detail on how to compare results to other populations.

8.3 Contextualizing PFAS Results with Comparison Populations

In addition to formal hypothesis testing, biomonitoring studies often compare PFAS levels in the study population to those from other populations to provide context. These comparisons help illustrate whether exposures are elevated relative to a reference population. Reference groups for a PFAS biomonitoring study in firefighters might include:

- **National reference populations** like NHANES, which is widely used for benchmarking because it is representative of the U.S. general population.
- **Other local biomonitoring programs** like MDH's East Metro studies, which may include populations from nearby areas or with similar environmental exposures (MDH, 2015, 2010).
- **Other firefighter cohorts**, from prior studies, which are occupationally relevant and can help assess how PFAS levels in Minnesota firefighters compare to those in other fire service populations (see Table 4).
- **Occupationally similar but non-exposed groups**, such as EMT personnel who do not use AFFF or wear turnout gear, which can help isolate firefighter-specific exposures (Mitchell et al., 2025) or office workers (Trowbridge et al., 2020).

When selecting reference populations, it is important to consider both demographic differences that may influence PFAS levels and study objectives. If the goal is to estimate how Minnesota firefighters compare to the general population, NHANES is the most widely used reference. It provides a national benchmark and allows for stratification by age and sex (e.g., males age 20 and older), which can improve comparability to firefighter cohorts. However, NHANES data may not be ideal for firefighter comparisons in all cases. The most recent publicly available PFAS data are several years old, and sampling protocols, laboratory methods, and detection limits have evolved over time. These factors can limit the utility of NHANES for temporally aligned comparisons.

Other firefighter cohorts from published studies may provide a more occupationally relevant comparison but these differ in location, time frame, and study design. Similarly, local studies like MDH's East Metro projects offer some regional context but were conducted more than a decade ago and may not reflect current background levels. Ideally, Minnesota would have a contemporaneous, demographically similar reference group collected using the same protocols. Establishing a state-level baseline population would improve the interpretability of firefighter biomonitoring results, though it would require additional resources.

In the absence of a perfect comparison population, a project should present a side-by-side comparison of results with the reference population with appropriate caveats that note any known differences in the populations that may be contributing to observed differences in PFAS levels. Formal statistical tests can be used to test whether there are significant differences between the different populations. Techniques such as age-adjustment or post-stratification can help align the study sample with the comparison group, making statistical interpretations more valid. However, these statistically valid adjustments are less common because of the data needs and additional effort required. These approaches are described in more detail in Section 8.2.

8.4 Examples from Other PFAS Biomonitoring Projects

All three state-led firefighter biomonitoring programs reviewed (Michigan's PFOMS project, California's FOX study, and Indiana's PFAS Testing Pilot Program) used NHANES data as a reference population to contextualize PFAS results. This approach was also common across published studies reviewed in the literature. Many studies also selected specific NHANES subgroups, such as adults aged 20 and older or adult men, to better align with the firefighter study population. These subgroup comparisons help improve interpretability when demographic characteristics differ between the study cohort and the general population.

Some studies also adjusted their results to better match their target population or comparison group. For example, PFAS Exposure Assessments conducted by the Agency for Toxic Substances and Disease Registry (ATSDR) in 10 communities used post-stratification to calculate two types of averages: one adjusted to reflect the age distribution of the local community and another adjusted to match the national age distribution (ATSDR, 2024b). This approach allowed the results to provide both locally representative average estimates and averages that enabled "apples-to-apples" comparisons to NHANES. Similar post-stratification methods have been applied in other statewide PFAS biomonitoring efforts (e.g., Yu et al., 2020).

In addition to comparisons to NHANES, all reviewed studies calculated descriptive statistics (e.g., geometric means, percentiles) and explored relationships between PFAS levels and questionnaire variables such as job duties, years of service, or AFFF use. These analyses followed the general statistical approaches described in Section 8.2.

9 COMMUNICATING AND REPORTING RESULTS

Communicating results confidentially to participants in a clear, accurate, and timely manner is important for building trust, supporting informed decision-making, and ensuring the usefulness of a PFAS biomonitoring study. Participants should understand what their results mean, how their data will be used, and what steps they can take in response, if any. This is particularly important in firefighter biomonitoring studies, where occupational exposures and evolving science around PFAS can raise questions or concerns.

This section outlines best practices for returning individual results to participants, provides guidance on interpreting results, and highlights key considerations for preparing summary reports for broader audiences.

9.1 Reporting Individual Results

Participant results should be communicated clearly, accurately, and in plain language to ensure they are understandable and meaningful. Results should be placed in context, with appropriate comparisons and supporting information to help participants interpret their PFAS levels.

The combined materials that are sent to a participant can be referred to a 'results package' and include some combination of a:

- **Personalized table showing** their PFAS concentrations for each compound measured.
- **Comparison to other participants** in the study (e.g., percentile rank) to help contextualize individual results.
- **Comparison to a reference population**, such as NHANES.
- **Brief explanation about PFAS**, how exposure can occur, and what is currently known about potential health effects.
- **Statement clarifying** that no federal health-based guidance values exist for most PFAS in blood, but interpretation frameworks may be available (discussed further in the next subsection).
- **Contact information for the study team** in case participants have questions or need more information.

Where possible, graphical elements like bar charts or shaded ranges can help make data easier to interpret. Participants should also be provided with educational materials, such as fact sheets or FAQs, to support their understanding of PFAS and the context of their results. For diverse populations, result materials should be translated into languages spoken by participants and reviewed for cultural appropriateness. Often custom materials are developed with the specific branding of the project or leading agency; however, materials from authoritative sources like the CDC can also be used.

Every effort should be made to return results to participants as soon as possible after sampling. However, many studies wait until all laboratory results have been received and processed to ensure that results are distributed to all participants at the same time.

Maintaining accurate and up-to-date contact information for participants can be difficult, particularly in cases where individuals move or retire during the study period. To avoid issues, study teams should

collect multiple methods of contact (e.g., email, phone, and mailing address) and provide opportunities to update this information to reduce loss to follow-up, particularly in long-running studies.

9.2 Health-based Screening Values

While PFAS biomonitoring results can be compared to population reference values, there are currently no established health-based cutoff levels for individual PFAS compounds in blood that indicate a definitive risk or safety threshold. However, two recent resources from national public health authorities offer useful tools and considerations for interpreting individual PFAS results in clinical or public health contexts.

National Academies of Sciences, Engineering, and Medicine (NASEM) 2022 Blood Guidance

In 2022, NASEM released clinical guidance for interpreting PFAS blood test results (NASEM, 2022). The recommendations are based on the *combined* serum concentrations of seven PFAS compounds (PFOA, PFOS, PFHxS, PFNA, PFDA, PFUnDA, and MeFOSAA), which were selected because they were the PFAS measured in NHANES at the time the report was developed. Based on the total concentration of these seven PFAS, individuals are categorized into three exposure levels:

- **>20 ng/mL**: Encourage exposure reduction and additional clinical screening beyond standard of care for conditions potentially associated with PFAS exposure, such as high cholesterol, thyroid abnormalities, and certain cancers.
- **2–20 ng/mL:** Encourage exposure reduction and screening for PFAS-related health effects within the usual standard of care.
- **<2 ng/mL**: No recommended follow-up. Provide usual standard of care.

While these guidelines are relatively new and have not yet been adopted by most state-led PFAS biomonitoring programs, they offer a structured approach for interpreting PFAS results in a clinical setting and may serve as a model for future public health communications. It is important to note that at current national levels, a large portion of the general population (>98%) would be above the lower threshold of 2 ng/mL (ATSDR, 2024).

ATSDR's Information for Clinicians (2024)

ATSDR has published *Information for Clinicians*, which provides advice on how healthcare professionals can discuss PFAS blood test results with patients (ATSDR, 2024). This resource emphasizes:

- Using PFAS test results as part of a broader conversation that includes the patient's exposure history, current health status, and concerns.
- The importance of shared decision-making between clinicians and patients.
- Avoiding alarm or over-interpretation of PFAS concentrations, especially given the current scientific uncertainties.
- Emphasizing exposure reduction strategies to reduce PFAS blood levels.

Both the NASEM and ATSDR documents highlight that individual results should be communicated in a way that is transparent, reassuring, and medically appropriate, particularly when participants may seek guidance from their healthcare providers. In line with these principles, communications should aim to:

- **Use screening values as informational, not diagnostic**: PFAS blood levels should be considered one piece of information in a broader assessment of health and exposure

history. Screening values are not intended to diagnose disease or predict future health outcomes.

- **Communicate limitations clearly**: It is important to clarify that current scientific understanding does not define individual toxicity thresholds for most PFAS. Therefore, PFAS concentrations should not be interpreted in isolation, and clinical decisions should not be based on PFAS levels alone.

9.3 Aggregate Reporting Practices

In addition to returning individual results, many biomonitoring projects develop public-facing reports that summarize aggregate results at the group level. These summary reports serve as a valuable tool for communicating findings to fire departments, policymakers, community members, and other interested parties. These reports focus on group-level patterns and avoid any information that could identify individual participants. To protect privacy, studies should follow established suppression rules (e.g., not reporting cell sizes below a threshold such as 10) and combine categories when needed.

Unlike detailed statistical analyses used internally or in peer-reviewed publications, public-facing summaries generally prioritize clarity, transparency, and usefulness. These reports often include:

- Average or median PFAS levels by subgroup (e.g., region, job role, or years of service).
- Comparisons to reference populations such as NHANES or other firefighter studies.
- Key takeaways about potential exposure patterns, expressed in plain language.

Sharing aggregate findings through clear and timely reports can strengthen transparency and build public trust. Some programs have used the following approaches:

- Sharing preliminary findings at conferences, public meetings, or public briefings.
- Collaborating with firefighter associations, unions, or community organizations to plan dissemination.
- Creating data dashboards or public-facing websites to make findings more accessible.
- Using accessible formats such as summary fact sheets, infographics, or online dashboards to share findings with diverse audiences

Taken together, these strategies help ensure that the study's findings are relevant to the communities they aim to serve.

10 RECOMMENDATIONS

Minnesota is well-positioned to implement a PFAS biomonitoring study in firefighters. If MDH or anyone conducting biomonitoring in Minnesota firefighter populations proceeds with such a project, study design choices should be grounded in the guidance in this report, the project's goals, available budget, and the characteristics of Minnesota's firefighter workforce. Each study design decision, such as the sampling strategy, target population, sample size, and use of probability-based methods, carries trade-offs in cost, feasibility, and interpretability. In some cases, decisions will be further shaped by legislative direction or resource constraints.

Based on the evidence reviewed and lessons learned from other state programs, the following recommendations highlight key considerations.

10.1 Define Study Goals and Sampling Approach Early

Clearly defining the purpose of the biomonitoring project at the outset is essential, as it will shape all subsequent study design decisions. Potential goals may include:

- Estimating average PFAS blood levels among Minnesota firefighters.
- Comparing levels across subgroups such as those near airports or with different years of service.
- Assessing whether use of AFFF is associated with elevate PFAS blood levels.
- Understanding the contribution of turnout gear to internal PFAS exposure.
- Tracking changes in PFAS levels over time (e.g., before and after regulatory or gear changes).
- Generating data to support health communication, policy development, or exposure reduction strategies.

Each of these goals has implications for decisions about sampling strategy, data collection protocols, IRB requirements, and how findings are ultimately applied. If generalizability is a key objective, the project should consider a stratified probability sampling approach to ensure representation across relevant subgroups (e.g., region, department type, service years). Comparison population should also be considered carefully at the outset. While more resource-intensive, a probability-based sampling approach improves equity and interpretability of results.

Biomonitoring projects should prioritize serum PFAS analysis, as it allows for comparison to national reference datasets like NHANES and provides reliable measures of internal exposure. Sample collection should be flexible and convenient for the participants to improve participation and reduce burden, such as conducting appointments at fire stations. Regardless of location, successful implementation will require trained phlebotomists, PFAS-free materials, field centrifuges, and robust cold chain logistics to preserve sample integrity. Biomonitoring projects should also anticipate the need for effective data systems, QA/QC protocols, and contingency plans for field collection.

10.2 Engage with Interested Parties Throughout the Process

Partnering with firefighter organizations, such as the Minnesota State Fire Marshal, the Minnesota State Fire Chiefs Association, firefighter unions, and other firefighter support agencies (e.g., MnFIRE), early in the process is essential to foster trust and ensure study relevance. These interested parties can advocate for the project, highlight its value, address concerns, and promote participation.

10.3 Engage Early with IRB

Project staff should engage with the MDH or other IRB early to determine whether the project qualifies as public health surveillance or human subjects research (MDH, 2024c). This determination affects review requirements and the consent process. If academic collaborators or federal funds are involved, additional IRBs may be relevant. Regardless of IRB classification, the project should follow best practices for informed consent, participant confidentiality, and communication. These steps are especially important when working with occupational populations that may have concerns about privacy or job-related impacts.

10.4 Leverage Existing Exposure History Questionnaires

A core exposure history questionnaire should collect relevant work history, gear use, AFFF exposure, and personal behaviors linked to PFAS. Biomonitoring projects can draw from the many questionnaires developed by other research projects and state programs. Consider using a combination of digital self-administered questionnaires before the sample collection appointment to reduce costs and improve efficiency, with optional in-person review for clarity.

10.5 Partner with State Public Health Laboratory

If possible, project staff should partner with the state public health laboratory, which has biomonitoring experience, PFAS analytical capabilities, reported capacity, and CLIA certification. Their methods are aligned with CDC protocols and support high-quality data with established QA/QC processes. If alternate labs are considered (e.g., academic or commercial), selection should be based on method comparability, lab capacity, and compatibility with study goals. In some cases, combining targeted methods with exploratory approaches (e.g., total organic fluorine) may be of value, depending on resources and partnerships.

10.6 Anticipate Resource and Staffing Needs

Successful implementation will require sufficient staffing, funding, and infrastructure. Key cost areas include sample collection and processing materials, phlebotomy supplies, cold storage and shipping, and laboratory analysis. Dedicated time for staff training and field QA/QC protocols is also essential. Projects should include contingency planning for delays, participant attrition, and resource constraints. If a representative study is not feasible initially, a smaller, convenience-based pilot could still yield valuable data and inform a future, larger-scale effort. A small-scale pilot study may be a valuable first step. It can help refine logistics, assess the feasibility of the sampling and recruitment strategy, test data collection tools (e.g., questionnaires), and build trust with firefighter communities. Early pilot results may also offer insights into PFAS exposure patterns and inform whether a larger, representative study is warranted.

10.7 Communicate Results Effectively and Transparently

Effective communication of both individual and aggregate results will further foster trust, support informed decision-making, and promote the responsible use of study findings. For individual-level reporting, a biomonitoring project should follow best practices for returning results, including the use of plain language, clear visual aids, and comparisons to appropriate reference populations (e.g., NHANES or a demographically similar population). Participants should be informed about what the results do and do not mean, particularly in the absence of health-based thresholds for most PFAS. Where applicable, the report-back materials may reference the 2022 NASEM blood guidance thresholds as a framework for discussing potential clinical relevance, while emphasizing that these are screening tools rather than diagnostic cutoffs.

Materials should also provide guidance for participants who wish to consult with their healthcare providers, including links to MDH resources and the ATSDR's *Information for Clinicians*. Given the occupational context, it is particularly important to provide assurance around data confidentiality and how individual data will (and will not) be used and protected.

At the population level, an aggregate report should be prepared that summarizes key findings across the firefighter cohort. This report should be carefully worded to avoid misinterpretation, clearly communicate the study's scope and limitations, and contextualize findings using relevant reference populations. Opportunities to present findings at conferences, department meetings, or through firefighter associations can further support transparency and engagement. As resources allow, project staff should also consider creating summary materials such as dashboards, fact sheets, or infographics that can reach broader audiences, including firefighters, policymakers, and the general public.

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APPENDIX A – LITERATURE REVIEW STRATEGY

ERG conducted systematic literature searches to identify relevant studies on PFAS exposure and biomonitoring in firefighters in the United States. ERG used PubMed to target articles that focused on 1) PFAS blood biomonitoring studies in firefighters and 2) studies in Minnesota firefighter population. The title and abstract of all articles identified in these searches (N=51) were reviewed and tagged as relevant for the goals of this report. Articles were primarily excluded if they were conducted in populations outside of the United States or were studies with no primary data collection. Below were the search strings used in our PubMed searches. A list of all articles that were deemed relevant for full-text review are included in Tabel A-1.

PubMed search string for PFAS blood biomonitoring studies in firefighters (n = 37 results)

> *("PFAS"[Title/Abstract] OR "per- and polyfluoroalkyl substances"[Title/Abstract] OR "perfluoroalkyl substances"[Title/Abstract] OR "PFOS"[Title/Abstract] OR "PFOA"[Title/Abstract] OR "Fluorocarbons"[Mesh]) AND ("biomonitoring"[Title/Abstract] OR "biological monitoring"[Title/Abstract] OR "exposure assessment"[Title/Abstract] OR "serum"[Title/Abstract] OR "blood"[Title/Abstract] OR "plasma"[Title/Abstract] OR "Biological Monitoring"[Mesh]) AND ("firefighter*"[Title/Abstract] OR "fire fighter*"[Title/Abstract] OR "Firefighters"[Mesh])*

PubMed search string for Minnesota studies in firefighters (n = 14 results)

> *("Minnesota"[Title/Abstract] OR "Minnesotan"[Title/Abstract] OR "Minneapolis"[Title/Abstract] OR "East Metro"[Title/Abstract] OR "St. Paul"[Title/Abstract] OR "Twin Cities"[Title/Abstract] OR "Minnesota"[Mesh]) AND ("firefighter*"[Title/Abstract] OR "fire fighter*"[Title/Abstract] OR "Firefighters"[Mesh])*

ERG also conducted a broader search for Biomonitoring studies in firefighters in the United States that did not necessarily focus on PFAS exposures. These articles were reviewed for relevance to the report. However, these articles were only considered as a source of additional context and to fill certain data gaps that were not already covered by more directly relevant articles. The PubMed search string for this search is shown below.

PubMed search string for Biomonitoring studies in firefighters in the United States (n = 150 results)

> *("biomonitoring"[Title/Abstract] OR "biological monitoring"[Title/Abstract] OR "exposure assessment"[Title/Abstract] OR "serum"[Title/Abstract] OR "blood"[Title/Abstract] OR "plasma"[Title/Abstract] OR "Biological Monitoring"[Mesh]) AND ("firefighter*"[Title/Abstract] OR "fire fighter*"[Title/Abstract] OR "Firefighters"[Mesh]) AND ("United States"[Title/Abstract] OR US[Title/Abstract] OR "Alabama"[Title/Abstract] OR "Alaska"[Title/Abstract] OR "Arizona"[Title/Abstract] OR "Arkansas"[Title/Abstract] OR "California"[Title/Abstract] OR "Colorado"[Title/Abstract] OR "Connecticut"[Title/Abstract] OR "Delaware"[Title/Abstract] OR "Florida"[Title/Abstract] OR "Georgia"[Title/Abstract] OR "Hawaii"[Title/Abstract] OR "Idaho"[Title/Abstract] OR "Illinois"[Title/Abstract] OR "Indiana"[Title/Abstract] OR "Iowa"[Title/Abstract] OR "Kansas"[Title/Abstract] OR "Kentucky"[Title/Abstract] OR "Louisiana"[Title/Abstract] OR "Maine"[Title/Abstract] OR "Maryland"[Title/Abstract] OR "Massachusetts"[Title/Abstract] OR "Michigan"[Title/Abstract] OR "Minnesota"[Title/Abstract] OR "Mississippi"[Title/Abstract] OR "Missouri"[Title/Abstract] OR "Montana"[Title/Abstract] OR "Nebraska"[Title/Abstract] OR "Nevada"[Title/Abstract] OR "New Hampshire"[Title/Abstract]*

OR "New Jersey"[Title/Abstract] OR "New Mexico"[Title/Abstract] OR "New York"[Title/Abstract] OR "North Carolina"[Title/Abstract] OR "North Dakota"[Title/Abstract] OR "Ohio"[Title/Abstract] OR "Oklahoma"[Title/Abstract] OR "Oregon"[Title/Abstract] OR "Pennsylvania"[Title/Abstract] OR "Rhode Island"[Title/Abstract] OR "South Carolina"[Title/Abstract] OR "South Dakota"[Title/Abstract] OR "Tennessee"[Title/Abstract] OR "Texas"[Title/Abstract] OR "Utah"[Title/Abstract] OR "Vermont"[Title/Abstract] OR "Virginia"[Title/Abstract] OR "Washington"[Title/Abstract] OR "West Virginia"[Title/Abstract] OR "Wisconsin"[Title/Abstract] OR "Wyoming"[Title/Abstract] OR "United States"[Mesh])

APPENDIX B – STRUCTURED INTERVIEW QUESTIONS

ERG conducted structured interviews with principal investigators and interested parties in other states, in addition to firefighter organizations. ERG spoke to representatives from state-led PFAS biomonitoring programs in firefighters and firefighter organizations within Minnesota. Below are the interview question ERG conducted for each group. Responses were incorporated throughout this report.

Interview Questions for Firefighter Organizations

Study Design

- What do you think your members see as the most important benefits of participating in a firefighter biomonitoring program (e.g., personal health insights, protecting future firefighters, advancing research)?
- What PFAS-related research questions are you or your members particularly interested in?

Recruitment and Consent

- What types of incentives, motivators, or recruitment methods would best encourage participation (e.g., compensation, protecting fellow firefighters, contributing to research)?
- What outreach methods are most effective for reaching a wide range of firefighters from across the state— email, social media, in-person meetings, flyers, text alerts?
- Who are the most trusted messengers within Minnesota's firefighting community (such as union leaders, chiefs, safety officers, or peer educators), and what role could they play in encouraging participation across departments and regions?
- What times of year, days of the week, or shifts are most convenient for participation?
- What concerns might you or your members have about participating in biomonitoring programs? Are there any specific concerns unique to Minnesota firefighters—such as negative past experiences with other programs?
- Are there barriers to participation for any specific type/category of firefighters? (e.g., those who work nights, weekends, or rural shifts; part-time; seasonal; tribal; or volunteer departments)?
- How concerned are your members about the privacy of their health or exposure data collected in a biomonitoring program?
- Is there anything you recommend the state do in a biomonitoring study to help build trust in this program?

Exposure Assessment

- Are there specific job roles, departments, or geographic areas in Minnesota that use or have used Aqueous Film-Forming Foam (AFFF) more than others?
- How different are the types of turnout gear used across roles, departments, or geographic areas?
- Are firefighters in Minnesota generally aware of potential PFAS exposures through AFFF, turnout gear, and/or dusty/foam residue environments?
- Are there particular tasks, trainings, or equipment cleaning practices that you believe may increase PFAS exposure?
- If asked, would individual firefighters be generally aware of their past or current use of AFFF?

- If asked, would individual firefighters be generally aware of the specific type of turnout gear they use?
- Can you describe the differences in the roles and daily practices of volunteer vs professional firefighters in Minnesota and how this might impact their potential exposures to PFAS? *(Follow-up with similar question to rural vs. urban settings or other categorical differences we should be aware of*).

Sample Collection

- What testing formats would be most feasible for your department— onsite events, mobile testing units, or offsite clinic visits?
- In your opinion, what amount of time would start to feel too long or burdensome for firefighters to spend participating in a biomonitoring session (which includes consent, sample collection, exposure assessment, and potential paperwork)?
- Would firefighters be willing/able to participate during duty hours, or would off-shift participation be preferable?

Lab Analysis

- Which organizations would you trust most to collect, manage, and report on exposure data (e.g., academic institutions, state agencies, independent third parties)?

Data Analysis

- Do you think your members would be more interested in individual results, department-level summaries, or both?
- What kinds of data comparisons would be most meaningful to your members when reviewing PFAS results? (e.g., general population levels, other firefighters in the state, other firefighter studies, communities in Minnesota with contaminated drinking water, other highly exposed occupational settings)
- Would it be helpful to group results by job role, years of service, or use of AFFF in interpreting exposure levels?
- Do you have any concerns about how data could be summarized (e.g., by departments, roles, years of service)?

Reporting Results

- What are the best ways to share program updates, results, or next steps (e.g., webinars, email updates, printed summaries, email lists, in-person briefings)?

Other/General

- What aspects of participating in past studies were positive? What aspects were challenging or frustrating?
- Do you have any other recommendations or thoughts on how a biomonitoring program should be designed to be accessible and relevant to all firefighters in the state?

Interview Questions for Principal Investigators/Other States

Study Design

- What were your primary goals when designing the [PFAS biomonitoring study for firefighters]?
- Was there a specific hypothesis being tested?
- Was the sampling design based on volunteers, random, or systematic selection?

- What factors influenced your decision on sample size, participant eligibility, or scope?
- Was IRB approval required? If so, what was included in the IRB package? What considerations were raised?

Recruitment and Consent

- Can you generally describe the recruitment approach?
- Did you engage with fire departments, unions, or firefighter organizations to gain support and participation? And If so, how?
- How long did it take to reach the recruitment goal?
- What were the main barriers to participation among firefighters, and how did you address them? (For example, were there concerns about privacy, job-related consequences, stigma, time commitment, or mistrust in government-led studies?)
- Did you offer incentives or compensation for participants? If so, what worked best?
- Were consent forms administered in person at time of data collection? Paper or Electronically?

Exposure Assessment

- How did you assess potential occupational sources of PFAS exposure in firefighters (e.g., turnout gear, AFFF, station dust)?
- Was there an exposure history questionnaire, and if so would you be willing to share this?
- Did your team conduct environmental sampling (e.g., gear wipe tests, station air/dust, water)? If so, how did you integrate that with biomonitoring data?

Sample Collection

- What biological medium did you collect (e.g., blood, urine)?
- How did you determine which PFAS analytes and biological samples to include?
- Can you generally describe the logistics of sample collection (e.g., phlebotomist went to individual stations, firefighters went to designated site)?

Lab Analysis

- Did you partner with a state laboratory, commercial laboratory, or university laboratory for PFAS analysis?
- What laboratory method was used and how many/which PFAS compounds were included?
- Would you be willing to share a description of the laboratory method?

Data Analysis

- Did you try to differentiate between occupational and non-occupational PFAS exposures in your study? If so, how?
- Did you attempt to account for variability in job roles, years of service, or other covariates in your analysis?
- What reference or comparison populations (e.g., NHANES, general public) did you use to contextualize results?

Reporting Results

- How did you report results back to individual participants, and did participants receive any interpretation of the results?
- What format did you use (e.g., letter, online portal, one-on-one consultation)?
- Did you communicate aggregate results to fire departments, unions, or policymakers within your state?

Lessons Learned

- Has the study had any impact on firefighter policies, PPE practices or exposure mitigation efforts in your state?
- Did you receive any feedback from individuals or the firefighter community? Were there any unexpected consequences or feedback?
- What were the biggest logistical challenges in implementing the biomonitoring program (e.g., recruitment, sample collection, lab analysis)?
- What advice would you give to another state trying to implement a similar PFAS biomonitoring program among firefighters?
- Are there any plans to conduct follow-up testing or longitudinal monitoring

APPENDIX C – COMPARISON OF TARGET ANALYTES ACROSS METHODS

Table C-1 provides a snapshot of targeted analytes reported by EPA, CDC, and MDH public health laboratory. Currently reported LODs or limits of quantification across these methods generally range from 0.025 to 0.1 nanograms per milliliter (ng/mL) across PFAS.

Table C-1. Comparison of Target Analytes (PFAS) across Selected Methods

Target Analyte Name	Abbreviation	EPA 1633A (1)	CDC/NHANES (2)	MDH PHL (3)
Perfluoroalkyl carboxylic acids				
Perfluorobutanoic acid	PFBA	x	—	x
Perfluoropentanoic acid	PFPeA	x	—	x
Perfluorohexanoic acid	PFHxA	x	x	x
Perfluoroheptanoic acid	PFHpA	x	x	x
Perfluorooctanoic acid	PFOA	x	x (L, Br)	x
Perfluorononanoic acid	PFNA	x	x	x
Perfluorodecanoic acid	PFDA	x	x	x
Perfluoroundecanoic acid	PFUnA	x	x	x
Perfluorododecanoic acid	PFDoA	x	—	x
Perfluorotridecanoic acid	PFTrDA	x	—	—
Perfluorotetradecanoic acid	PFTeDA	x	—	—
Perfluoroalkyl sulfonic acids				
Perfluorobutanesulfonic acid	PFBS	x	—	x
Perfluoropentanesulfonic acid	PFPeS	x	—	—
Perfluoro(2-ethoxyethane)sulfonic acid	PFEESA		—	—
Perfluorohexanesulfonic acid	PFHxS	x	x	x
Perfluoroheptanesulfonic acid	PFHpS	x	x	x
Perfluorooctanesulfonic acid	PFOS	x	x (L, Br)	x
Perfluorononanesulfonic acid	PFNS	x	—	—
Perfluorodecanesulfonic acid	PFDS	x	—	x
Perfluorododecanesulfonic acid	PFDoS	x	—	—
Perfluoropropanesulfonic acid	PFPrS		—	—
Perfluoroethylcyclohexane sulfonate	PFECHS		—	—
Fluorotelomer sulfonic acids				
1*H*,1*H*,2*H*,2*H*-Perfluorohexane sulfonic acid	4:2FTS	x	—	x
1*H*,1*H*,2*H*,2*H*-Perfluorooctane sulfonic acid	6:2FTS	x	—	x
1*H*,1*H*,2*H*,2*H*-Perfluorodecane sulfonic acid	8:2FTS	x	—	x
Perfluorooctane sulfonamides				
Perfluorooctanesulfonamide	PFOSA	x	x	x
N-methyl perfluorooctanesulfonamide	NMeFOSA	x	x	—
N-ethyl perfluorooctanesulfonamide	NEtFOSA	x	x	—
Perfluorooctane sulfonamidoacetic acids				
N-methyl	NMeFOSAA	x	—	x

Target Analyte Name	Abbreviation	EPA 1633A (1)	CDC/NHANES (2)	MDH PHL (3)
perfluorooctanesulfonamidoacetic acid				
N-ethyl perfluorooctanesulfonamidoacetic acid	NEtFOSAA	x	—	x
Perfluorooctane sulfonamide ethanols				
N-methyl perfluorooctanesulfonamidoethanol	NMeFOSE	x	—	—
N-ethyl perfluorooctanesulfonamidoethanol	NEtFOSE	x	—	—
Per- and polyfluoroether carboxylic acids				
Hexafluoropropylene oxide dimer acid	HFPO-DA	x	x	x
4,8-Dioxa-3*H*-perfluorononanoic acid	ADONA	x	x	x
Perfluoro-3-methoxypropanoic acid	PFMPA	x	—	—
Perfluoro-4-methoxybutanoic acid	PFMBA	x	—	—
Nonafluoro-3,6-dioxaheptanoic acid	NFDHA	x	—	—
Ether sulfonic acids				
9-Chlorohexadecafluoro-3-oxanonane-1-sulfonic acid	9Cl-PF3ONS	x	x	x
11-Chloroeicosafluoro-3-oxaundecane-1-sulfonic acid *	11Cl-PF3OUdS	x	—	x
Perfluoro(2-ethoxyethane)sulfonic acid	PFEESA	x	—	—
Fluorotelomer carboxylic acids				
3-Perfluoropropyl propanoic acid	3:3FTCA	x	—	—
2*H*,2*H*,3*H*,3*H*-Perfluorooctanoic acid	5:3FTCA	x	—	—
3-Perfluoroheptyl propanoic acid	7:3FTCA	x	—	—

L=Linear isomer; Br=Branched isomer

(1) EPA. 2024. Method 1633, Revision A, Analysis of Per- and Polyfluoroalkyl Substances (PFAS) in Aqueous, Solid, Biosolids, and Tissue Samples by LC-MS/MS. EPA 820-R-24-007.

(2) CDC Method 6304.09

(3) MDH Public Health Laboratory