Evaluation of First Responders' Biological Monitoring Results After Maui County Hawaii Wildfires

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Availability of Report

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Introduction

Request

The National Institute for Occupational Safety and Health (NIOSH) received technical assistance requests from Maui County and the Hawai‘i National Guard through a mission assignment from the Federal Emergency Management Agency to evaluate first responders’ exposures to chemicals during the 2023 Maui Wildfires. The requests included Maui County firefighters, police, Ocean Safety Officers, Other Maui County employees, and Hawai‘i National Guard servicemembers who responded to the Lahaina and Kula wildfires.

Maui Wildfires

On August 8, 2023, wildfires developed on Maui, Hawaii, and burned thousands of structures. Kula and Lahaina suffered catastrophic damage. Active fires were present throughout August 8–9 and continued to smolder during August 10–12. The president declared the wildfires a national emergency and a public health emergency. Firefighters and Ocean Safety Officers from the Maui County Department of Fire and Public Safety were part of the initial response. They were involved in fire suppression, structure protection, and life-saving actions. Personnel from the Maui Police Department and Maui County Department of Public Works were also involved in the early response to the Lahaina wildfire. After the active fire, firefighters, police, and Hawai‘i National Guard servicemembers were embedded with Urban Search and Rescue teams.

To learn more about the workplace, go to Section A in the Supporting Technical Information

Our Approach

We visited Maui County and the Maui County Fire Department in September 2023 to evaluate potential chemical exposures in firefighters and others who responded to the Maui wildfires. We chose biomarkers of exposure based on their known association with wildfires, potential health effects, and half-lives consistent with the timing of our visit. We completed the following activities during our evaluation:

- Measured the amount of markers of exposure to the substances in the list below and compared our measurements with reference values, such as occupational exposure limits or United States general population levels:
    - Inorganic elements (lead, cadmium, manganese, and selenium) in responders’ blood
    - Per- and polyfluoroalkyl substances (PFAS) in responders’ blood
    - Polybrominated diphenyl ethers (PBDEs) in responders’ blood
    - Inorganic elements (chromium, nickel, and arsenic) in responders’ urine
    - Organophosphate esters (OPEs) in responders’ urine

- Administered two questionnaires to collect responders' demographic, work, and potential exposure characteristics while responding to the wildfires.
- Analyzed the exposure marker results by self-reported demographic, occupational, and exposure characteristics collected on the questionnaires.
- Categorized participating responders by employer and job into the following occupational subcategories:
    - All Maui County employees who participated included
        - 179 Firefighters
        - 19 Ocean Safety Officers
        - 39 Police Department Employees
        - 22 Other Maui County Employees (e.g., laborers and equipment operators)
    - 28 Hawai'i National Guard servicemembers participated (including Air and Army National Guard)

To learn more about our methods, go to Section B in the Supporting Technical Information

Our Key Findings

Some employees had levels of inorganic elements above relevant reference values

- Cadmium, lead, arsenic, and chromium were compared with occupational exposure limits; manganese, selenium, and nickel were compared with U.S. general population levels.
- Most employees' exposures were below the relevant reference values.
- No Maui County employees or National Guard servicemembers had results at or above the occupational exposure limits for cadmium and lead.
- The percentage of Maui County employees with results at or above the reference values for the following substances were as follows:
    - Inorganic-related arsenic species (9%)
    - Chromium (5%)
    - Manganese (5%)
    - Selenium (11%)
    - Nickel (4%)

- The percentage of National Guard servicemembers with results at or above the reference values for the following substances were as follows:
    - Inorganic-related arsenic species (8%)
    - Chromium (25%)
    - Manganese (7%)
    - Selenium (14%)
    - Nickel (7%)

As expected, almost all Maui County and Hawai‘i National Guard participants had detectable levels of PFAS, PBDEs, and OPEs

- Most people in the general population have PFAS in their bodies due to the presence of these contaminants in our water systems and some food, packaging, or household items.
    - At least one participant had a result above the reference values for four individual PFAS chemicals.
- The National Academies of Sciences, Engineering, and Medicine (NASEM) has proposed health screenings for people exposed to PFAS based on the sum of certain PFAS chemicals in serum, with a clinical threshold of 20 micrograms per liter.
    - Only one Maui County participant (out of 258 tested) had a PFAS summation concentration above the NASEM clinical threshold, and it was only slightly above (21 micrograms per liter).
    - No National Guard servicemembers had a PFAS summation concentration above the NASEM clinical threshold.
- Most members of the general population have PBDEs and OPEs in their bodies because they are commonly found in flame retardants used in household furnishing or other building materials.
    - At least one participant had a result above the reference value for 5 of the 11 PBDE chemicals and 4 of the 8 OPE chemicals.

We found some associations between occupation and the levels of inorganic elements and exposure markers measured in Maui County employees

- Workers in the category of “Other Maui County Employees” were more likely than other subgroups to have chromium levels over the recommended occupational exposure limit.
- Police department employees had higher median manganese concentrations than other subgroups.
- Firefighters had the highest median sum of PFAS concentrations.

We did not observe clear patterns between self-reported exposure characteristics and the exposure markers we measured in blood and urine

- For the Maui County responders, the self-reported amount of time in the impact zone did not show clear patterns with the biomarker levels in any of the subgroups.
- For National Guard servicemembers, we did not find an association between exposure marker levels and the specific dates during August 8–12 that servicemembers responded to the fires.
- There is no consistent association between reported personal protective equipment (PPE) use and biomarker levels among any of the responder categories. More sophisticated analyses beyond the scope of this report would be needed to help elucidate the contribution of tasks and PPE to the biomarker measurements.

To learn more about our results, go to Section B in the Supporting Technical Information

Our Recommendations

Implementing controls during disaster response is challenging. Taking actions to incorporate and train on the control measures can help facilitate their adoption in emergent situations.

Potential Benefits of Improving Workplace Health and Safety:

↑ Improved worker health and well-being	↑ Enhanced image and reputation
↑ Better workplace morale	↑ Superior products, processes, and services
↑ Easier employee recruiting and retention	↑ May increase overall cost savings

The recommendations below are based on the findings of our evaluation and on best practices for prevention of work-related health effects. The listing of these recommendations does not necessarily indicate that control measures were not followed during the Maui wildfire response, or that policies were lacking. A thorough evaluation of these measures or policies was not conducted. Additionally, the nature of our evaluation was such that we had limited ability to determine whether exposures could be directly attributed to work in responding to the recent fires, versus to other fire responses or occupational exposures, or (in some cases) to non-occupational activities.

For each recommendation, we list a series of actions that can be taken to address the issue. The actions at the beginning of each list are preferable to the ones listed later. The list order is based on a well-accepted approach called the "hierarchy of controls." The hierarchy of controls is a way of determining which actions will best control exposures. In most cases, the preferred approach is to eliminate hazards or to replace the hazard with something less hazardous (i.e., substitution). Installing engineering controls to isolate people from the hazard is the next step in the hierarchy. Until such controls are in place, or if they are not effective or practical, administrative controls and PPE might be needed. Read more about the hierarchy of controls at https://www.cdc.gov/niosh/hierarchy-of-controls/about/index.html.

We encourage the organizations to use a health and safety committee to discuss our recommendations and develop an action plan. Both employee representatives and management representatives should be included on the committee. Helpful guidance can be found in *Recommended Practices for Safety and Health Programs* at https://www.osha.gov/safety-management.

Recommendation 1: Follow best practices during wildfires and during fire debris cleanup to prevent exposure to inorganic elements, PFAS, flame retardants, and other chemicals related to products of combustion.

Exposure to inorganic elements such as lead, cadmium, manganese, selenium, arsenic, and nickel in the air and on the hands can lead to inhalation and ingestion of these substances. We found some employees had arsenic, manganese, selenium, and nickel concentrations above the applicable reference values. Exposure to these inorganic elements has been associated with different types of health effects. Where we identified levels above relevant reference values, participants were encouraged to share their individual results with their healthcare provider.

Flame retardants have been added to manufactured materials for many years to delay the production of flames. Firefighters may be exposed to these chemicals when items containing flame retardants burn. Some responders had levels of flame retardants that were higher than the National Health and Nutrition Examination Survey 95th percentile for the general population. Reducing exposure to these elements in air to prevent inhalation and on the skin to prevent ingestion or absorption remains essential for worker protection.

How? At your workplace, we recommend these specific actions:

Minimize exposure to dust.

- Consider using soil stabilizers or applying a water spray during cleanup activities to reduce dust generation.
- Do not use leaf blowers or take other actions (e.g., dry sweeping) that will put ash into the air. Shop vacuums and other common vacuum cleaners do not filter out small particles, but rather blow the particles out the exhaust into the air. To clean up ash, use vacuums equipped with high-efficiency particulate air (HEPA) filters.

Follow best practices during wildfires and fire debris cleanup to implement all aspects of Emergency Responder Health Monitoring and Surveillance (ERHMS).

- Roster responders, track responder activities and potential exposures, and implement biomonitoring if appropriate and feasible.
  - Systematic employer rostering and exposure tracking of first responders may facilitate rapid deployment of exposure scientists and other personnel to permit blood or urine collection within days of the disaster. This will help to more accurately characterize potential response-related exposures.
- Additional information about ERHMS can be found at [Emergency Responder Health Monitoring and Surveillance | Emergency Responder Health Monitoring and Surveillance | CDC].
- If there is concern that firefighters or other responders might have been exposed to hazardous substances, the fire department or other managing organization can reach out to the state Occupational Safety and Health Administration (OSHA) office to discuss the usefulness of biological monitoring.
- For firefighters, consider enrolling in the National Firefighter Registry for Cancer to permit long-term tracking of exposures and health outcomes. Go to https://nfr.cdc.gov/.

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Provide annual training on wildfire best practices including hazards during cleanup following wildfires.

- See the NIOSH Fact Sheet [Wildland Fire Fighting Hot Tips to Stay Safe and Healthy]. It summarizes the most common work-related hazards faced on the fire line, including ash, dust, and burning debris. Some recommended actions are as follows:
  - Rotate crews out of areas with heavy smoke.
  - Avoid attacking from downwind positions.
  - Locate camps, staging areas, incident command headquarters, and other areas where people will spend extended periods of time upwind from the fire.
- Train on the risk and health effects of smoke inhalation and exposure to ash.

- Consider the additional recommendations in the NIOSH Health Hazard Evaluation Report titled Evaluation of Fire Debris Cleanup Employees' Exposure to Silica, Asbestos, Metals, and Polyaromatic Hydrocarbons while cleaning up debris following urban-rural interface fires.

Train and encourage employees to limit their dermal exposure by maintaining fire response gear properly.

- Keep work clothes, turnout gear, or other protective gear as clean as possible.
- Follow all cleanup and decontamination protocols in place.
- Store gear in designated areas and outside of living areas or personal vehicles.
- Do not wear turnout gear or wildland gear when performing activities where the gear is not necessary.

Require employees to wash their hands, neck, or other areas of the skin as soon as possible after contact with fire debris or ash.

- Ensure adequate handwashing facilities are available when possible. Temporary water stations would be appropriate to use for this application.
- Encourage employees to wash their hands or skin thoroughly as soon as possible after coming in contact with fire debris or ash.
- Require washing hands during fire events before hand to mouth actions, such as eating, drinking, vaping, or smoking.
- Provide time and facilities for showering as soon as possible after completing response activities.

Require employees to wear proper respiratory protection for the task.

- Follow all requirements in the OSHA Respiratory Protection Standard available at 1910.134 - Respiratory protection. | Occupational Safety and Health Administration (osha.gov).
- Complete a thorough hazard assessment to determine what types of respirators are needed for each exposure scenario.
- Wear a self-contained breathing apparatus respirator when exposed to smoke from structure fires, vehicle fires, or combustion of other manmade materials.
- Wear particulate respirators when exposure to dust, ash, or other particulate from wildfires is anticipated.

Continue to wear PPE even after the active fire is extinguished. This is especially true for workers with continued exposure to smoke, smoldering material, ash, or debris.

- Always wear proper PPE (long sleeve shirts, pants, gloves, and safety glasses) when working around ash. If you do get ash on your skin, wash it off as soon as possible.
- Especially concerning is ash from wooden decks, fences, and retaining walls made from wood, pressure-treated with chromated copper arsenate, as it may contain harmful amounts of arsenic.
- Lithium-ion batteries including power walls and electric vehicles may contain harmful amounts of lithium, nickel, and manganese.
- Use only nitrile gloves when tight-fitting chemical resistant gloves are required. Do not use latex gloves.
- Provide methods to decontaminate footwear, personal protective equipment, tools, and other frequently handled or worn items to reduce continued exposures.

Report and track health symptoms associated with workplace exposures.

- Encourage employees with work-related health concerns or adverse health symptoms to discuss them with their healthcare provider or a provider knowledgeable in occupational medicine.
    - The American College of Occupational and Environmental Medicine and the Association of Occupational and Environmental Clinics maintain databases of providers to help locate someone in your geographic area.
- Encourage employees to discuss their biomonitoring results with their healthcare provider.
- Consider sharing a copy of this report with the healthcare provider.

Recommendation 2: Follow best practices to prevent other fire responder exposures to PFAS, including from aqueous film forming foams (AFFF)

Per- and polyfluoroalkyl substances, known as PFAS, are a large group of synthetic chemicals that have been used in industry and consumer products worldwide since the 1950s. Some PFAS can stay in peoples' bodies for a long time (e.g., years), and some do not break down in the environment. Studies have shown that PFAS exposure is associated with a range of health effects (e.g., increased cholesterol levels, increased risk of high blood pressure or preeclampsia in pregnant women, and increased risk of testicular or kidney cancer). However, there is not enough data to fully inform occupational exposure limits.

We found measurable amounts of PFAS in blood samples, some in levels higher than in the general population. Within this evaluation, we found that firefighters had the highest median sum of PFAS concentrations compared with the other occupational groups. In addition to following the measures recommended above for preventing exposures from PFAS from burning household products, steps can be taken to prevent fire responder exposure to PFAS from AFFF and other sources.

How? At your workplace, we recommend these specific actions:

Develop and implement a PFAS exposure control plan.

- Perform a hazard assessment for activities that may involve PFAS exposure (e.g., use of foams that contain PFAS). OSHA recommendations for how to perform a hazard assessment are available at Recommended Practices for Safety and Health Programs.
- Implement a hierarchy of controls approach to limit exposures to PFAS in a feasible and effective manner. A hierarchy of controls approach for PFAS-containing foams may include these actions:
    - Elimination—where possible, remove PFAS-containing firefighting foams from current available stores. This may not be possible for every site.
    - Substitution—utilize safer alternative firefighting foams when they are approved for use and equally effective at controlling Class B fires.
    - Engineering controls—use enclosed systems for transfer or testing of AFFFs to minimize exposure from splashing or other releases.
    - Administrative controls—if firefighters must use PFAS-containing foams for any reason, ensure that they are adequately trained on safe use. Implement policies for decontamination and laundering of gear after use of foam and do not use firefighting foam containing PFAS in training.
    - PPE—use protective nitrile gloves and other barrier protective equipment if working with PFAS-containing foams.
- Another potential source of PFAS exposure is firefighting gear that contains PFAS. Following the best practices in Recommendation 1 above for the proper maintenance of firefighting gear will reduce exposure to PFAS from the gear itself. Proper gear maintenance also helps in reducing exposure to PFAS in ash and other fire debris.

Supporting Technical Information

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Section A: Maui Wildfire Information

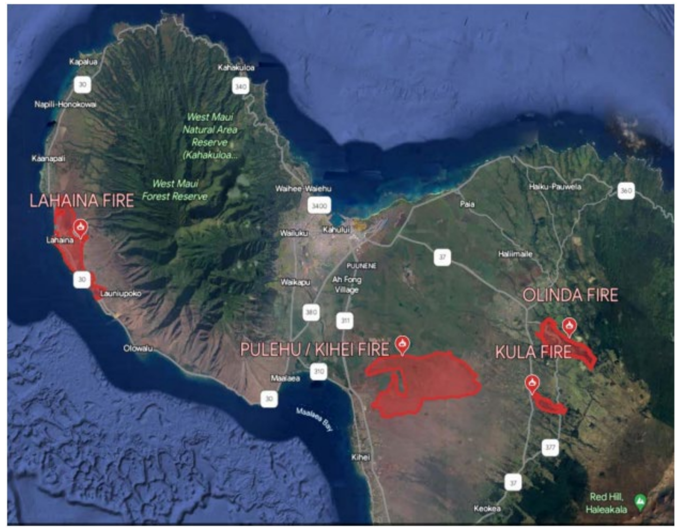

Figure 1. Map of the locations of the four major fires that occurred on the western part Maui during August 2023. Source: Maui Police Department Report 2024.

On August 8, 2023, wildfires developed on Maui, Hawaii, and destroyed over 2,200 structures and 1,550 parcels on the island [EPA 2024a,b; HI DOH 2023; Maui PD 2024]. Kula and Lahaina suffered catastrophic damage. The active fires were present during August 8–9 and continued to smolder during August 10–12. Around 100 people lost their lives in the Lahaina fire, and some residents were forced to flee to the ocean for safety. The president declared the wildfires to be a national emergency and a public health emergency. Firefighters and Ocean Safety Officers from the Maui County Department of Fire and Public Safety, Maui Police Department officers, and personnel from the Maui County of Public Works were all involved in the initial response to the fires, including fire suppression, structure protection, water rescue, and evacuations. Firefighters, police, and Hawai‘i Air and Army National Guard servicemembers also served on Urban Search and Rescue teams after the active phase of the Lahaina fire. These entities conducted coordinated foot searches of the burn zone looking for survivors and human remains [Maui PD 2024].

On August 28, 2023, the Maui Fire Chief requested assistance from the Federal Emergency Management Agency (FEMA) in evaluating exposures that firefighters and Ocean Safety Officers who may have experienced exposures during response activities. A Request for Assistance was routed through the federal unified command structure for the 2023 Maui Wildfire response, tasking CDC/NIOSH to assist with public health surveillance of firefighters and other Maui County responders for potential exposure to toxic substances. Maui Police Department and Maui Department of Public Works employees were added to the request for assistance because they also responded to the active fires.

On September 15, 2023, the Hawai‘i National Guard Emergency Management Specialist requested similar assistance from CDC/NIOSH in evaluating the potential health effects from wildfire response personnel from the National Guard and to assess exposure magnitude to improve future health and safety decisions.

NIOSH responded to the requests by visiting Maui County and the Maui County Fire Department in September 2023 to evaluate potential chemical exposures in firefighters and others who responded to the Maui wildfires. In this evaluation, we performed measurements of markers of exposure (biological monitoring) and administered questionnaires to try to better understand potential exposures for these workers (as described in detail below). Biological monitoring is a tool that can provide information about the actual amount of substances that are in the body. It can also serve as a component of a health surveillance program (if levels of exposure are tracked over time) and as a tool to identify trends that may indicate emerging health risks.

As we planned our evaluation, it was apparent that the biological monitoring and questionnaires would have some limitations. For example, it would be difficult to collect information that would specifically address how much the work of responding to the fires contributed to substances we found in the workers' samples. This is the result of several factors, including that (1) our evaluation took place one month after the fire, and (2) we had no information about the substances in the body before the fire. The planning of this evaluation also considered the potential for future benefit to the workers in Maui and to future evaluations of exposures among responders to wildfire disaster events in Maui County or elsewhere.

Occupational Subgroups

For our evaluation, we categorized emergency responders into occupational subgroups based upon their general job tasks, activities, and employer. These subgroups allow for result comparison among groups. The subgroups also allow for readers of this report to find results for specific occupational groups more easily. We defined the following occupational subgroups:

- All Maui County employees
    - Firefighters
    - Maui Police Department Employees
    - Ocean Safety Officers
    - Other Maui County Employees
- Hawaiʻi National Guard servicemembers (including Air and Army National Guard)

Section B: Methods, Results, and Discussion

Methods: Participant Recruitment

During our visit in September 2023, we invited Maui County firefighters and other Maui County workers and Hawaiʻi National Guard servicemembers to provide blood and urine samples to measure markers of exposure. We also invited them to fill out two questionnaires. We evaluated only the employees who met the following conditions:

- A firefighter or Ocean Safety Officer who was employed by the Maui Fire and Public Safety at any time during August 8–12, and was currently employed by Maui Fire and Public Safety on the day of initiating participation in this evaluation, OR
- A non-firefighter, non-Ocean Safety Officer Maui County employee who responded to either the Lahaina or Kula fires during August 8–12, and was currently employed by Maui County on the day of initiating participation in this evaluation, OR
- A Hawaiʻi National Guard servicemember who responded to either the Lahaina fire or Kula fire during August 8–12.

We chose the date range of August 8–12 because it included days with the highest potential exposure to toxic substances from active (August 8–9) and smoldering fire (August 10–12).

The invitation to participate was extended to firefighters, Ocean Safety Officers, Other Maui County employees, and Hawaiʻi National Guard servicemembers by their supervisory chain. NIOSH did not individually solicit employees. An eligible Maui County firefighter, Ocean Safety Officer, Other Maui County employee, or Hawaiʻi National Guard servicemember must have attended one of the onsite sample collection days (September 13–19, 2023) for participation. All participants were allowed by their employers to attend a sample collection day during work hours. Of the 294 active Maui County firefighters (all of whom were eligible), 183 attended an onsite sample collection day. NIOSH did not obtain precise information on the number of eligible participants for the other employee groups.

During onsite sample collection days, we explained the objectives and methods of the evaluation. We also described the substances being tested for in blood and urine samples and addressed any employees' questions. Written informed consent was obtained from each participant. Participants had the option to consent to all, none, or specific parts of the evaluation, which included questionnaires, urine sample, and blood sample. One of the questionnaires, the exposure worksheet, was developed specifically for Maui County responders. Participants were also told that they would receive personal notification letters with their individual results. Participants with a result above an occupational exposure limit (OEL) were notified of that result as soon as possible.

Results: Participant Recruitment

Maui County participation in each part of the evaluation is summarized in Figure 2. A total of 183 firefighters attended one of the sample collection days. Of these, 179 agreed to fill out the questionnaires, 178 agreed to blood sampling, and 177 agreed to urine sampling. All 39 Maui Police

Department Employees, 19 Ocean Safety Officers, and 22 Other Maui County employees who were eligible for the evaluation and attended one of the sample collection days agreed to perform all parts of the evaluation. Job titles among the Other Maui County Employees included electronic technician, laborer, equipment operator, and supervisor.

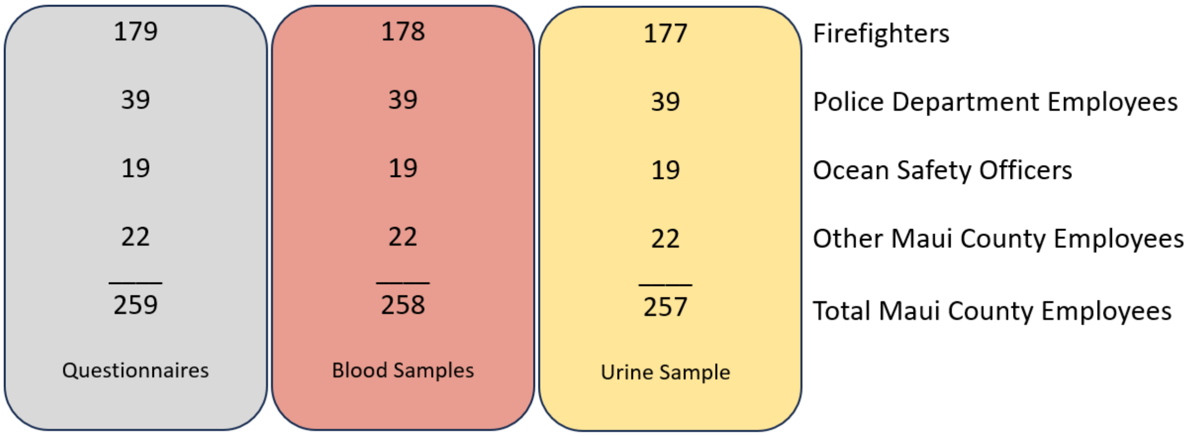

Figure 2. Number of Maui County employees consenting to each evaluation component by occupational subgroup.

A total of 28 Hawaiʻi National Guard servicemembers participated in the evaluation. All agreed to all three parts of the evaluation. These servicemembers were not asked to complete the exposure worksheet, so they only filled out the NIOSH questionnaire.

Methods: Demographic Characteristics and Exposure Assessment Questionnaires

All Maui County participants completed two questionnaires. One questionnaire was developed by NIOSH and consisted of brief demographic and work characteristic questions. Participants were asked to "Select all that apply" for race, therefore, results do not sum to 100%. Maui County developed the second questionnaire. It consisted of free-text (open-ended) questions about work duration, locations, activities, and personal protective equipment (PPE) worn during August 8–12 to gather more detailed exposure characteristics. Free-text responses were reviewed by NIOSH staff to identify themes, which were used to design a REDCap instrument to code for location, activities, and PPE. The free-text responses and corresponding codes were then recorded in REDCap.

National Guard servicemembers only completed the NIOSH questionnaire. They did not complete the Maui County exposure assessment questionnaire.

We analyzed information gathered in the questionnaires using R 4.3.3 (R Foundation for Statistical Computing, Vienna, Austria) and SAS 9.4 (SAS Institute, Cary, NC) statistical software.

Results: Demographic Characteristics

Demographic characteristics for all Maui County employees and subcategories are found in Table C1 and for Hawai‘i National Guard servicemembers in Table C2.

Maui County Employees

Participating Maui County employees (n = 259) had a median age of 40.0 years (range: 20.6–68.7 years), were 94% male, and most commonly self-identified as White (54%), Asian (48%), Native Hawaiian or other Pacific Islander (46%), American Indian or Alaska Native (7%), or Black or African American (1%).

National Guard Servicemembers

Participating servicemembers (n = 28) had a median age of 38 years (range: 24.0–56.1 years), were 79% male, and most commonly self-identified as Asian (79%), Native Hawaiian or other Pacific Islander (21%), and/or White (14%).

Results: Exposure Assessment Questionnaires

Firefighters Occupational Subgroup

Of the 179 participating firefighters, 70% responded to either the Kula or Lahaina fires on August 8, 58% responded on August 9, 35% responded on August 10, 40% responded on August 11, and 26% responded on August 12 (Figure 3).

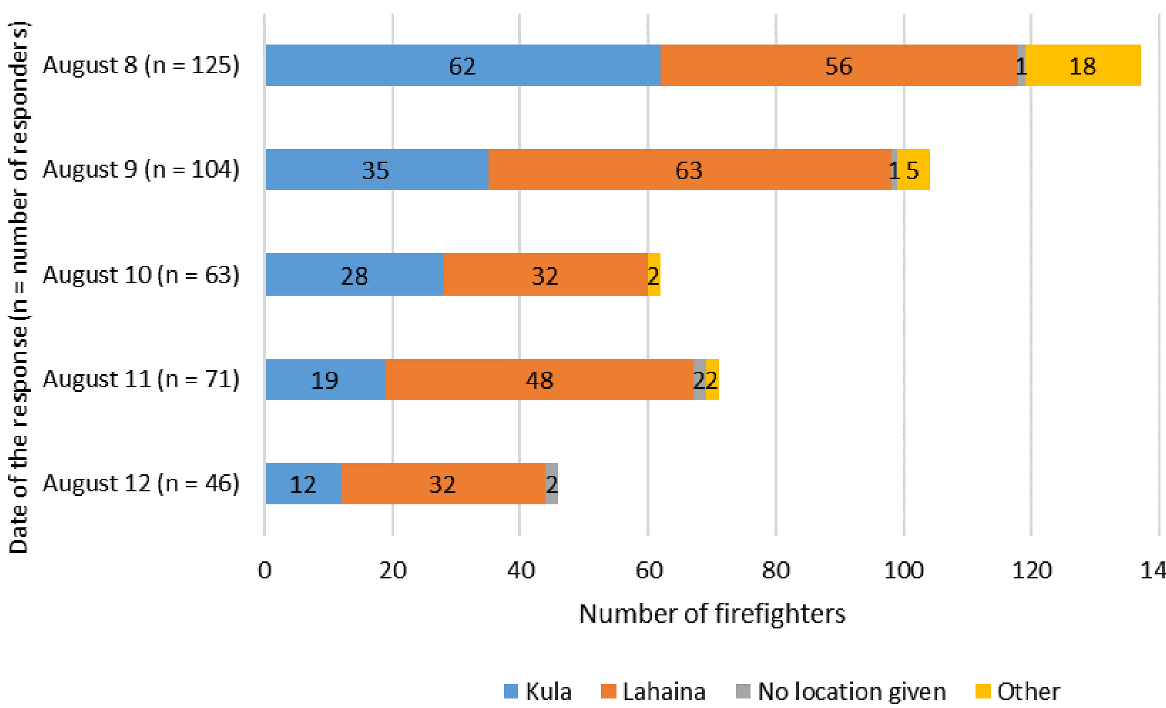

Figure 3. Daily responders among the firefighters (n = 179) responding to the Kula and Lahaina wildfires by day. Note: “No location given” refers to those who were on duty but did not report which fire they responded to. Firefighters could respond to multiple fires in one day.

Among the firefighters who responded on August 8, the median (range) time spent in the impact zone was 12.0 (0.0–26.0) hours, 12.0 (1.0–24.0) hours on August 9, 11.5 (2.0–26.5) hours on August 10, 12.0 (0.0–24.0) hours on August 11, and 12.0 (1.0–24.0) hours on August 12. Questions regarding time in the impact zone were open-ended, so responders were able to report working > 24 hours for one response day. During response, firefighters either wore wildland firefighting gear (Nomex®) or structural firefighting gear (turnout gear) (Figure 4).

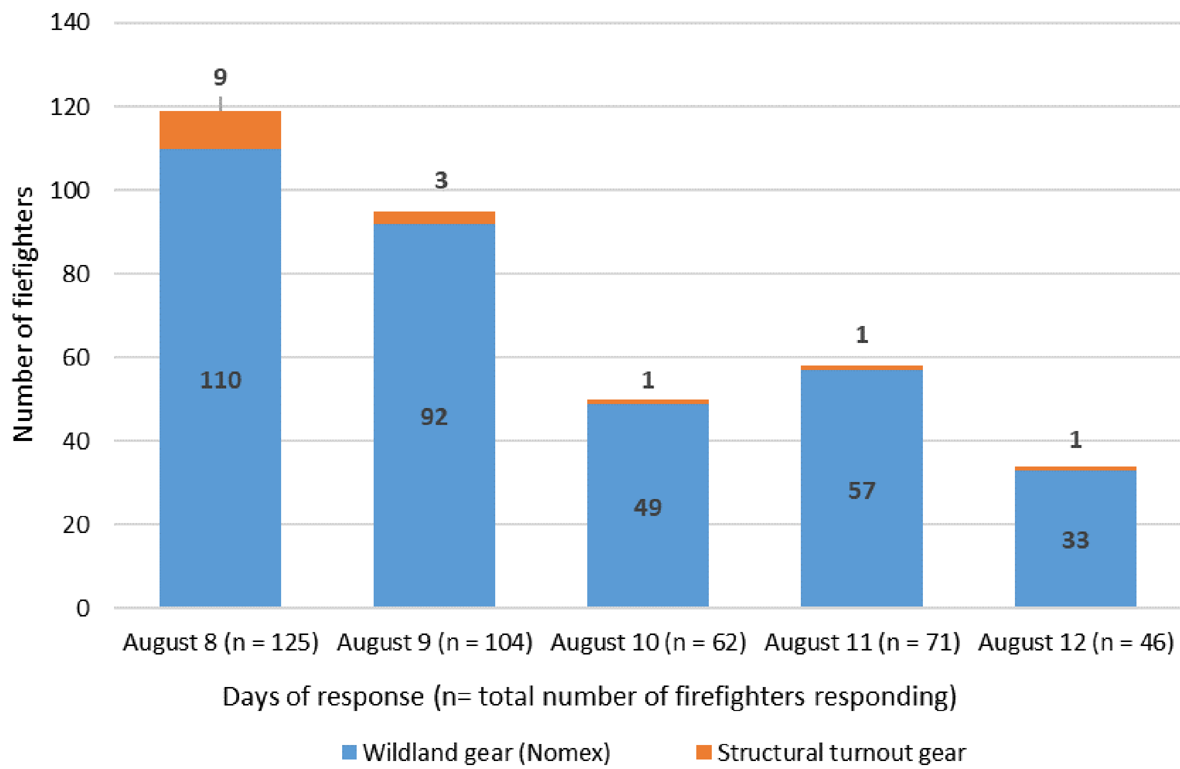

Figure 4. Gear worn by firefighters (n = 179) by day. (Note: Firefighters could wear both wildland gear and structural turnout gear in the same day.

For respiratory protection, firefighters wore air purifying respirators (APRs), self-contained breathing apparatus (SCBAs), no respiratory protection, or they did not answer the question about respiratory protection (Figure 5). Firefighters reported performing the following types of activities during August 8–12: fire suppression (including fire attack and fire control); overhaul (hot-spot mitigation and flare ups; checking the fire scene to ensure no fire remains, removing and cooling materials to prevent rekindling), mop-up (removal of burned and unburned materials for safety [i.e., for reoccupation], investigation, decrease fire load), exposure mitigation (structure protection, which are tactics used to prevent the fire from reaching a structure[s]), evacuation, and search and rescue/recovery (Figure 6).

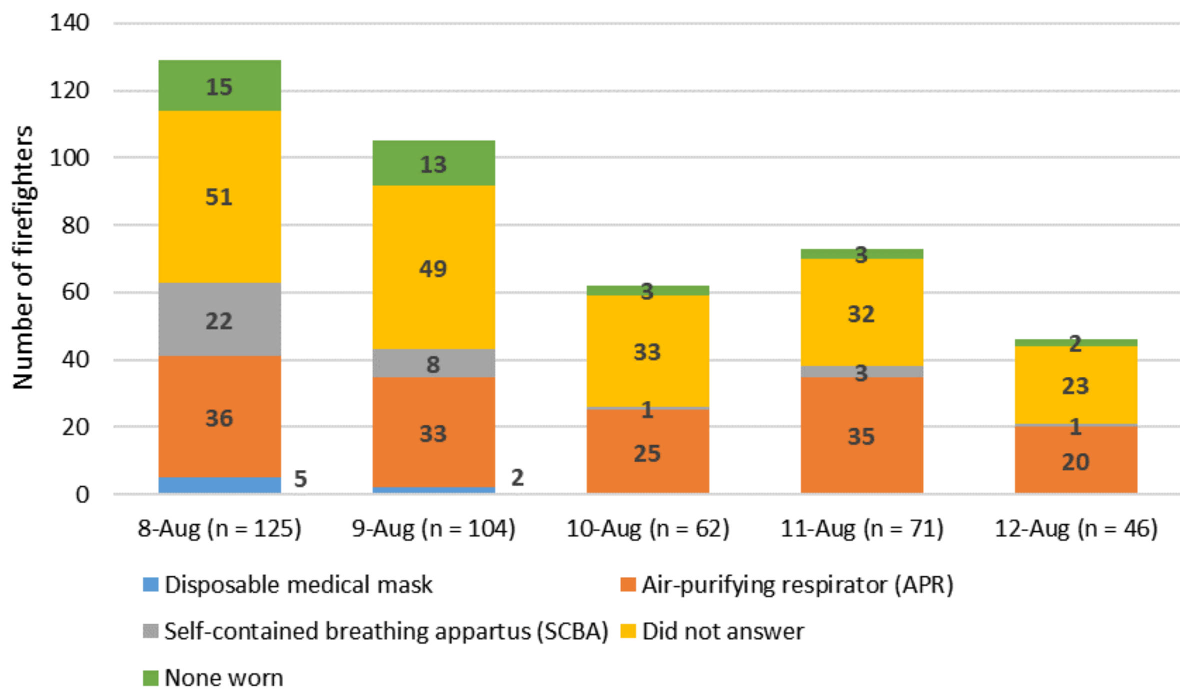

Figure 5. Respiratory protection used by firefighters (n = 179), by day.

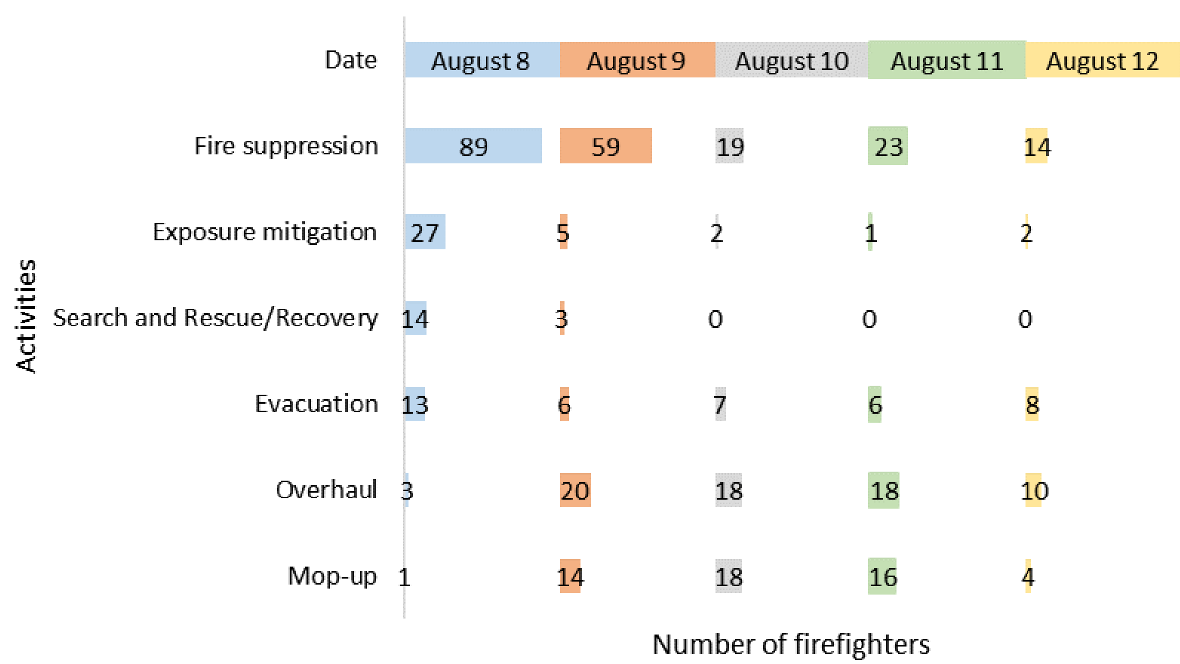

Figure 6. Most frequently reported activities by firefighters (n = 179). 125 firefighters responded on August 8, 104 on August 9, 62 on August 10, 71 on August 11, and 46 on August 12. Firefighters can do more than one activity each day.

Police Occupational Subgroup

Of the 39 participating police department employees, 56% responded to either the Kula or Lahaina fires on August 8, 87% responded on August 9, 35% responded on August 10, 40% responded on August 11, and 87% responded on August 12.

Most police employees reported responding to the Lahaina fires (Figure 7). Of the police department employees who responded each day, they spent a median (range) of 12.0 (3.0–30.0) hours in the impact zone on August 8, 12.0 (4.0–19.0) hours on August 9, 12.0 (4.0–19.0) hours on August 10, 12.0 (4.0–16.0) hours on August 11, and 12.0 (4.0–16.0) hours on August 12.

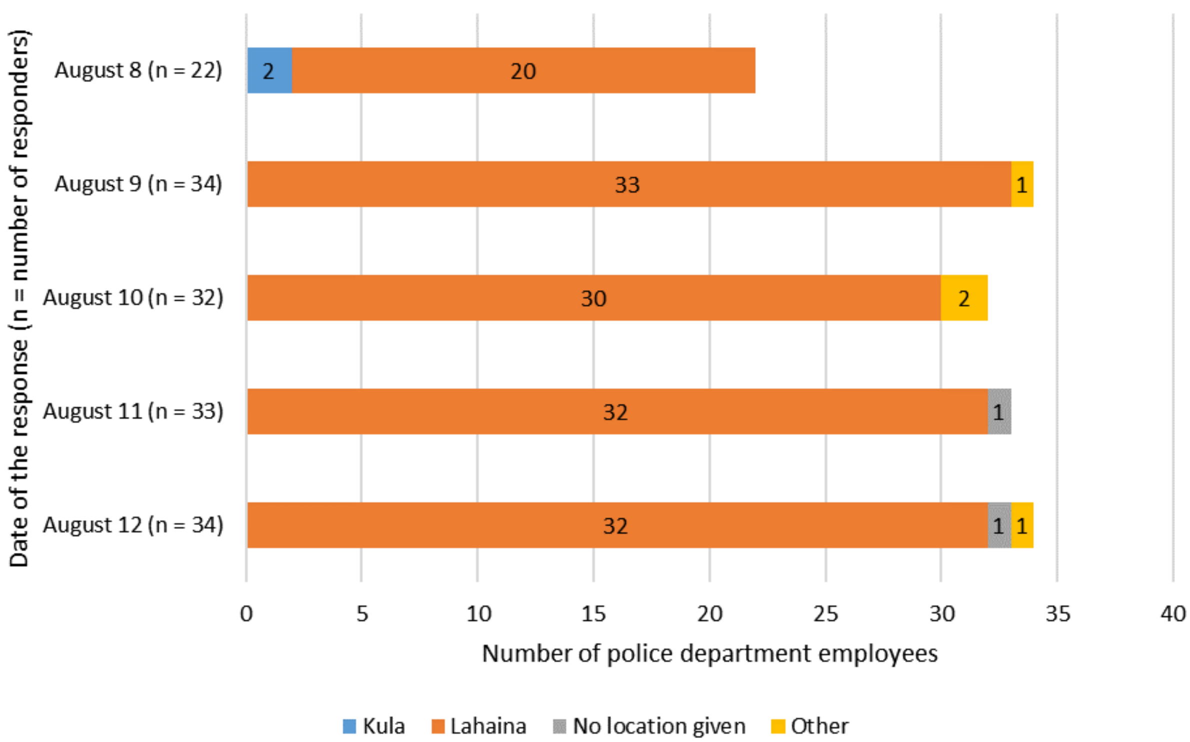

Figure 7. Number of police department employees (n = 39) responding per day to the Kula and Lahaina fires.

Police department employees reported either wearing APRs, no respiratory protection, or did not answer the question about respiratory protection (Figure 8). Very few (< 2) police department employees reported wearing non-respiratory PPE. The type of activities that police department employees reported doing most frequently during August 8–12 included evacuation, foot patrol, vehicle patrol and traffic posts, search and rescue/recovery, working within the impact zone, and logistics (Figure 9).

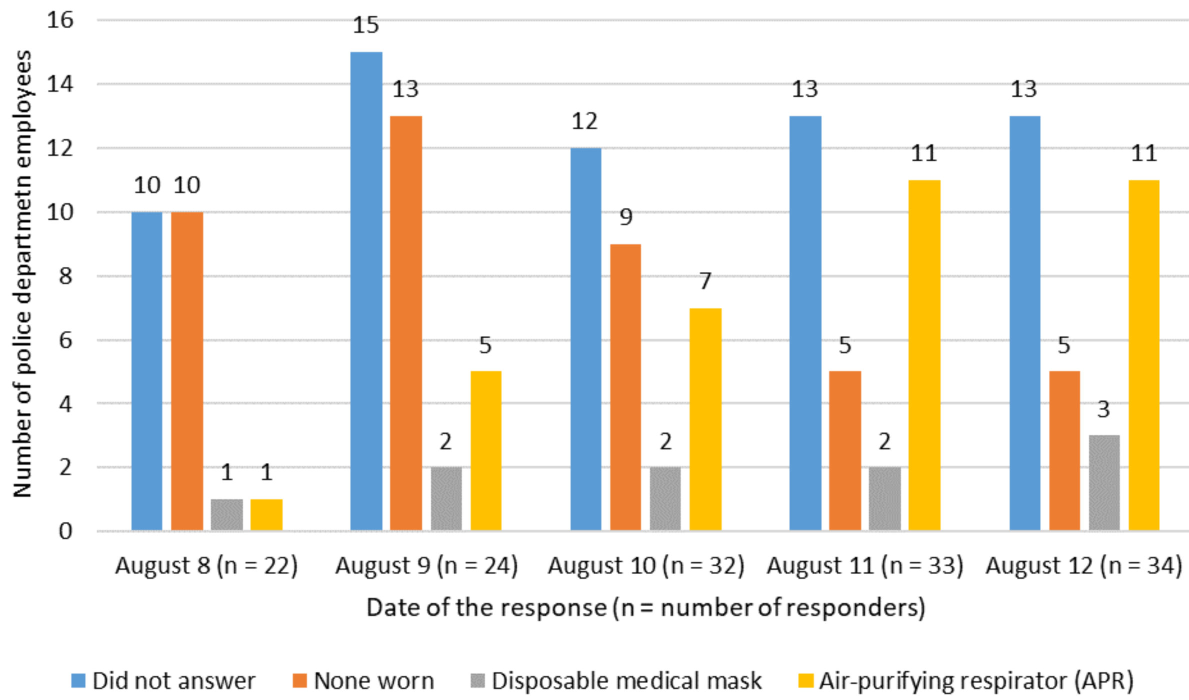

Figure 8. Respiratory protection worn by police department employes (n = 39), by day.

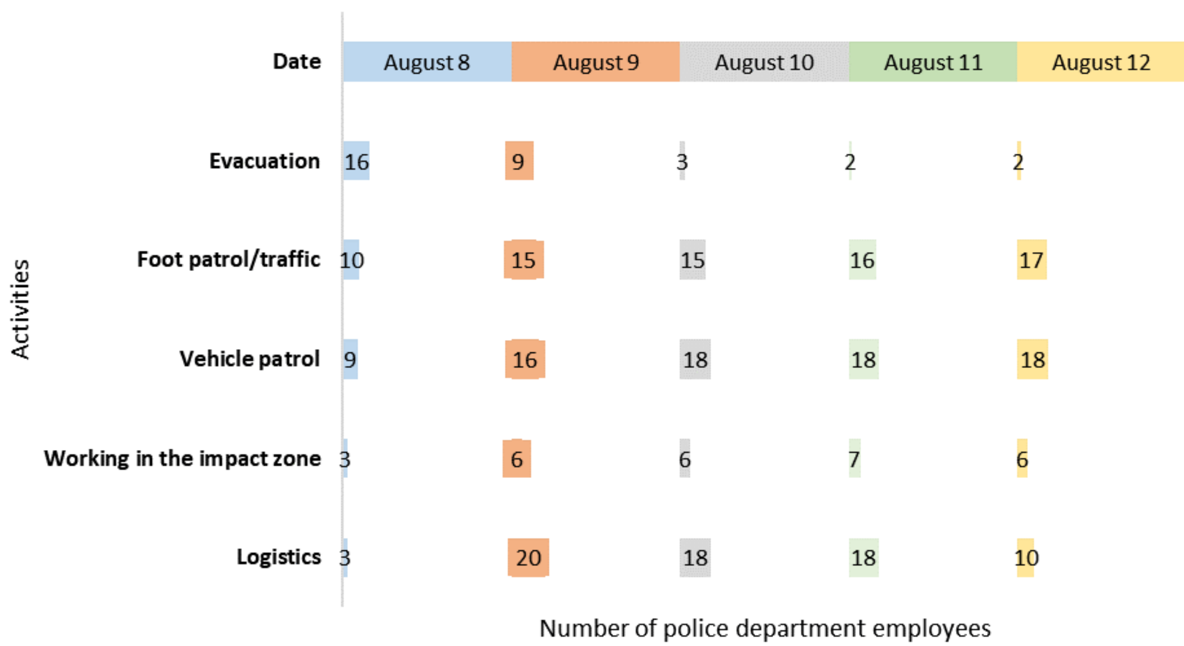

Figure 9. Most frequently reported police department employee (n = 39) activities. Twenty-two police department employees responded on August 8, 24 on August 9, 32 on August 10, 33 on August 11, and 34 on August 12. Note that police department employees can do more than one activity per day.

Ocean Safety Officers Occupational Subgroup

Of the 19 participating Ocean Safety Officers, 21% responded to the Lahaina fires on August 8, 68% responded on August 9, 32% responded on August 10, 58% responded on August 11, and 32% responded on August 12 (Figure 10).

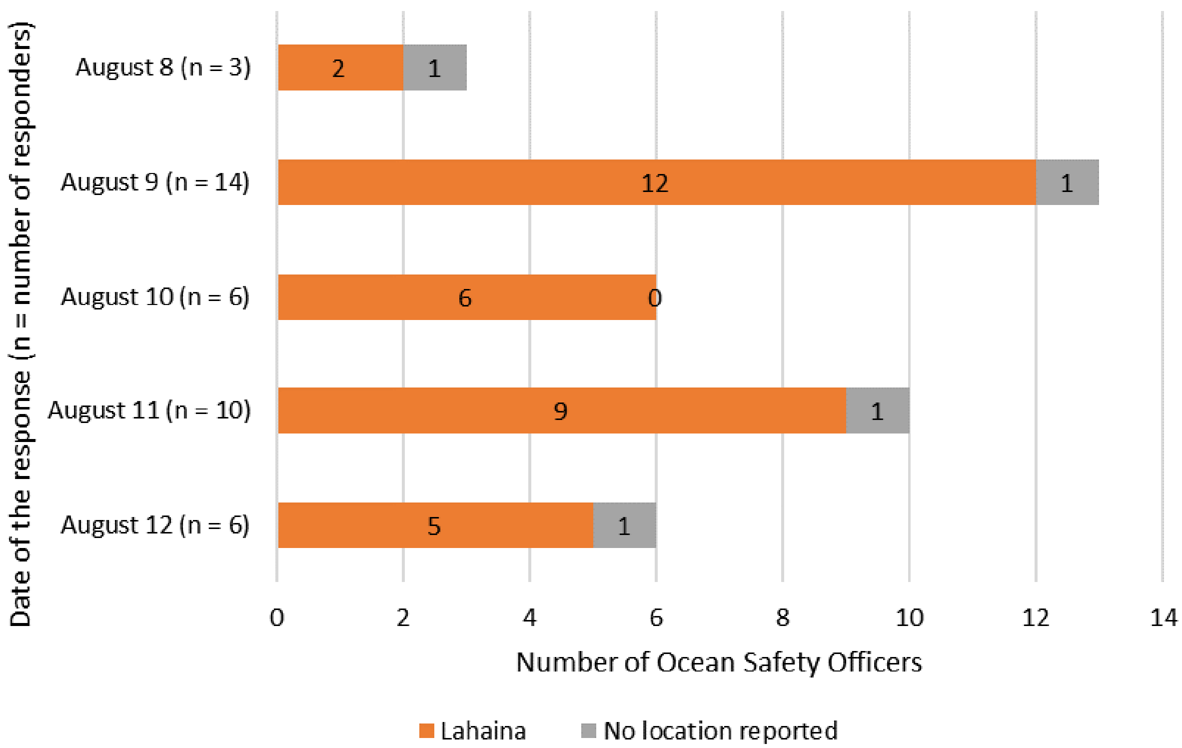

Figure 10. Number of Ocean Safety Officers (n = 19) responding per day to the Lahaina fire.

Of the Ocean Safety Officers who responded each day, they spent a median (range) of 8.0 (6.0–8.5) hours in the impact zone on August 8, 7.5 (4.0–13.0) hours on August 9, 8.0 (4.0–12.0) on August 10, 8.0 (4.0–13.0) hours on August 11, and 6.0 (4.0–12.0) hours on August 12. Most Ocean Safety Officers did not answer the question regarding respiratory protection (Figure 11). Very few Ocean Safety Officers reported any non-respiratory PPE. The most frequently reported activities were ocean search and rescue/recovery, jet ski or boat operator, evacuation, and logistics (Figure 12).

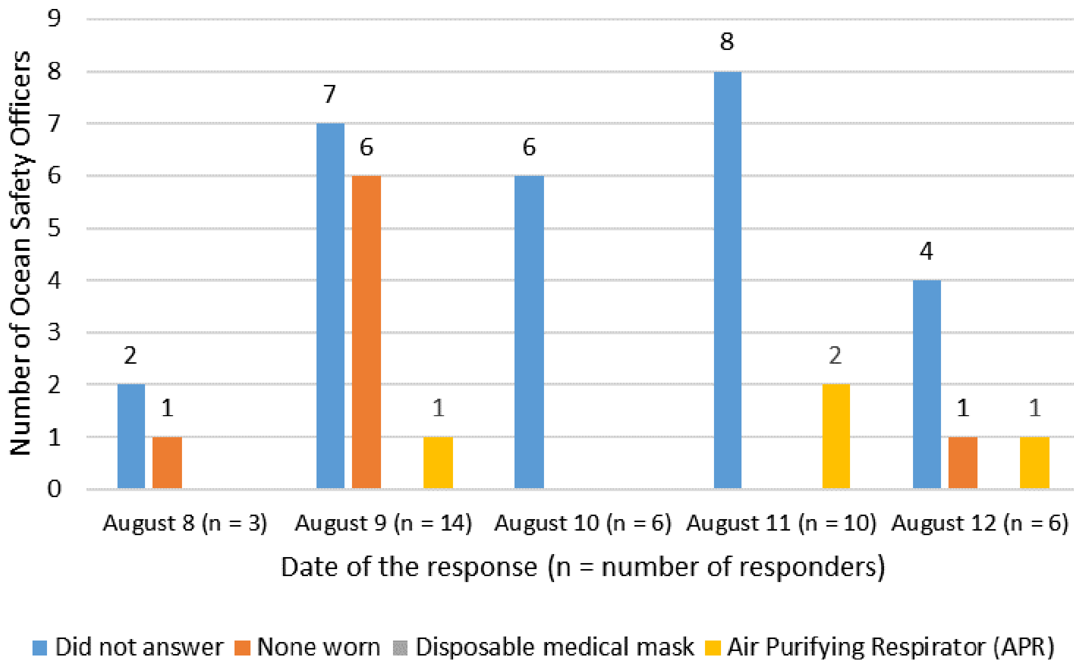

Figure 11. Respiratory protection worn by Ocean Safety Officers (n = 19), by day.

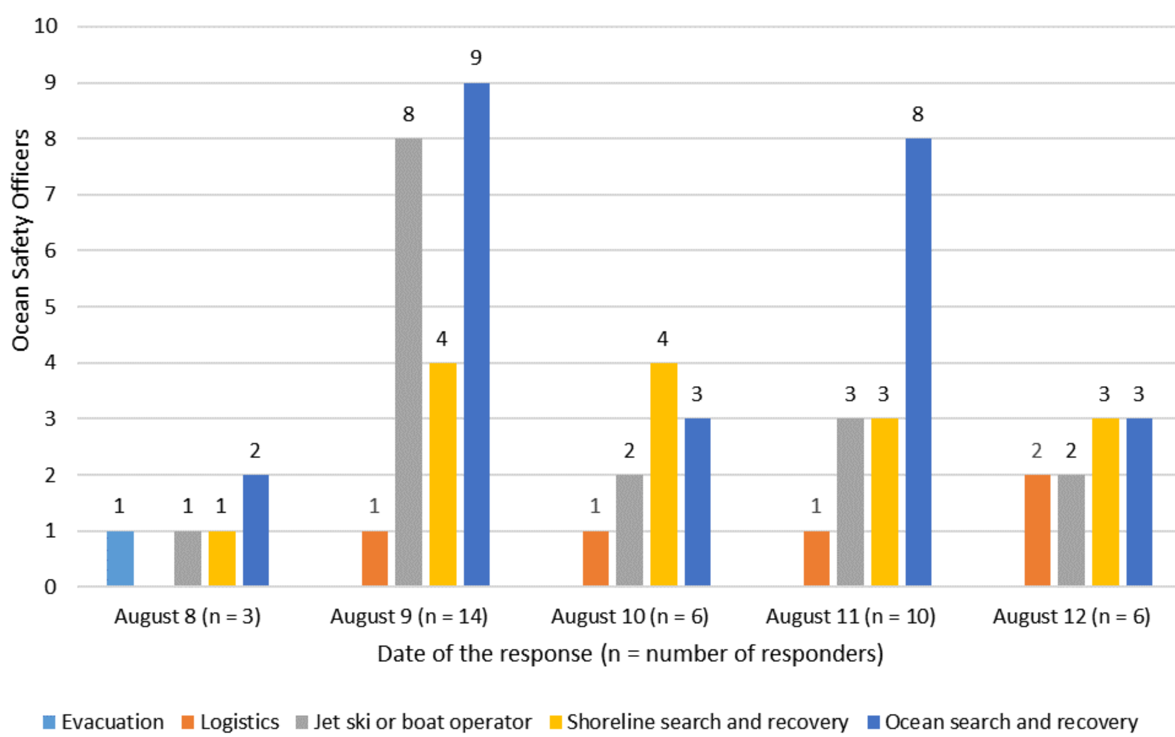

Figure 12. Most frequently reported Ocean Safety Officers' (n = 19) activities. Note Ocean Safety Officers can do more than one activity.

Other Maui County Employees Occupational Subgroup

Of the 22 participating Other Maui County employees, 32% responded to either the Kula or Lahaina fires on August 8, 73% responded on August 9, 68% responded on August 10, 82% responded on August 11, and 14% responded on August 12.

Most Other Maui County Employees responded to the Lahaina fire (Figure 13). Of the Other Maui County employees who responded each day, they spent a median (range) of 6.5 (1.0–8.5) hours on August 8, 6.3 (1.0–18.5) hours on August 9, 8.0 (1.0–11.5) hours on August 10, 8.5 (1.0–14.0) hours on August 11, and 2.0 (1.5–6.0) hours on August 12.

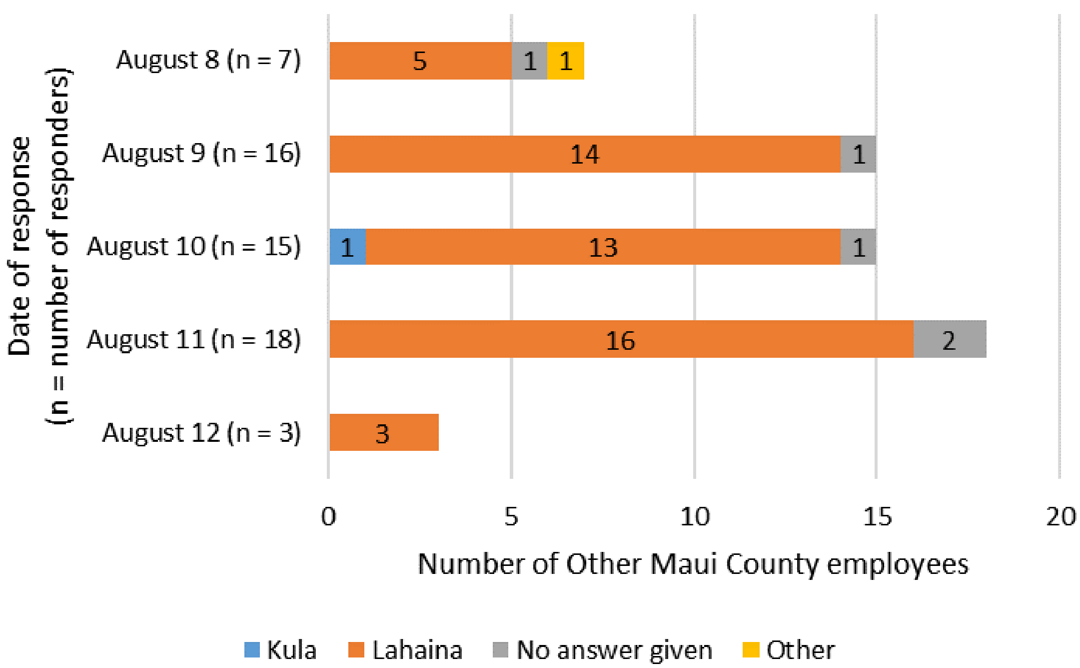

Figure 13. Number of Other Maui County employees (n = 22) responding per day to the Kula and Lahaina fires.

Other Maui County Employees wore disposable medical masks and APRs for respiratory protection (Figure 14). They also wore helmets, boots, gloves, safety glasses, and safety vests for non-respiratory PPE (Figure 15). The most frequently reported activities were evacuation, clearing debris/cutting trees, maintenance, foot patrol/traffic, property survey, and other service calls (Figure 16).

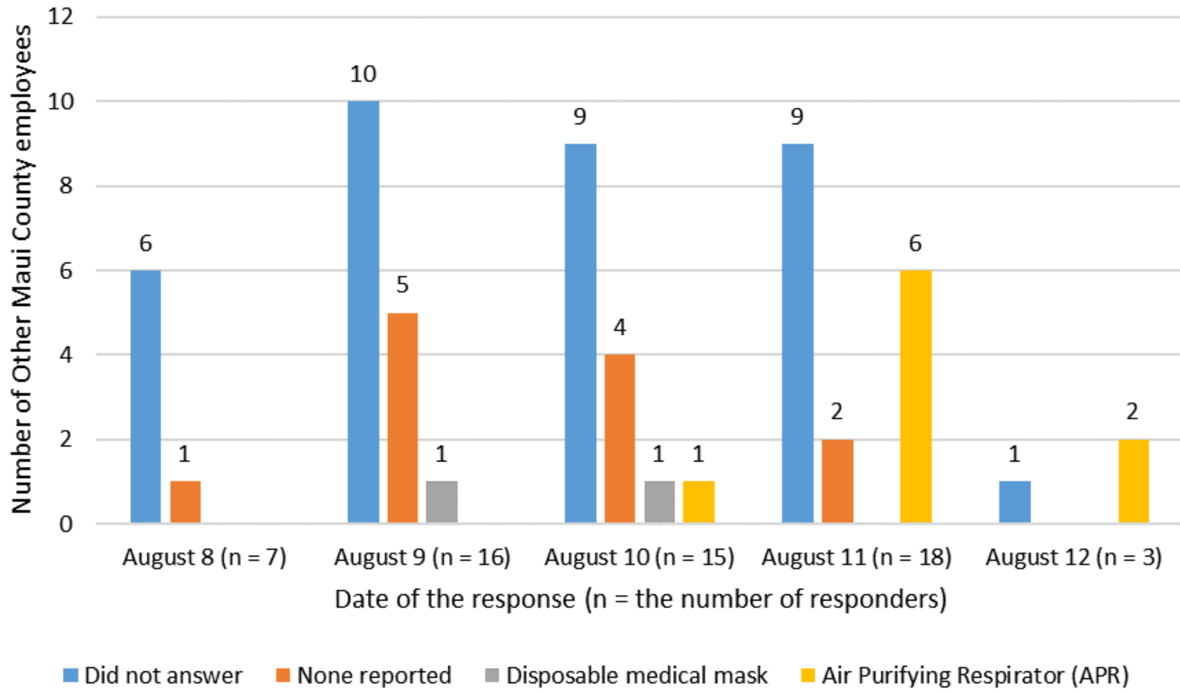

Figure 14. Respiratory protection worn by Other Maui County employees (n = 22), by day.

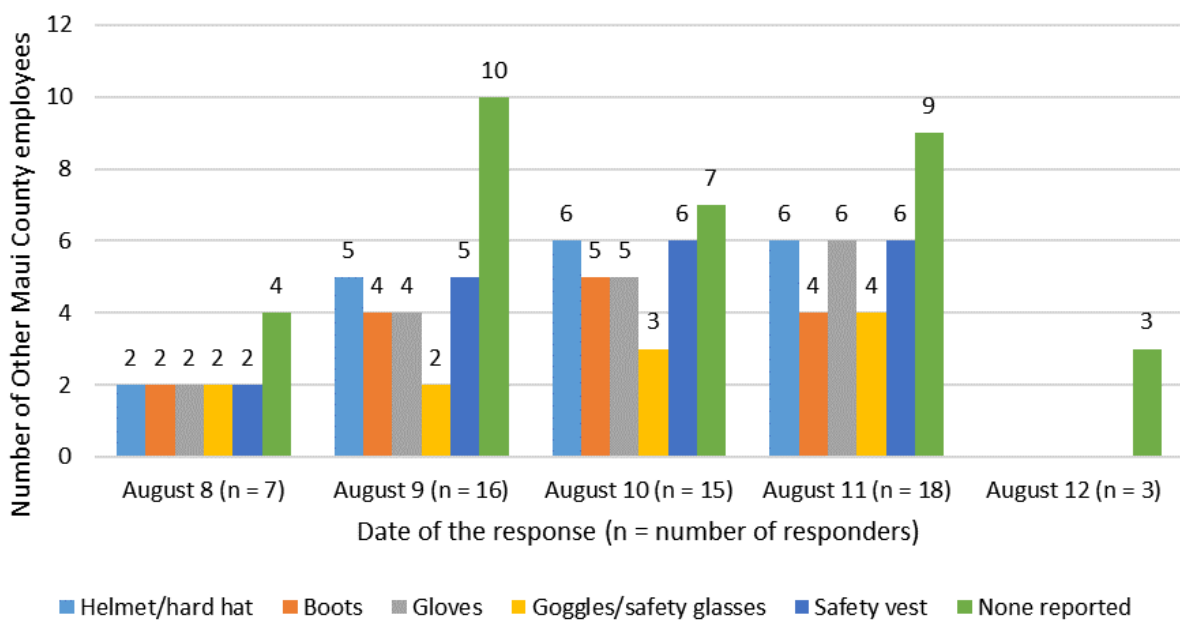

Figure 15. Personal protective gear worn by Other Maui County employees (n = 22), by day.

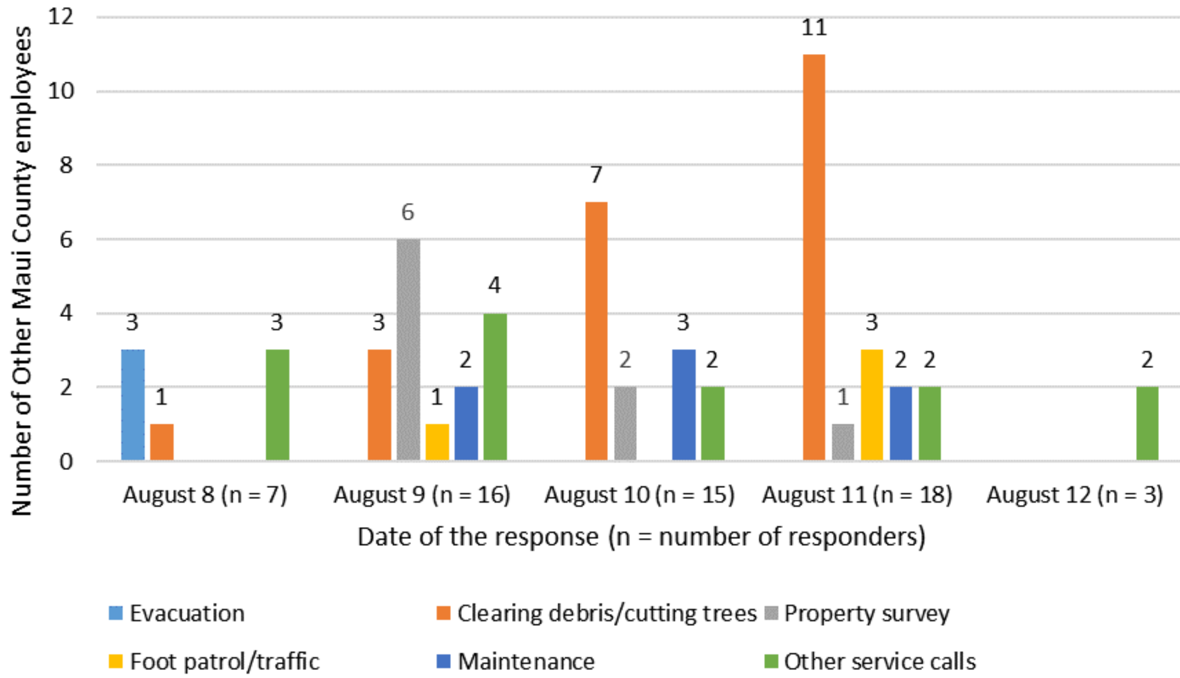

Figure 16. Most frequently activities reported by Other Maui County employees (n = 22). Note: More than one activity can be performed each day.

National Guard Servicemembers Subgroup

Of the 28 participating National Guard servicemembers, 23 responded to either the Kula or Lahaina fires responded on August 8, 20 responded on August 9, 22 responded on August 10, 13 responded on August 11, and 8 responded on August 12. Most National Guard servicemembers responded to the Lahaina area (Figure 17).

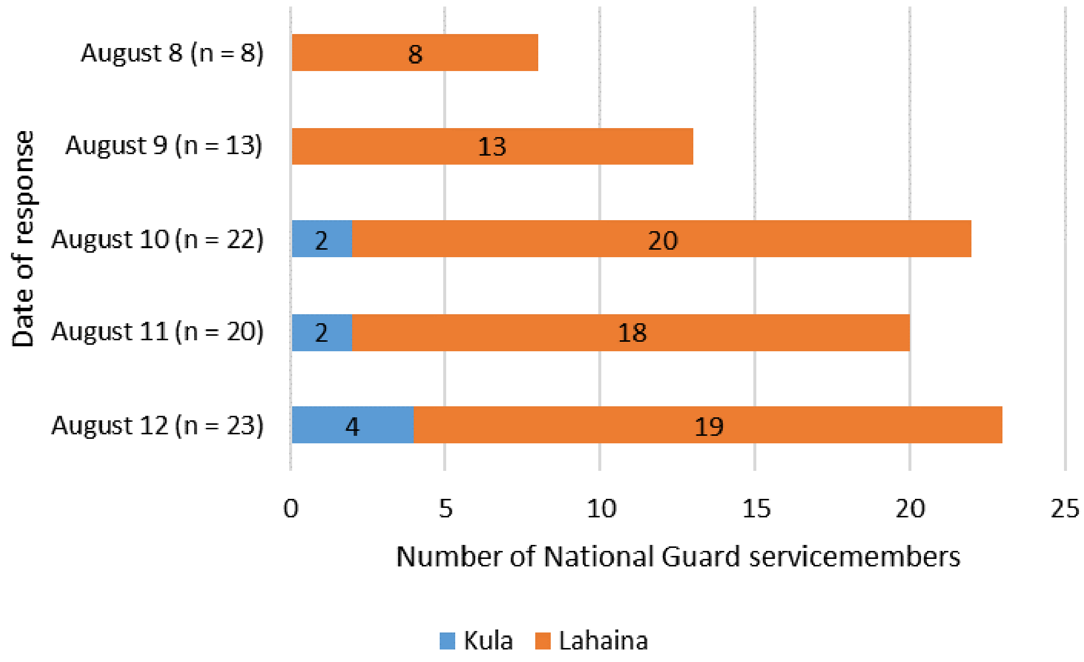

Figure 17. Number of National Guard servicemembers (n = 28) responding per day to the Kula and Lahaina fires. Note: National Guard Servicemembers were not given the option to go to other locations.

Methods: Exposure Markers and Substances of Concern

We collected blood and urine samples from consenting participants for laboratory testing. We analyzed the samples for a wide range of substances and potential exposure markers applicable for a wildfire emergency. Biomarkers were chosen based on their known presence in wildfire smoke and residual debris, as well as half-lives consistent with the time of our evaluation. The following substances were analyzed during this evaluation:

Blood

- Inorganic elements
    - Lead
    - Cadmium
    - Manganese
    - Selenium
- Per- and polyfluoroalkyl substances (PFAS)
    - Perfluorooctanoic acid (PFOA)
        - Linear isomer of PFOA (n-PFOA)
        - Sum of branched isomers of PFOA (Sb-PFOA)

- Perfluorooctane sulfonic acid (PFOS)
    - Linear isomer of PFOS (n-PFOS)
    - Sum of monomethyl branched isomers of PFOS (Sm-PFOS)
- Perfluorohexane sulfonic acid (PFHxS)
- Perfluorodecanoic acid (PFDA)
- Perfluorononanoic acid (PFNA)
- Perfluoroundecanoic acid (PFUnDA)
- 2-(N-Methyl-perfluorooctane sulfonamido) acetic acid (MeFOSAA)
- Sum of n-PFOA, Sb-PFOA, n-PFOS, Sm-PFOS, PFHxS, PFDA, PFNA, PFUnDA, and MeFOSAA (NASEM sum)

- Polybrominated diphenyl ethers (PBDEs)
    - 2,2´,4- Tribromodiphenyl ether (BDE-17)
    - 2,4,4´-Tribromodiphenyl ether (BDE-28)
    - 2,2´,4,4´-Tetrabromodiphenyl ether (BDE-47)
    - 2,2´,3,4,4´-Pentabromodiphenyl ether (BDE-85)
    - 2,2´,4,4´,5-Pentabromodiphenyl ether (BDE-99)
    - 2,2´,4,4´,6-Pentabromodiphenyl ether (BDE-100)
    - 2,2´,4,4´,5,5´-Hexabromodiphenyl ether (BDE-153)
    - 2,2´,4,4´,5,6´-Hexabromodiphenyl ether (BDE-154)
    - 2,2´,3,4,4´,5´,6-Heptabromodiphenyl ether (BDE-183)
    - Decabromodiphenyl ether (BDE-209)
    - 2,2´,4,4´,5,5´-Hexabromobiphenyl (PBB-153)[1]
- Lipids to help interpret the PBDE sampling results

Urine

- Inorganic elements
    - Chromium
    - Nickel
    - Arsenic

[1] PBB-153 is a brominated biphenyl, not a PBDE, however it was measured in the same analysis as the PBDEs. PBB-153 is an older flame retardant with a half-life measured in decades.

        - When urinary total arsenic was above 15 micrograms per gram (μg/g) creatinine, we determined the amounts of the following inorganic arsenic and methylated arsenic species:
            - Trivalent inorganic arsenic (III)
            - Pentavalent inorganic arsenic (V)
            - Monomethylarsonic acid
            - Dimethylarsinic acid
- Organophosphate esters (OPEs)
    - Bis(2-chloroethyl) phosphate (BCEtP), a metabolite of tris(2-chloroethyl) phosphate
    - Bis(1-chloro-2-propyl) phosphate (BCPP), a metabolite of tris(1-chloro-2-propyl) phosphate
    - Bis(1,3-dichloro-2-propyl) phosphate (BDCPP), a metabolite of tris(1,3-dichloro-2-propyl) phosphate
    - Di-n-butyl phosphate (DbuP) is a metabolite of Tributyl phosphate
    - Diphenyl phosphate (DPhP), a metabolite of triphenyl phosphate, isopropylphenyl triphenyl phosphate, isopropylphenyl diphenyl phosphate, t-butylphenyl diphenyl phosphate, and 2-ethylhexyl diphenyl phosphate
    - 2,3,4,5-Tetrabromobenzoic acid (TBBA), a metabolite of 2-ethylhexyl-2,3,4,5-tetrabromobenzoate
    - 2-[(Isopropyl)phenyl]phenyl hydrogen phosphate (iPPPP), a metabolite of isopropylphenyl diphenyl phosphate
    - 4-[(Tert-butyl)phenyl]phenyl hydrogen phosphate (tBPPP), a metabolite of tertbutylphenyl diphenyl phosphate
- Creatinine to help interpret the arsenic and OPE sampling results

Blood Collection and Analysis

Blood samples were collected, processed, and shipped according to their respective analytical method protocols to the following laboratories:

1. Centers for Disease Control and Prevention (CDC) National Center for Environmental Health (NCEH), Division of Laboratory Science (DLS; Atlanta, GA) for inorganic elements in blood and PBDEs and PFAS in serum.
2. Clinical Labs of Hawaiʻi (CLH, Kahului, HI) protocol for lipids.

Figure 18. Phlebotomists drawing blood to be analyzed for inorganic elements, PFAS, and PBDEs. Photo by NIOSH.

Blood inorganic element collection supplies were pre-screened for metals. Samples were collected using universal precautions. Briefly, using standard phlebotomy practices, a 6 milliliter (mL) ethylenediaminetetraacetic acid (EDTA) tube was used to collect blood for inorganic element analysis, followed by collection of two 10 mL serum tubes for analysis of PFAS and PDBEs and one 8.5 mL serum separator tube for lipids analysis (Figure 18). Immediately after collection, all blood collection tubes were inverted 8–10 times. The EDTA tubes were stored upright in portable refrigerators until shipment overnight on ice packs to the NCEH/DLS laboratories for analysis. The serum tubes were allowed to clot for 30–60 minutes and were centrifuged for 15 minutes at 1300 × g force to separate the serum. Serum for PFAS and PDBEs analyses were aliquoted from the 10 mL serum tubes into 2 mL tubes and stored at or below −20°C until shipped on dry ice to the NCEH/DLS laboratory for analysis. The serum separator tubes for lipid analysis were stored on cold packs and transported daily to CLH for analysis.

Blood samples were analyzed for inorganic elements (lead, cadmium, manganese, and selenium) using method NCEH/DLS 3040 [CDC 2019]. Serum samples were analyzed for a panel of PBDEs as described by Jones et al. [2012] and according to method NCEH/DLS 6701 [CDC 2016a]. Serum samples were also analyzed for a panel of PFAS according to method NCEH/DLS 6304 [CDC 2016a; Kato et al. 2018].

Serum lipids were measured using enzymatic colorimetric methods. They were collected to correct the PBDE results because PBDEs are fat soluble compounds [EPA 2014].

Urine Collection and Analysis

Urine inorganic element collection supplies were pre-screened for metals. Urine samples were collected, processed, and shipped according to the NCEH/DLS protocols for urine inorganic elements, OPEs, and creatinine.

Figure 19. Urine collection for inorganic elements and PFAS. Photo by NIOSH.

Prior to providing a urine sample, participants were instructed to wash their hands with soap and water, rinse well, and allow them to air dry (Figure 19). Spot urine samples for inorganic elements, OPEs, and creatinine analyses were collected in a 120 mL sterile urine cup, frozen, and stored at or below −20°C. They were then shipped on dry ice to the NCEH/DLS laboratories where they were thawed, aliquoted, and analyzed.

Urine samples were analyzed for inorganic elements (arsenic, chromium, and nickel) using NCEH/DLS 3031 [CDC 2018]. Arsenic was analyzed in a two-step process. First, we determined the total arsenic concentration. If the total arsenic concentration was at or above 15 µg/g creatinine, speciation was performed. Speciated arsenic was analyzed using method NCEH/DLS 3000 [CDC 2016b]. Urine samples were also analyzed for OPEs using method NCEH/DLS 6121 [CDC 2016b] as described by Jayatilaka et al. [2017, 2019].

Urinary creatinine was measured by an enzymatic method with a Roche/Hitachi Cobas® c501 chemical analyzer (Roche Diagnostics Inc., Indianapolis, IN). Creatinine was collected to correct the arsenic and OPE results.

Analysis of Results

Analysis was performed with R and SAS statistical software. For results below the limit of detection (LOD), we computed LOD/√2 to be used when calculating summary statistics [Hornung and Reed 1990]. Arsenic and OPE results were corrected using urine creatinine concentration. Samples with creatinine below the normal range were excluded from arsenic and OPE analyses because the urine was considered too dilute to accurately reflect substance concentrations.

We compared the results with existing reference values as shown in Figure 20 and discussed in detail in Section D. We used a hierarchical approach in choosing the reference values. We preferentially used mandatory OELs, such as OSHA medical removal limits. If OSHA OELs were not available or not exceeded, we considered OELs recommended by professional organizations. These included, the American Conference of Governmental Industrial Hygienists (ACGIH®) Biological Exposure Indices (BEI®). Overexposures were defined as an exposure level above an OEL or a BEI. If no OEL or BEI was available, we compared results with the National Health and Nutrition Examination Survey (NHANES) 95th percentiles for U.S. adults ≥ 20 years old for the most recently available survey year (usually 2017–2018). NHANES results are considered representative of exposures in the U.S. general population. We further compared the PFAS results with the NASEM sum of PFOA, PFOS, PFHxS, PFDA, PFNA, PFUnDA, and MeFOSAA. The NASEM sum is a proposed health screening level above which there is an increased risk for adverse health effects.

SUBSTANCE	BIOLOGICAL SOURCE	REFERENCE VALUE	REFERENCE VALUE CATEGORY
CADMIUM	BLOOD	5 µg/L	ACGIH BEI and OSHA medical removal limit
LEAD	BLOOD	20 µg/dL / 60 µg/dL	ACGIH BEI and OSHA medical removal limit
MANGANESE	BLOOD	16.0 µg/L	2017–2018 NHANES 95th percentile
SELENIUM	BLOOD	234 µg/L	2017–2018 NHANES 95th percentile
INORGANIC- RELATED ARSENIC SPECIES	URINE	15 µg/g cr	ACGIH BEI
CHROMIUM	URINE	0.7 µg/L	ACGIH BEI
NICKEL	URINE	3.95 µg/L	2017–2018 NHANES 95th percentile
PFAS SUMMED	BLOOD	≥20 g/L	NASEM Clinical threshold
PFAS	BLOOD	Substance specific	2017–2018 NHANES 95th percentile
PBDE	BLOOD	Substance specific	2003–2004 NHANES 95th percentile
			2015–2016 NHANES average of pooled samples
OPE	URINE	Substance specific	2017–2018 NHANES 95th percentile

Abbreviations:
ACGIH®: American Conference of Governmental Industrial Hygienists
BEI®: Biological Exposure Indices
NASEM: National Academies of Sciences, Engineering, and Medicine
NHANES: National Health and Nutrition Examination Survey
OSHA: Occupational Safety and Health Administration
PFAS: Per- and Polyfluoroalkyl substances
PBDE: Polybrominated diphenyl ether
OPE: Organophosphate ester
µg/L: micrograms per liter
µg/dL: micrograms per deciliter
µg/g cr: micrograms per gram creatinine
g/L: grams per liter

Figure 20. Comparative reference values for each substance of concern and exposure marker.

Results: Exposure Markers and Substances of Concern

Maui County Participants Overall

Inorganic Elements

Summary results for blood and urine samples for all Maui County employees (firefighters, police department employees, Ocean Safety Officers, and Other Maui County employees) are available in Table C3.

Inorganic Elements in Blood

Of the 259 Maui County participants, one individual did not participate in the blood draw, and another blood sample clotted before separation and therefore was unable to be analyzed. Therefore, 257 blood samples were analyzed for inorganic elements.

- The median cadmium concentration was 0.15 microgram per liter (µg/L) (range: < LOD–0.79 µg/L). No cadmium samples were above the OSHA medical removal level and ACGIH BEI of 5 µg/L.
- The median lead concentration was 0.60 microgram per deciliter (µg/dL) (range: 0.27–2.24 µg/dL). No lead samples were at or above the OSHA medical removal level of 60 µg/dL and ACGIH BEI of 20 µg/dL.
- The median manganese concentration was 9.18 µg/L (range: 3.3–23.4 µg/L). Twelve (5%) manganese samples were at or above the NHANES 95th percentile of 16.0 µg/dL.
- The median selenium concentration was 198 µg/L (range: 133–344 µg/L). Twenty-eight (11%) selenium samples were at or above the NHANES 95th percentile of 234 µg/dL.

Inorganic Elements in Urine

Of all 259 Maui County participants, two declined to provide a urine sample, and one sample was compromised during shipment to the laboratory. Therefore, 256 urine samples were analyzed for inorganic elements. For the creatinine-corrected urine arsenic results, 12 samples were below the normal range for creatinine, so we excluded them from analysis. Therefore, 244 samples were analyzed for arsenic. We compared inorganic element results with their applicable reference values and summarized the percentage of overexposures in Figure 6.

- Of the 244 samples analyzed for total arsenic, 159 (65%) were above 15 µg/g creatinine and further analyzed for inorganic-related arsenic species. The median concentration for the inorganic-related arsenic species was 8.55 µg/g creatinine (range: 2.76–173). Twenty-three (9%) of the 244 samples analyzed for arsenic were above the ACGIH BEI of 15 µg inorganic-related arsenic species/g creatinine.
- The median chromium concentration was < LOD (range: < LOD–3.9). Thirteen (5%) of the chromium samples were above the ACGIH BEI of 0.7 µg/L.
- The median nickel concentration was 1.1 µg/L (range: < LOD–9.6). Ten (4%) of the nickel samples were above the NHANES 95th percentile of 3.95 µg/L.

PFAS

Maui County results are presented in Table C4 for each of the PFAS chemicals tested among 258 blood samples. At least one participant had a result above the NHANES 95th percentile for four of the PFAS chemicals. Those results are summarized here:

- PFHxS (median 1.1 µg/L, range: < LOD–9.3 µg/L), 256 (99%) above the LOD, 9 (3%) were at or above the NHANES 95th percentile of 3.8 µg/L.
- PFDA (median 0.2 µg/L, range: < LOD–0.9 µg/L), 244 (95%) above the LOD, 17 (7%) were at or above the NHANES 95th percentile of 0.6 µg/L.
- PFNA (median 0.4 µg/L, range: 0.1–1.7 µg/L), 254 (100%) above the LOD, 4 (2%) were above the NHANES 95th percentile of 1.4 µg/L.

- PFUnDA (median 0.3 µg/L, range: < LOD–1.8 µg/L), 244 (95%) above the LOD, 103 (40%) were above the NHANES 95th percentile of 0.4 µg/L.

The sum of seven specific PFAS chemicals used in NASEM clinical guidance for medical providers (MeFOSAA, PFHxS, PFDA, PFUnDA, PFOS, PFOA, and PFNA) had a median of 6.64 µg/L, (range: 0.92–21.6 µg/L) and had 1 (0.4%) result above the NASEM clinical threshold of 20 µg/L.

PBDE

Maui County results are presented in Table C5 for each of the 11 PBDE chemicals tested for among 258 blood samples. PBDEs with a < 50% detection rate were excluded from further analyses. At least one participant had a result above the NHANES 95th percentile for 4 of the 11 PBDE chemicals. Those results are summarized here:

- BDE-28 (range: < LOD–20.6 nanograms per gram [ng/g] lipid), 152 (59%) were over the LOD, 1 (0.4%) was over the NHANES 95th percentile, 28 (11%) were above the 2015–2016 NHANES mean of 0.86 ng/g lipid.

- BDE-47 (range: < LOD–251.8 ng/g lipid), 196 (76%) above the LOD, 1 (0.4%) was over the NHANES 95th percentile, 23 (9%) were above the 2015–2016 NHANES mean of 16.70 ng/g lipid.

- BDE-100 (range: < LOD–42.2 ng/g lipid), 219 (85%) above the LOD, 1 (0.4%) was over the NHANES 95th percentile, 19 (7%) were above the 2015–2016 NHANES mean of 3.63 ng/g lipid.

- BDE-153 (range: 1.6–229.1 ng/g lipid), 258 (100%) above the LOD, 11 (4%) were above the NHANES 95th percentile, 113 (44%) were above the 2015–2016 NHANES mean of 12.10 ng/g lipid.

NHANES data from 2003–2004 did not have reported values for BDE-209 because so many of the samples were below the LOD of 5.8 ng/g lipid. However, in NHANES data from 2015–2016, 98.4% of results were above the new more sensitive LOD of 0.85 ng/g lipid, and 25 (10%) were over the mean of 2.13 ng/g lipid.

Measurements among Maui County responders were below the 2003–2004 NHANES 95th percentile for PBB-153 (range: < LOD–23.8), 95% above the LOD.

OPE

Maui County results are presented in Table C6 for each OPE tested in 256 urine samples. For BCPP, only 251 urine samples were tested because there were interfering substances in four vials, and one vial was compromised during shipping. OPEs with a < 50% detection rate were excluded from additional analyses. At least one participant had a result higher than the NHANES 95th percentile for four of the OPE chemicals. Those results are presented below.

We also examined creatinine-corrected OPE results (Table C6). Twelve samples had creatinine concentrations below the normal range and were excluded from the creatinine-corrected analysis. When we corrected the OPE results with creatinine, we observed only a slight reduction in the number of individuals over the NHANES 95th percentile. Additionally, most of the participants in this evaluation were male, and urinary concentrations of creatinine in men can be higher than in women. We opted to focus on uncorrected OPE results for subsequent analyses and comparisons with NHANES, given that NHANES has equal proportions of men and women.

- BCEtP (median: 0.19 µg/L, range: < LOD–7.12) had 187 (73%) above the LOD. Four (2%) were above the NHANES 95th percentile (uncorrected). Three (1%) were above the NHANES 95th percentile (creatinine corrected).
- BCPP (median: 0.13 µg/L, range: < LOD–6.26) had 158 (63%) above the LOD. Twelve (5%) were above the NHANES 95th percentile (uncorrected). Nine (4%) of the 251 urine samples tested for BCPP were above the NHANES 95th percentile (creatinine corrected).
- BDCPP (median: 0.90 µg/L, range: < LOD–22.70) had 246 (96%) above the LOD. Eleven (4%) were above the NHANES 95th percentile (uncorrected). Four (2%) were above the NHANES 95th percentile (creatinine corrected).
- DPhP (median: 0.58 µg/L, range: < LOD–14.10) had 243 (95%) above the LOD. Thirteen (5%) were above the NHANES 95th percentile (uncorrected). Two (1%) were above the NHANES 95th percentile (creatinine corrected).

Firefighter Occupational Subgroup

Inorganic Elements

Results for inorganic elements for all Maui County occupational groups are available in Table C7. A brief summary of the inorganic element results for firefighters above the applicable reference value are presented here.

Inorganic Elements in Blood

Seven of the 177 (4%) firefighters' results for manganese were above the NHANES 95th percentile of 16 µg/L, and 17 (10%) were above the NHANES 95th percentile for selenium of 234 µg/L. The highest manganese concentration was 23.4 µg/L, and the highest selenium concentration was 344 µg/L.

Inorganic Elements in Urine

Sixteen of the 167 (10%) firefighters had inorganic arsenic species concentrations above the ACGIH BEI. The highest concentration in firefighters was 51.5 µg/g creatinine, which is approximately 3.5 times higher than the BEI. Eight (5%) firefighters had urinary chromium results above the BEI of 0.7 µg/L, and 8 (5%) had urinary nickel above the NHANES 95th percentile of 3.95 µg/L.

PFAS

Results for all Maui County occupational groups are in Table C8. A brief summary for specific PFAS chemicals that had at least one result higher than the NHANES 95th percentile among firefighters is given here:

- Eleven (6%) were above the NHANES 95th percentile for PFUnDA of 0.4 µg/L.
- Seven (4%) were above the NHANES 95th percentile for PHFxS of 3.8 µg/L.

- Four (2%) were above the NHANES 95th percentile for PFDA of 0.6 µg/L.
- Two (1%) were above the NHANES 95th percentile for PFNA of 1.4 µg/L.
- One (0.6%) firefighter had a NASEM sum value of 21.6 µg/L, which is slightly above the references value of 20 µg/L.
- The highest PFHxS concentration was 9.3 µg/L, which is almost 2.5 times the NHANES 95th percentile.

PBDE

Results for PBDEs for all Maui County occupational groups are presented in Table C9. A brief summary for specific chemicals within the PBDE class of chemicals that had at least one result higher than the NHANES 95th percentile among firefighters is given here:

- Ten (6%) firefighters had BDE-153 levels above the NHANES 95th percentile of 73.3 ng/g lipid. BDE-153 values ranged from 2.2–229.1 ng/g lipid, the highest of which was about 3.1 times the NHANES 95th percentile.
- Median concentration for BDE-209 was 0.92 ng/g lipid (< LOD–7.3 ng/g lipid).
- No other PBDEs were present above the applicable reference value.

OPE

Results for urine OPEs among all Maui County occupational groups are in Table C10. A brief summary for specific chemicals within the OPE class of chemicals that had at least one result higher than the NHANES 95th percentile among firefighters is given here:

- 134 (76%) of BCEtP results were above the LOD, and 3 (2%) of the results were higher than the NHANES 95th percentile.
- 120 (70%) of BCPP results were above the LOD, and 9 (5%) of the results were above the NHANES 95th percentile.
- 167 (95%) of BDCPP results were above the LOD, and 5 (3%) were above the NHANES 95th percentile.
- 171 (97%) of DPhP results were above the LOD, and 11 (6%) were above the NHANES 95th percentile.

Police Occupational Subgroup

Inorganic Elements

Inorganic element results for police department Employees are presented in Table C7. A brief summary of elements in blood and urine for the 39 police department employees with results above the applicable reference value are presented here:

Inorganic Elements in Blood

Two (5%) police department employees' blood manganese levels were above the NHANES 95th percentile of 16 µg/L, and 5 (13%) were above the NHANES 95th percentile for selenium of

234 µg/L. The highest manganese concentration was 16.3 µg/L, and the highest selenium concentration was 297 µg/L.

Inorganic Elements in Urine

Two (6%) police department employees had inorganic urinary arsenic concentrations above the ACGIH BEI. One (3%) police department employee had urinary chromium concentrations above the ACGIH BEI, and 1 (3%) had urinary nickel concentrations above the NHANES 95th percentile. The highest concentration was 19.8 µg/g creatinine for inorganic arsenic, 0.89 µg/L for chromium, and 3.98 µg/L for nickel.

PFAS

Results for the police department employee PFAS results are in Table C8. A brief summary of specific PFAS chemicals for the 39 police department employees who had at least one result higher than the NHANES 95th percentile is given here:

- Two (5%) police department employees were above the NHANES 95th percentile for PFHxS of 3.8 µg/L.
- Three (8%) were above the NHANES 95th percentile for PFDA of 0.6 µg/L.
- Twelve (31%) were above the NHANES 95th percentile for PFUnDA of 0.4 µg/L.
- No police department employees had a NASEM sum value over 20 µg/L.
- No other PFAS results were above the applicable reference value for police department employees.

PBDE

PBDE results for the police department employees are in Table C9. A brief summary for specific chemicals within the PBDE class for the 39 police department employees who had at least one result higher than the NHANES 95th percentile is given here:

- BDE-28 was detected in 21 (54%) of the samples, and 1 (3%) was over the NHANES 95th percentile.
- BDE-47 was detected in 25 (64%) of the samples, and 1 (3%) was over the NHANES 95th percentile.
- BDE-100 was detected in 30 (77%) of the samples, and 1 (3%) was over the NHANES 95th percentile.

The 95th percentile for BDE-209 is not available in NHANES data. BDE-209 was detected in 38% of the samples. The median was 0.71 ng/g lipid (range, < LOD–3.23 ng/g lipid).

OPE

OPE results for the police department employees are in Table C10. A brief summary for specific chemicals within the OPE class among police department employees who had at least one result higher than the NHANES 95th percentile is given here:

- Twenty-nine (74%) of samples had BCEtP detected, and 1 (3%) was above the NHANES 95th percentile.
- Thirty-nine (100%) of samples had BDCPP detected, and 4 (10%) were above the NHANES 95th percentile.
- Twenty-nine (74%) of samples had DPhP detected, and 2 (3%) was above the NHANES 95th percentile.
- No other OPEs had concentrations above their applicable NHANES references values.

Ocean Safety Officers Occupational Subgroup

Inorganic Elements

Results for the Ocean Safety Officer inorganic element results are presented in Table C7. A brief summary of inorganic elements in blood and urine for the 19 Ocean Safety Officers with results above the applicable reference value are presented here:

Inorganic Elements in Blood

One (5%) Ocean Safety Officer had a manganese concentration above the NHANES reference value of 16.0 µg/L. Two (11%) Ocean Safety Officers had selenium concentrations above the NHANES reference value of 234 µg/L. The highest manganese concentration was 16.2 µg/L, and the highest selenium concentration was 239 µg/L.

Inorganic Elements in Urine

No Ocean Safety Officers had urinary inorganic arsenic levels or chromium levels above their respective ACGIH BEIs. One (5%) Ocean Safety Officer had urinary nickel levels above the NHANES 95th percentile of 3.95 µg/L. The highest nickel concentration was 5.27 µg/L.

PFAS

FAS results for the Ocean Safety Officers are in Table C8. A brief summary for specific PFAS chemicals for the 19 Ocean Safety Officers who had at least one result higher than the NHANES 95th percentile is given here:

- One (5%) was at the NHANES 95th percentile for PFDA of 0.6 µg/L.
- Four (21%) were above the NHANES 95th percentile for PFUnDA of 0.4 µg/L.
- None of the Ocean Safety Officers had a NASEM sum value above 20 µg/L.
- No other PFAS results were above the applicable reference value for the Ocean Safety Officers.

PBDE

PBDE results for the Ocean Safety Officers are in Table C9. A brief summary for specific chemicals within the PBDE class for the 19 Ocean Safety Officers is presented here. The 95th percentile for BDE-209 is not available in NHANES data. The median concentration for BDE-209 was 0.99 ng/g lipid (range: < LOD–4.3 ng/g lipid). None of the PBDEs had results higher than the NHANES 95th percentile.

OPE

Results for the Ocean Safety Officer OPE results are in Table C10. A brief summary for specific chemicals within the OPE class for the 19 Ocean Safety Officers who had at least one result higher than the NHANES 95th percentile is given here:

- BCPP was detected in 10 (55%) of samples. One (5%) Ocean Safety Officer had BCPP levels above the NHANES 95th percentile.
- BDCPP was detected in 15 (77%) of samples. One (5%) had BDCPP levels above the NHANES 95th percentile.
- No other OPEs were detected above the respective NHANES 95th percentile for the Ocean Safety Officer occupational subgroup.

Other Maui County Employee Occupational Subgroup

Inorganic Elements

Inorganic element results for the Other Maui County employees are presented in Table C7.
A brief summary of the inorganic elements in urine and blood for the 22 Other Maui County employees with results above the applicable reference value are presented here:

Inorganic Elements in Blood

Two (9%) participants had manganese and 4 (18%) participants had selenium levels above their respective NHANES reference values. The highest manganese concentration was 22.6 µg/L, and the highest selenium concentration was 296 µg/L.

Inorganic Elements in Urine

Five (23%) participants had urinary inorganic arsenic levels above the ACGIH BEI. The highest value (173 µg/g creatinine) was approximately 11.5 times higher than the BEI of 15 µg/g creatinine. Five (23%) participants had urinary chromium levels above the ACGIH BEI. None of the participants had urinary nickel above the NHANES 95th percentile. The highest nickel concentration was 3.5 µg/L.

PFAS

Results for the Other Maui County employee PFAS results are in Table C8. A brief summary for specific PFAS chemicals for the 22 Other Maui County employees who had at least one result higher than the NHANES 95th percentile is given here:

- Three (14%) were above the NHANES 95th percentile for PFDA of 0.6 µg/L.
- One (5%) was over the NHANES 95th percentile for PFNA of 1.4 µg/L.
- Nineteen (86%) were above the NHANES 95th percentile for PFUnDA of 0.4 µg/L.
- None of the Other Maui County employees had a NASEM sum value above 20 µg/L.
- No other PFAS results were above the applicable reference value for the Other Maui County employees.

PBDE

Results for the Other Maui County employee PBDE results are in Table C9. A brief summary for specific chemicals within the PBDE family for the 22 Other Maui County employees is presented here. Of the PBDE chemicals that were detected in ≥ 50% of participant samples, no samples from Other Maui County Employees were above the NHANES 95th percentile.

The 95th percentile for BDE-209 is not available in NHANES data. The median concentration for BDE-209 was 1.2 ng/g lipid (range: < LOD–5.1 ng/g lipid).

OPE

Results for the Other Maui County employee OPE results are in Table C10. A brief summary for specific chemicals within the OPE class for the 22 Other Maui County employees who had at least one result higher than the NHANES 95th percentile is given here:

- Sixteen (76%) of samples had BCPP detected, with two (9%) Other Maui County employees above the NHANES 95th percentile.
- Twenty-two (100%) of samples had BDCPP detected, with one (5%) Other Maui County employee above the NHANES 95th percentile.
- Twenty-two (100%) of samples had DPhP detected, with one other Maui County employee (5%) above the NHANES 95th percentile.

Hawai'i National Guard Servicemembers Subgroup

Inorganic Elements

Results for inorganic elements in blood and urine for the 28 Hawai'i National Guard servicemembers are presented in Table C11.

Inorganic Elements in Blood

The median cadmium concentration was 0.17 µg/L (range: 0.08–0.75 µg/L) and the median lead concentration was 0.59 µg/dL (range: 0.34–1.36 µg/dL). No servicemember was above the applicable OSHA medical removal limit or ACGIH BEI.

The median manganese concentration was 10.2 µg/L (range: 4.5–19.3 µg/L). Two (7%) servicemembers had manganese concentrations above the NHANES 95th percentile of 16.0 µg/L. The median selenium concentration was 192 µg/L (range: 165–281 µg/L). Four (14%) servicemembers were above the NHANES 95th percentile of 234 µg/L.

Inorganic Elements in Urine

Fourteen (54%) samples had total arsenic results of 15 µg/g creatinine or higher and were further analyzed for inorganic-related arsenic species. The median inorganic-related arsenic species level was 9.16 µg/g creatinine (range: 3.54–17.70 µg/g creatinine) and 2 (8%) results were above the ACGIH BEI. The median chromium concentration was 0.3 µg/L (range: < LOD–25.1 µg/L) and 7 (25%) of the results were above the ACGIH BEI. The median urinary nickel concentration was 1.3 µg/L (range: < LOD–5.3 µg/L) and 2 (7%) servicemembers were above the NHANES 95th percentile.

PFAS

Table C12 presents PFAS results for Hawai‘i National Guard servicemembers (n = 28). A brief summary for specific PFAS chemicals that had at least one result higher than the NHANES 95th percentile is given here:

- Nine (32%) were over the NHANES 95th percentile for PFUnDA of 0.4 µg/L.
- None of the National Guard servicemembers had a NASEM sum value above 20 µg/L.
- No other PFAS results were above the applicable reference value for the servicemembers.

PBDE

PBDE results for Hawai‘i National Guard servicemembers are presented in Table C13. Of the PBDE chemicals that were detected in ≥ 50% of participant samples, no samples from National Guard servicemembers were above the NHANES 95th percentile.

The 95th percentile for BDE-209 is not available in NHANES data. The median concentration for BDE-209 was 0.85 ng/g lipid (range: < LOD–3.90 ng/g lipid).

OPE

OPE results for Hawai‘i National Guard servicemembers are presented in Table C14. A brief summary for specific chemicals within the OPE class that had at least one result higher than the NHANES 95th percentile is given here:

- BDCPP was detected in 26 (93%) of samples and one (4%) was over the NHANES 95th percentile (uncorrected). One (4%) was over the NHANES 95th percentile (creatinine corrected).

Methods: Analysis of Exposure Markers with Demographic and Exposure Characteristics

Results from the urine and blood sampling were analyzed with the self-reported exposure and demographic data to evaluate the characteristics of individuals who were above the reference values (i.e., above the OEL or NHANES 95th percentile). Similar analyses were conducted for individual PFAS, PBDE, and OPE chemicals if they were detected in at least 50% of the specimen samples regardless of whether or not they were over the NHANES 95th percentile.

We used Fisher's exact test to determine significant differences (*P* value < 0.05) for the number of individuals below and above the applicable reference value for each compound by age, seafood consumption in the last 3 days, sex, race, ethnicity, respirator use by day, time spent in the impact zone during August 8–12, occupational subcategory, and job tenure as a firefighter (firefighter occupational subgroup only). Result comparisons were conducted for the National Guard by whether servicemembers reported responding to the fire each day during August 8–12. An individual could be included multiple times if they reported being in the impact zone on multiple days. Analysis of variance (ANOVA) on the log of the exposure values was conducted to determine significant differences (*P* value < 0.05) of continuous biomarker results for the same characteristics listed above. A significant result for the ANOVA and Fisher's exact test indicated that at least one of the groups was significantly different than the other groups (no referent group was included in these analyses). For each compound, tables were created for all Maui County employees, Maui County firefighters, and National Guard servicemembers.

Though some differences by race, sex (e.g., women tend to have higher levels of some analytes because they tend to have a higher percentage of body fat [Flegal et al. 2009]), and ethnicity were observed, those characteristics were not presented in the subsequent tables. Additionally, no clear associations were observed between the biomarker results and exposure characteristics, including respirator use by day and cumulative time spent in the impact zone during the first 24 hours and first 48 hours. So those results are not reported in the tables. Lastly, we considered exploring the relationship between job task during the response and the biomarker results, but it was determined that these analyses were beyond the scope of this report. The relationship between biomarker results and exposure characteristics may be further explored in subsequent analyses included in peer-reviewed scientific manuscripts.

Results: Analysis of Exposure Markers with Demographic and Exposure Characteristics

Inorganic Elements

Manganese

Median manganese concentrations for Maui County employees were stratified by demographic and exposure characteristics and presented in Table C15. While individuals under 25 years of age had the highest median manganese concentrations compared with the other age groups, the differences by age were not statistically significant. No significant differences were found for seafood consumption or time spent in the impact zone. However, there were significant differences by job category: police department employees had higher median concentrations (11.2 µg/L) compared with all of the other occupational subcategories (i.e., Ocean Safety Officers, Firefighters, and Other Maui County Employees) (*P* value = 0.01).

Table C16 presents Maui County firefighters' median manganese concentrations, stratified by demographic and exposure characteristics. Similar to all Maui County employees, Maui County firefighters under 25 years of age had higher median manganese concentrations compared with the other age groups, though the differences by age were not significant. Hispanic firefighters had significantly higher median manganese concentrations (10.4 µg/L) than non-Hispanic firefighters (8.71 µg/L) (*P* value = 0.03) (not shown). No significant differences were found for the other characteristics.

Median manganese concentrations for National Guard servicemembers were stratified by demographic and exposure characteristics and presented in Table C17. The age classification groups for the National Guard are different from Maui County occupational subgroups (≥ 40 and < 40 years) because of the small sample size. No significant differences were found for any of the characteristics evaluated in this table.

Selenium

Median selenium concentrations for all Maui County employees, stratified by demographic and exposure characteristics, are presented in Table C18. Individuals who reported having eaten seafood in the last 3 days had higher median selenium concentrations compared with those who had not; overall, there were significant differences based on seafood consumption (*P* value = 0.01). No other significant results were found.

Median selenium concentrations for the firefighter occupational subgroup, stratified by demographic and exposure characteristics, are summarized in Table C19. There were significant differences in median selenium concentrations in firefighters based on self-reported cumulative hours spent in the impact zone during August 8–12 (*P* value = 0.02). Those who spent 12–23 hours in the impact zone had the highest median concentrations (207.9 μg/L). Significant differences were found when comparing selenium concentrations and seafood consumption (*P* value = 0.04). Median selenium concentrations were higher for those firefighters who had eaten seafood in the last 3 days compared with those who had not.

Table C20 presents the median selenium concentration for National Guard servicemembers, stratified by demographic and exposure characteristics. No significant findings were found for any of the stratifications.

Arsenic

Table C21 summarizes all Maui County employees' median inorganic-related arsenic species concentrations and the proportion below and above ACGIH BEI of 15 μg/g creatinine, stratified by demographic and exposure characteristics. Maui County employees over 50 years of age had the highest median inorganic-related arsenic species concentrations (11.2 μg/g creatinine) and the highest proportion of individuals above the ACGIH BEI (17%), significant differences were found by age groups (*P* value = 0.04).

Maui County employees who reported eating seafood in the last 3 days had slightly higher median inorganic-related arsenic species concentrations compared with those who did not eat seafood, but that difference was not significant (*P* value = 0.07). There were significant differences in the proportion of individuals above the ACGIH BEI for inorganic-related arsenic species (*P* value = 0.02). Those who reported eating seafood in the last 3 days were more likely to be above the ACGIH BEI compared with those who had not.

Median inorganic-related arsenic species concentrations and the proportion of Maui County firefighters below and above the ACGIH BEI, stratified by demographic and self-reported exposure characteristics are presented in Table C22. No significant differences were found.

Table C23 summarizes median inorganic-related arsenic species concentrations and the proportion of National Guard servicemembers below and above ACGIH BEI, stratified by demographic and self-reported exposure characteristics. Servicemembers who reported responding to the impact zone on August 11 had significantly higher (*P* value = 0.04) median concentrations (12.9 μg/g creatinine) than those who did not report responding that day (7.6 μg/g creatinine). Although we did not observe significant differences, we did find a similar trend where those that responded to the impact zone on August 9, August 10, and August 12 had higher median concentrations compared with those did not respond.

Chromium

The proportions of all Maui County employees below and above ACGIH BEI for chromium of 0.7 µg/L, stratified by demographic and self-reported exposure characteristics, are presented in Table C24. Median concentrations were not compared because more than 50% of the samples were below the LOD. Other Maui County employees were more likely to be above the ACGIH BEI compared with employees in the other occupational subcategories, and the differences between the groups were significant (*P* value = 0.01). There were significant differences based on cumulative time spent in the impact zone for Other Maui County employees (*P* value = 0.04). Those who cumulatively spent 24–35 hours in the impact zone during August 8–12 were more likely to be above the chromium BEI (17%) compared with individuals who spent more time (> 36 hours; < 5% above BEI) or less time (< 24 hours; < 5% above BEI) in the impact zone.

The proportions of Maui County firefighters and National Guard servicemembers below and above the ACGIH BEI of 0.7 µg/L for chromium, stratified by demographic and self-reported exposure characteristics, are provided in Tables C25 and C26. No significant differences were found among Maui County firefighters and National Guard servicemembers.

Nickel

Tables C27, C28, and C29 present median nickel concentrations for all Maui County employees, Maui County firefighters, and National Guard servicemembers, respectively, stratified by demographic and self-reported exposures characteristics. No significant differences were found among all Maui County employees and Maui firefighters. National Guard servicemembers who reported responding on August 10 or August 11 had significantly higher median nickel concentrations compared with those who did not respond on these days (both *P* values = 0.01).

PFAS

Of the individual PFAS evaluated in this report, PFDA, PFNA, PFHxS, PFUnDA, PFOS, PFOA were included in this analysis because they were detected in nearly all individuals (over 90%). Results for each PFAS are presented for all Maui County employees, Maui County firefighters, and National Guard servicemembers in Tables C30–C32.

Significant differences among the medians were found based on seafood consumption for PFDA (*P* value < 0.01), PFNA (*P* value = 0.01), and PFUnDA (*P* value < 0.01) for all Maui County employees. Significant differences in PFHxS concentrations were also found by job category. Firefighters' median PFHxS concentrations were the highest amongst the job categories. Job tenure also appeared to impact PFHxS, PFNA, PFOS, and PFOA concentrations. In general, firefighters with a longer job tenure had higher median concentrations for PFHxS, PFNA, and PFOS compared with firefighters with a shorter job tenure.

Figure 21 shows the summed PFAS (PFOA, PFOS, PFHxS, PFDA, PFNA, PFUnDA, and MeFOSAA), stratified by job tenure as a firefighter. Overall, it appeared that firefighters with a longer job tenure (≥ 30 years) had higher median summed PFAS concentrations compared with firefighters with shorter tenures.

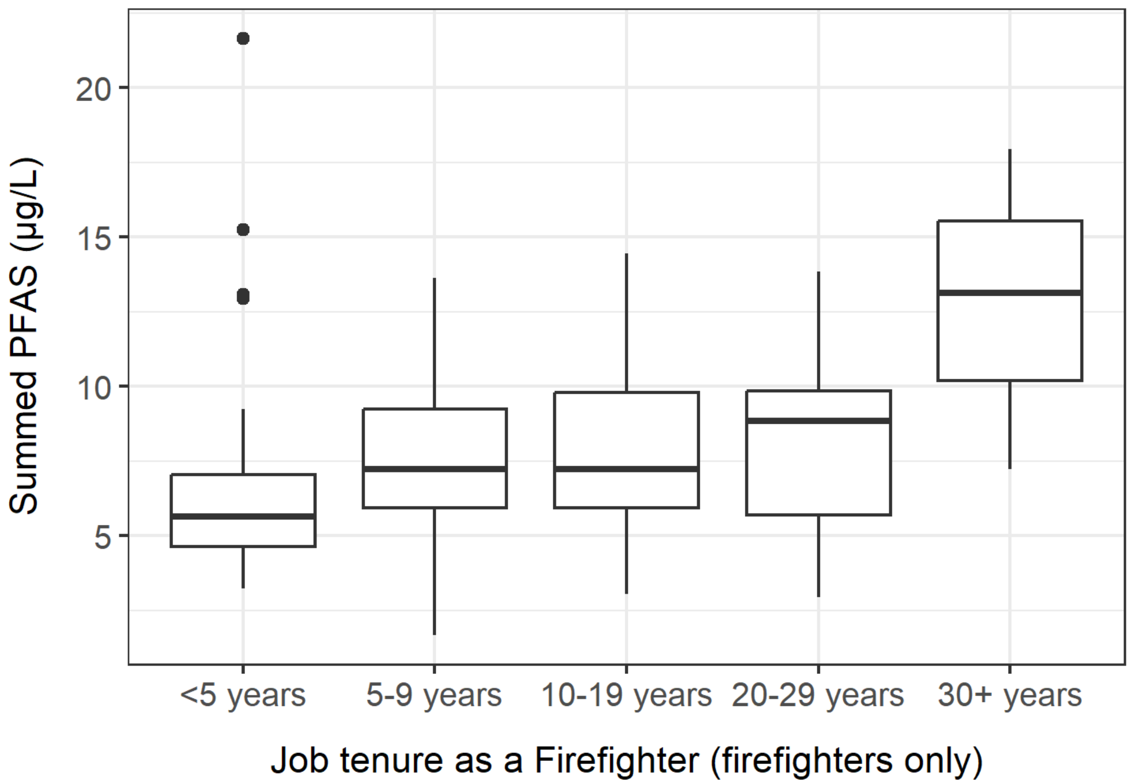

Figure 21. Box and whisker plot of summed PFAS (PFOA, PFOS, PFHxS, PFDA, PFNA, PFUnDA, and MeFOSAA) concentrations for firefighters (n = 178), stratified by job tenure. The box shows the middle 50% of summed PFAS for each job tenure category. The bold horizontal line is the median value. The lines extending above and below the box show the upper quartile to the maximum value and the lower quartile to the minimum value. Block dots signify outliers.

PBDEs

Of the PBDEs evaluated in this report, BDE-28, BDE-47, BDE-100, BDE-153, BDE-209, and PBB-153 were detected in at least 50% of the samples and were included in this analysis. Results for each PBDE are presented for all Maui County employees, Maui County firefighters, and National Guard servicemembers in Tables C33–C35.

Age was significantly related to PBDE exposure (*P* value < 0.05). Specifically, significant differences in median BDE-28, -47, -100, -153, -209, and PBB-153 concentrations for all Maui County employees stratified by age. Firefighters aged < 25 or ≥ 50 years of age had higher BDE-28, -47, -100, and PBB-153 concentrations than firefighters aged 25–50 years. For BDE-153, firefighters aged 50 years and above had higher levels than younger firefighters (*P* value = 0.19), but it was not significant. Age was also related when evaluating National Guard servicemembers' PBDE exposures. Servicemembers ≥ 40 years of age had significantly higher PBB-153 concentrations than servicemembers < 40 years of age.

There were also significant differences between the job tenure stratifications for Maui County firefighters for BDE-28 (*P* value = 0.01), BDE-47 (*P* value = 0.01), BDE-100 (*P* value = 0.02), and PBB-153 (*P* value < 0.01), respectively. Overall, it appeared that exposure to PBDEs were higher for firefighters with a longer job tenure.

Significant differences were found by job category (Table C33) for only BDE-209 (*P* value = 0.01). Other Maui County employees (median: 1.2 ng/g lipid), Maui County Ocean Safety Officers (median: 1.0 ng/g lipid) and Maui County firefighters (median: 0.9 ng/g lipid) had higher BDE-209 concentrations compared with Maui County Police department employees (median: 0.7 ng/g lipid). No other significant differences were found, but the same three job categories had elevated concentrations compared with Maui County Police department employees for BDE-47 and BDE-153.

The National Guard servicemembers (Table C35) generally had concentrations that were closer to those found in Maui County Police department employees. National Guard servicemembers who responded to the wildfires on August 11 had significantly higher median PBB-153 concentrations compared with those who did not respond on August 11 (*P* value = 0.01).

OPEs

Of the OPEs evaluated in urine, BCEtP, BCPP, BDCPP, and DPhP had detection frequencies above 50% and were included in this analysis. Results for each OPE are summarized for all Maui County employees, Maui County firefighters, and National Guard servicemembers in Tables C36–C38.

There were significant differences in BCPP (*P* value = 0.02), BDCPP (*P* value < 0.01), and DPhP (*P* value < 0.01) concentrations based on job category. Maui County Police department employees (median=1.4 µg/L) and Other Maui County employees (median = 1.4 µg/L) had higher median BDCPP concentrations compared with Maui County firefighters (0.9 µg/L) and Ocean Safety Officers (0.5 µg/L). Maui County firefighters had higher median DPhP concentrations (median 0.7 µg/L) compared with the other job categories. Maui County firefighters and Other Maui County employees had elevated BCPP concentrations compared with the other occupational subcategories.

Additionally, we found significant differences in median DPhP concentrations for Maui County Firefighters (Table C37) based on job tenure. Interestingly, firefighters with a shorter tenure had higher median DPhP concentrations. This might be an artifact of the impact of firefighter age, as Maui County firefighters under 25 years of age had the highest median DPhP concentrations among all age groups.

Discussion

Firefighting and responding to fire events, especially responses to major wildfires near built structures and vehicles, may involve exposure to several classes of chemicals known to cause adverse health effects. For the purposes of this evaluation, we focused on the following groups of potential hazards:

- Inorganic elements (such as heavy metals) that are present in homes and vehicles. High exposure to heavy metals may result in damage to organs, impaired development, and a higher risk of developing cancer.
- PFAS, used in a wide range of products such as non-stick cookware, water and stain repellent fabrics and carpeting, and certain types of firefighting foam. High exposure to PFAS has been linked to multiple cancers, thyroid dysfunction, small changes in birthweight, and high cholesterol.

- PBDEs that are used as flame retardants in home products like electronics, foam furniture, and padding. High exposure to PBDEs has been linked with health outcomes like cancer, thyroid disruption, and reproductive changes.
- OPEs that are used as flame retardants or plasticizers in products found in homes including foams, padding, fabrics, electronics, building materials, and nail polish. High exposure to OPEs has been linked with impaired neurological development and interference with the body's hormones.

The next sections will discuss each of these potential hazard groups and provide the rationale for including them in this evaluation.

Inorganic Elements

The sources of metals and other inorganic elements in soil and ash are commonly linked to structural burning during wildland urban-rural interface fires [Alexakis 2020]. When structures and their contents are burned, these metals can melt and contaminate the ground below them.

In Hawaii, arsenic is a heavy metal found in the soils due to volcanic activity and its use as an herbicide in the early 1900s. It is also commonly found in building materials made of sugar cane and wood treated for termite control [HI DOH 2010, 2024]. Arsenic can also be found in food such as rice, fish, meats, and seaweed [ATSDR 2023a].

Following the Maui wildfires, ash sampling conducted by the Hawaiʻi Department of Health (DOH) revealed high levels of arsenic, 280 milligrams per kilogram (mg/kg) in Lahaina and 3,193 mg/kg in Kula, compared with the EPA's Soil Environmental Action Level of 23 mg/kg [HI DOH 2024]. This contamination may have been a source of the inorganic-related arsenic species measured in the urine of the responders. It may at least partially explain why 9% of the Maui County employees and 7% of the Hawaiʻi National Guard servicemembers were overexposed when compared with the ACGIH BEI. However, the half-life (time that it takes half of the original amount of a substance to disappear) of inorganic arsenic in humans is approximately 10 hours, suggesting that our results may represent more recent sources of arsenic exposure [ATSDR 2016]. Consumption of seafood could be contributing to higher arsenic levels, as was seen in our combined analysis.

Chromium is an essential element that the body needs in trace amounts. However, it became a concern for wildfire smoke and debris after discovering that the heat of the severe wildfires in California likely transformed naturally occurring chromium in the soil into hexavalent chromium, which is a known carcinogen [IARC 2012; Lopez et al. 2023]. Hexavalent chromium may also be present in treated timbers and concrete [Alexakis 2020].

Current urine analysis methods, including those used in this evaluation, are unable to differentiate hexavalent chromium from other forms of chromium. It is possible that hexavalent chromium was produced during the Maui wildfires and that some portion of the chromium detected among evaluation participants was hexavalent chromium. In this evaluation, 25% of National Guard servicemembers and 5% of Maui County employees participating in this evaluation had urinary chromium level results above the BEI. The urinary half-life of chromium is less than 2 days. Therefore, its presence in urine among participants might reflect a more recent exposure than the wildfires [Paustenbach et al. 1997].

Varying amounts of manganese, nickel, cadmium, and lead are often found in rechargeable batteries. In addition, manganese is often found in high concentrations in wildfire-impacted areas because of burned biomass and the breakdown process of organic matter and because of its presence in melted steel [Alexakis 2020; Chambers and Attiwill 1994]. Although manganese is an essential nutrient required to support some biological functions, it can be problematic in too high of a concentration.

Manganese was one of the several metals with high concentrations in particulate matter in air during the 2018 Camp Fire in California [California Air Resources Board 2021]. In this evaluation, 7% of the National Guard servicemembers and 5% of Maui County employees had levels of manganese that were higher than the NHANES 95th percentile, suggesting that manganese exposure may be a concern for this population. The half-life of manganese in blood is between 10 and 42 days [Wong et al. 2022] suggesting that the biomarker results could be indicative of exposures from the active Maui wildfires. Interestingly, police department employees had higher median concentrations of manganese than the other occupational groups, which could be reflective of their limited use of respiratory protection during the wildfires, other occupational exposures (e.g., metals exposures in firing ranges), or that they primarily responded to the Lahaina fire which occurred in a more urban area. However, more research would be needed to confirm this.

Nickel can be present in wildfire smoke and ash from natural and manmade sources. Nickel can be naturally present in soils, vegetation, or other natural material that may be released when burnt by fire. In addition, during urban-rural interface fires, building material such as stainless steel may burn and release nickel. In this evaluation, 7% of the National Guard servicemembers and 4% of the Maui County employees were above the NHANES 95th percentile. Nickel has a urinary half-life of 30–53 hours [Kuo et al. 2022]. As such, more recent sources of nickel exposure could have contributed to the biomarker levels we measured.

Although selenium is an essential micronutrient and is required to support some biological functions, it can be problematic when concentrations are too high. Selenium is naturally present in the soil, and plants can accumulate it through their roots. When vegetation burns, it may release selenium into the smoke. In addition to the natural sources, some manmade sources such as fertilized crops may contribute to selenium exposure. In this evaluation, 14% of the National Guard servicemembers and 11% of Maui County employees had blood selenium levels above the NHANES 95th percentile.

Typically, the half-life of selenium in blood ranges from a few days to several weeks, suggesting that the selenium levels we measured could possibly be from the wildfire exposure but could also be influenced by other sources. The finding that those who had eaten seafood in the last 3 days had higher median selenium concentrations compared with those who did not suggests that seafood was an important source of selenium [ATSDR 2003].

An additional ash contaminant was lead, a heavy metal that is often present due to it use in lead paint on houses built before 1978 and in solder and old galvanized pipes [Alexakis 2020]. Although the Kula and Lahaina ash samples showed high levels of lead (410 mg/kg in Lahaina and 688 mg/kg in Kula) compared with the soil environmental action level of 200 mg/kg, our sample population had relatively low blood lead levels. No participant was over any applicable exposure limits or the 2017–2018 NHANES 95th percentile of 2.62 µg/dL [HI DOH 2024]. This discrepancy could be due to good work practices within our employee group such as good hand hygiene and or proper use of PPE. The half-life of lead in blood is estimated to be 28 days [ATSDR 2023b].

Although cadmium is often a concern in wildfire smoke, ash, and soil, we did not find any responders with overexposures. Because cadmium excretion is slow, cadmium tends to bioaccumulate. However, cadmium measured in the blood typically reflects both recent and cumulative cadmium exposure [ATSDR 2023c].

PFAS

Consistent with the finding in this responder population, most people in the United States and in other industrialized countries have measurable amounts of PFAS in their blood. Most research in occupational settings has evaluated PFAS exposure in workers known to be exposed more than the general public. Studies on fluorochemical production workers, first responders including firefighters, and ski wax technicians have been done [Christensen and Calkins 2023; NIOSH 2022]. In occupational settings, exposure to PFAS generally occurs through inhalation of PFAS in aerosols or vapors or incidental ingestion of PFAS in dust [Christensen and Calkins 2023]. Workers may also be exposed to PFAS by getting them on their skin [ATSDR 2024].

Many studies suggest that first responders, specifically firefighters, have elevated levels of some PFAS in their bodies compared with the general U.S. population [Dobraca et al. 2015; Leary et al. 2020; Rotander et al. 2015; Trowbridge et al. 2020]. Consistent with what has been observed in previous work, we found that firefighters had the highest median sum of PFAS concentrations. Their levels were higher than Maui County police department employees and Maui County Ocean Safety Officers.

Consistent with other studies, serum concentrations of PFHxS, one of the most biologically persistent PFAS, were elevated in some firefighters and Other Maui County employees, with maximum concentrations (9.3 μg/L) near 2.5 times the NHANES 95th percentile (3.8 μg/L). However, for PFOA and PFOS, two of the most studied and more biologically persistent PFAS, median serum levels in Maui County firefighters of 1.3 μg/L and 3.1 μg/L, respectively, were lower than levels measured in previously studied firefighter populations. These results were similar to levels measured in U.S. general populations [Christiansen and Calkins 2023].

There are multiple ways firefighters and other first responders may be exposed to PFAS through their work. Firefighters may be exposed to PFAS through use of firefighting foams that contain PFAS (e.g., AFFF); through dust containing PFAS during emergency response (e.g., from combustion of stain-resistant upholstery or carpeting) or at the firehouse. Exposure could also potentially occur through contact with gear used to protect them from heat-related hazards during emergency response (e.g., turnout gear) [NIOSH 2022].

In addition, different types of firefighters may have different potential for exposure based on the PFAS-containing products they use or come into contact with and the job tasks they perform [Christensen and Calkins 2023]. Studies of sources and pathways of exposure to PFAS for firefighters remains a topic of active research [NIOSH 2022].

Although pathways of exposure exist, we do not yet have enough information to know how these exposures affect the concentration of PFAS in firefighters' bodies. We determined that AFFF, one of the most common PFAS exposures for firefighters, was not likely used during this wildfire response. It is important to note that some of the biological half-lives of the PFAS evaluated here are longer than a year. This means that the levels observed here reflect both recent and past exposure and therefore cannot be attributed to solely the 2023 Maui Wildfire response.

We found firefighters with longer job tenure had higher median sum of PFAS concentrations relative to firefighters with shorter job tenure. This finding may indicate that longer job tenure is associated with more exposure. It could also reflect that employees with longer job tenure are usually older and have had more opportunity to bioaccumulate these substances over their lifetime. Additionally, the use of products containing PFAS (e.g., AFFF) has changed over time, with greater exposures occurring years ago [Rotander et al. 2015].

Irrespective of the source of exposure, NASEM has provided guidance on medical screenings for specific conditions depending on serum levels of selected PFAS [NASEM 2022]. Only one participant had a PFAS summation concentration above 20 μg/L (ng/mL), in which health screenings beyond the usual standard of care are recommended.

PBDEs

We examined serum PBDE concentrations and compared them with the 95th percentile of serum results from the 2003–2004 NHANES because of the lack of OELs for these flame retardants. We also compared the results with the mean concentrations from the more recent 2015–2016 NHANES data. Levels of PBDEs in the general population have been decreasing [Sjödin et al. 2019] from the early 2000s until now because of the phase out of these compounds in consumer goods and building products. The percentage of serum concentrations that were above the limit of detection among responders was less than 50% for BDE-17, -85, -99, -154, and -183.

BDE-153 was detected in 100% of both the general population and workers participating in this evaluation. It is also one of the PBDE congeners for which levels are increasing in the U.S. population for people who are older than 40 years [Sjödin et al. 2019]. When comparing BDE-153 serum concentrations and occupational subcategories (Firefighter, Police, Other Maui County Employees, and Ocean Safety Officers), there was not a statistically significance difference among the groups.

Age was significantly associated with BDE-153 concentrations, with the oldest Maui County participants having the highest median BDE-153 concentration of 13.4 ng/g lipid. Job tenure also appeared to impact PBDE exposures, as BDE-47, BDE-100, and PBB-153 median concentrations were higher for firefighters with longer job tenure. Job tenure could be related to age and body mass index (BMI); however, BMI was not measured in this evaluation.

PBDEs are lipophilic and reside primarily in fat cells, which may increase with age in some populations. Estill et al. [2024] found that 100% of exposed workers studied in 2015–2017 had detectable serum concentration of BDE-153, with the highest geometric mean (10.47 ng/g lipid) among spray polyurethane foam workers who installed insulation in buildings. Maui County workers in this study had a geometric mean of 11.5 ng/g lipid concentration for BDE-153. Mayer et al. [2021] collected serum from firefighters training in 2015 and found median concentrations well below what is reported here (4.61 ng/g lipid).

Mayer et al. [2021] evaluated pre- and post- fire serum concentrations of PBDEs in firefighters. They found that the median post-fire serum BDE-209 concentration was 3.44 ng/g lipid, whereas in this evaluation, the Maui County Firefighters' median BDE-209 serum concentration was lower at 0.92 ng/g lipid. In this evaluation, there was a difference (*P* value = 0.01) observed in BDE-209 serum concentrations among occupational subcategories with Other Maui County employees, Ocean Safety Officers, Firefighters, and Police Department employees, which had median concentrations of 1.2, 1.0, 0.9, and 0.7 ng/g lipid, respectively. Occupational exposures beyond just the Maui Wildfire 2023 response may have contributed to serum PBDE concentrations in our participants.

Little evidence is seen of these PBDEs exposures in the Maui County employees and National Guard servicemembers being greater than those of general population when comparing with NHANES data. However, the major limitation to this comparison is that PBDE levels in the United States are going down and the last comparison year is 2015–2016. Half-lives for these PBDEs range from days to years [Sjödin et al. 2020; Thuresson 2006]. Therefore, the measured concentrations could be related to the 2023 Maui Wildfires or from bioaccumulation over long periods. Exposures could be related to workplace factors (e.g., debris from work) or lifestyle factors (e.g., home furnishings, seafood consumption) among these job groups.

OPEs

OPE flame retardants have largely replaced the PBDE flame retardants in many consumer goods and building products since the early 2000s. Wang et al. [2020] recently reported that urine half-lives for the metabolites of TPhP (DPhP), TDCPP (BDCPP), and TCPP (BCPP) are 9.6, 53.8, and 15.2 days, respectively. These are longer than previous estimates that were on the order of hours [Carignan et al. 2016]. NHANES has measured OPE urinary metabolites in the general population for the years 2017 and 2018 [CDC 2024]. Four of the eight measured urinary metabolites (BCEtP, BCPP, BDCPP, and DPhP) were above the LOD for most participants. For the entire group, the median urinary concentrations of BCEtP, BCPP, BDCPP, and DPhP were below the reported NHANES general population medians, but all occupational subcategories had at least one employee with OPE urinary concentrations greater than the 95th percentile general population concentration.

DPhP is a metabolite of TPhP. It is a common flame retardant used in plastics such as polyvinyl chloride (PVC) and polycarbonate/ABS alloy (PC/ABS), polyurethane foam, and hydraulic fluids [Marklund et al. 2003]. It is also used as a plasticizer in photographic film and nail polishes. DPhP urinary median concentration was 0.58 μg/L (geometric mean of 0.60 μg/L) for all Maui County employees combined. However, firefighters had higher median concentrations at 0.72 μg/L, while the other subgroups had median concentrations ≤ 0.40 μg/L. Although the result for firefighters was higher than the other groups, it was lower than the general population median of 0.89 μg/L for DPhP (NHANES).

In a 2016 study of nail salon workers [Estill et al. 2021], unadjusted post-shift and pre-shift geometric mean urinary DPhP concentrations were 1.25 μg/L and 0.97 μg/L, respectively. Mayer et al. [2021] reported firefighters' pre-fire median unadjusted DPhP concentrations at 1.24 μg/L. Estill et al. [2024] studied various worker groups and found chemical manufacturing workers, roofers, gymnastics workers, foam manufacturing workers, and spray polyurethane foam workers to have urinary concentrations greater than the general population.

Urinary BDCPP is a metabolite of TDCPP. Its main use is in polyurethane foams, which are used in furniture and carpet padding. BDCPP, compared with other OPEs, has a fairly long half-life of 53.8 days [Wang et al. 2020]. The median uncorrected BDCPP urinary concentration for all the Maui County employees was 0.90 µg/L (geometric mean 0.91 µg/L). Median uncorrected concentrations were slightly lower among firefighters (0.86 µg/L) compared to police and other Maui County workers who had median urinary BDCPP concentration of 1.4 µg/L.

Estill et al. [2024] identified worker groups with BDCPP urinary concentrations higher than the general population. These included chemical and foam manufacturing workers, roofing workers, gymnastics workers, spray polyurethan foam workers, and electronic scrap recycling workers. Mayer et al. [2021]. Reported firefighters' pre-fire urinary median unadjusted concentration of BDCPP of 1.24 µg/L, which was similar to the levels found here.

BCEtP is a urinary metabolite of tris(2-chloroethyl) phosphate (TCEP). TCEP was listed under California Proposition 65 as a carcinogen. It has been phased out in the last 10 years or so [Zhou and Puttmann 2019]. The median uncorrected BCEtP urinary concentration among all Maui County employees was 0.19 µg/L (geometric mean 0.21 µg/L). It was detectable in 73% of the samples. The NHANES geometric mean for BCEtP was 0.41 µg/L. Estill et al. [2024] reported that roofing and electronic scrap workers were occupationally exposed to TCEP with geometric mean urinary concentrations of 0.9 µg/L or greater. The highest occupational subcategory of workers in this evaluation were the other Maui County workers, who had median uncorrected BCEtP level of 0.31 µg/L. However, differences among occupational subcategories were not statistically significant.

As a group, all Maui County employees and National Guard servicemembers in this study do not appear to have OPE exposures that are higher than the general population nor higher than other worker populations studied by Estill et al. [2024]. However, these flame retardants have short half-lives. Therefore, any exposures that could have occurred during the 2023 Maui Wildfires might not have been detected because of the time interval between the fires and when these biological fluids were collected.

Overall Conclusions, Limitations, and Future Work

In summary, this evaluation found that most participants' exposures to inorganic elements were below the relevant reference values. However, a small percentage of Maui County participants and National Guard servicemembers had levels of manganese, selenium, inorganic-related arsenic species, chromium, and nickel at or above the reference values. No participants exceeded the OELs for cadmium and lead. Detectable levels of PFAS, PBDEs, and OPEs were found in almost all participants, which is expected due to their presence in water systems and common household items. While some individuals showed concentrations exceeding reference values for certain PFAS chemicals, only one participant slightly surpassed the clinical threshold suggested by NASEM for additional health screenings. At least one participant had a result above the reference value for 5 of the 11 PBDE chemicals and 4 of the 8 OPE chemicals. Associations were observed between occupation and levels of inorganic elements and exposure markers among Maui County participants. However, no discernible patterns emerged between self-reported exposure characteristics and biomarker levels in blood and urine among responders.

This technical assistance evaluation has several limitations. Several exposure markers of combustion byproducts (e.g., urinary metabolites of polycyclic aromatic hydrocarbons and volatile organic compounds) have half-lives less than 24 hours, so we were not able to incorporate these exposure markers into our evaluation. Additionally, we were not able to capture a pre-exposure specimen sample from participants because the request for assistance understandably occurred after the disaster. In addition, sampling for comparison to BEIs is recommended to be collected at the end of the shift and end of the work week. With the lag between exposure and collection, we likely underestimated what was absorbed during the Maui Wildfire response. Also, because the time lag between the exposure period of interest and the biological sampling was approximately 1 month, we cannot rule out the possibility that personnel had other occupational or non-occupational exposures (e.g., seafood consumption) not related to the Maui wildfire response that contributed to the results. This is especially likely for exposure markers with shorter half-lives (e.g., nickel).

Although Maui wildfire responders might have been exposed to these inorganic elements, much of the absorbed elements would have been excreted before the blood and urine specimens were collected. However, some of the exposure markers included in this evaluation have long half-lives (on the order of years), which means we cannot rule out the possibility that the exposure may have occurred from other sources before the 2023 Maui Wildfires (e.g., previous firefighting responses, diet, etc.). We did not collect any health or symptom information from the responders; therefore we were unable to make any conclusions related to short-term health effects from the wildfires. In addition, we did not collect air samples, which limited our comparisons to existing OELs. Lastly, other metals of concern in the HI DOH ash sampling include antimony, cobalt, copper, lithium, and mercury; however, we did not analyze the specimens for those elements [HI DOH 2024].

Despite the limitations associated with the varying biological half-lives and timing of the specimen collections, it is likely that the wildfires did contribute—at least partially—to some of the biomonitoring results. This conclusion is supported by the presence of some of these compounds (e.g., arsenic) in the ash collected from the Lahaina and Kula impact zones by HI DOH. In addition, there also appeared to be an occupational association with some of the exposure markers (e.g., PFAS in firefighters) unrelated to the Maui wildfires that warrants further research. In-depth analysis, including careful consideration of other occupational and non-occupational factors not related to the Maui fires and sources of exposure, would help to better understand the contribution from the Maui wildfires. This is beyond the scope of this report.

Future biomonitoring missions of responders to wildfire disaster events could prioritize rapid deployment of exposure scientists and other personnel to permit blood or urine collection within days of the disaster to more accurately characterize potential response-related exposures. A more rapid deployment would also minimize recall bias among participants, a likely limitation in this evaluation, with the delay between the event and filling out questionnaires about exposure information. However, this would require overcoming the significant logistical and social challenges of responding to disasters [Decker et al. 2013].

Despite the complexities associated with interpreting the biomonitoring results, because we selected panels of exposure markers reported by NHANES, we were able to compare results from this evaluation with the U.S. general population, as well as any industry-specific data available in the literature. While NHANES data are weighted to be representative of the entire U.S. population, NHANES does not travel to Hawaii to conduct examinations. Given the geographic variability in the levels of some substances we evaluated, the representativeness of NHANES data for the population in Hawaii might be limited.

Statistically significant differences from NHANES values do not necessarily mean that the differences are clinically relevant. However, we were also able to compare some biomonitoring results with BEIs and OSHA medical removal levels that are based on risk of experiencing an adverse health effect. Where exposures over applicable reference values were identified, participants were encouraged to share their individual results with their healthcare provider. Biomonitoring results may also highlight potential occupational sources of exposure and areas for risk mitigation or exposure reduction (see Our Recommendations).

Section C: Tables

Table C1. Demographic characteristics of Maui County employees (n = 259)

Characteristic	All Maui County Employees n (%)	Firefighters n (%)	Police Department Employees n (%)	Other Maui County Employees n (%)	Ocean Safety Officers n (%)
Number of participants	259 (100%)	179 (100%)	39 (100%)	22 (100%)	19 (100%)
Age (years), median (range)	40.0 (20.6–68.7)	39.7 (21.2–59.9)	39.2 (24.9–68.7)	48.7 (27.6–61.4)	34.4 (20.6–58.8)
Male	244 (94%)	175 (98%)	31 (80%)	21 (95%)	17 (90%)
Hispanic or Latino ethnicity	19 (7%)	12 (7%)	4 (10%)	1 (5%)	2 (11%)
Race*					
White	140 (54%)	111 (62%)	12 (31%)	4 (18%)	13 (68%)
Native Hawaiian or Other Pacific Islander	120 (46%)	79 (44%)	19 (49%)	14 (64%)	8 (42%)
Asian	123 (48%)	92 (51%)	14 (36%)	7 (32%)	10 (53%)
Black or African American	3 (1%)	3 (2%)	0 (0%)	0 (0%)	0 (0%)
American Indian or Alaska Native	17 (7%)	12 (7%)	1 (3%)	0 (0%)	4 (21%)
Eaten seafood within the last 3 days	163 (63%)	117 (65%)	22 (56%)	16 (73%)	8 (42%)

* Participants instructed to select all that apply.

Table C2. Demographic characteristics of Hawaiʻi National Guard servicemembers (n = 28)

Characteristic	Number (%)
Age (years), median (range)	38.1 (24.0–56.1)
Male	22 (79%)
Hispanic or Latino ethnicity	3 (11%)
Race*	
White	4 (14%)
Asian	22 (79%)
Native Hawaiian or Other Pacific Islander	6 (21%)
Black or African American	1 (4%)
Native Indian or Alaska Native	2 (7%)

* Participants instructed to select all that apply.

Table C3. Summary of inorganic elements results in blood (n = 257) and urine (n = 256) for all Maui County employees

Source†	Participant Results*				Reference Value		
	Substance (units)	Median (range)	Geometric mean (GSD)	n (%) ≥ reference value	OSHA medical removal limit	ACGIH BEI	NHANES 95th percentile‡
Blood	Cadmium (μg/L)	0.15 (< LOD–0.79)§	0.15 (1.56)	0 (0%)	5	5	—
	Lead (μg/dL)	0.60 (0.27–2.24)	0.64 (1.51)	0 (0%)	60	20	—
	Manganese (μg/L)	9.18 (3.3–23.4)	9.21 (1.37)	12 (5%)	—	—	16.0
	Selenium (μg/L)	198 (133–344)	201.12 (1.14)	28 (11%)	—	—	234
Urine	Total arsenic (μg/g cr)	22.4 (2.18–906)	23.17 (3.45)	N/A	—	—	—
	Inorganic-related arsenic species (μg/g cr)¶	8.55 (2.76–173)	9.04 (1.80)	23 (9%)	—	15	—
	Chromium (μg/L)	< LOD (< LOD–3.90)§	0.19 (1.90)	13 (5%)	—	0.7	—
	Nickel (μg/L)	1.10 (< LOD–9.64)§	1.03 (2.14)	10 (4%)	—	—	3.95

Abbreviations: ACGIH: American Conference of Governmental Industrial Hygienists; BEI: Biological Exposure Indices; GSD: geometric standard deviation; LOD: limit of detection; NHANES: The National Health and Nutrition Examination Survey; OSHA: Occupational Safety and Health Administration; μg/dL: micrograms per deciliter; μg/g cr: micrograms per gram creatinine; μg/L: micrograms per liter

* For results below the LOD. We computed a value using LOD/√2 to calculate medians and geometric means.

† Blood and urine samples were collected as random spot samples.

‡ The NHANES 95th percentiles are determined from NHANES survey years 2017–2018 for people aged ≥ 20 years.

§ LOD values: cadmium: 0.065 μg/L; lead: 0.049 μg/dL; manganese: 0.52 μg/L; selenium 9.9 μg/L; total arsenic: 0.23 μg/g cr; chromium: 0.19 μg/L; nickel: 0.31 μg/L

¶ Inorganic-related arsenic species values were determined only when total arsenic values were at or above 15 μg/g cr (n = 244 for total arsenic and n = 159 for inorganic related arsenic species). They were calculated as the sum of arsenous (III) acid, arsenic (V) acid, dimethylarsinic acid, and monomethylarsonic acid.

Table C4. Summary of PFAS results in blood for all Maui County employees (n = 258)

Substance	Participant Results*				Reference Value	
	n (%) ≥ LOD	Median (range) (µg/L)	Geometric mean (GSD) (µg/L)	n (%) ≥ Reference value	NHANES 95th percentile† (µg/L)	NASEM sum PFAS (µg/L)
PFOA	258 (100%)	1.3 (0.1–3.5)	1.21 (1.59)	0 (0%)	3.9	—
n-PFOA	257 (99%)	1.2 (< LOD–3.4)	1.13 (1.66)	0 (0%)	3.8	—
Sb-PFOA	0 (0%)	< LOD (All < LOD)	0.07 (1.00)	0 (0%)	2	—
PFOS	258 (100%)	3.0 (0.3–11.0)	3.06 (1.66)	0 (0%)	15.1	—
n-PFOS	258 (100%)	2.2 (0.3–8.4)	2.22 (1.66)	0 (0%)	11.0	—
Sm-PFOS	257 (99%)	0.8 (< LOD–3.3)	0.80 (1.79)	0 (0%)	4.6	—
PFHxS	256 (99%)	1.1 (< LOD–9.3)	1.04 (1.97)	9 (3%)	3.8	—
PFDA	244 (95%)	0.2 (< LOD–0.9)	0.22 (1.79)	17 (7%)	0.6	—
PFNA	254 (100%)	0.4 (0.1–1.7)	0.45 (1.64)	4 (2%)	1.4	—
PFUnDA	244 (95%)	0.3 (< LOD–1.8)	0.30 (2.00)	103 (40%)	0.4	—
MeFOSAA	0 (0%)	< LOD (< LOD–0.5)	0.07 (1.25)	0 (0%)	0.6	—
NASEM sum	258 (100%)	6.64 0.92–21.6	6.69 (1.56)	1 (0.4%)	—	20

Abbreviations: GSD: geometric standard deviation; LOD: limit of detection; NASEM: National Academies of Sciences, Engineering, and Medicine; NHANES: The National Health and Nutrition Examination Survey; PFAS: per- and polyfluoroalkyl substances; µg/L: micrograms per liter

Substances: PFOA: Perfluorooctanoic acid; n-PFOA: Linear isomer of PFOA; Sb-PFOA: Sum of branched isomers of PFOA; PFOS: Perfluorooctane sulfonic acid; n-PFOS: Linear isomer of PFOS; Sm-PFOS: Sum of monomethyl branched isomers of PFOS; PFHxS: Perfluorohexane sulfonic acid; PFDA: Perfluorodecanoic acid; PFNA: Perfluorononanoic acid; PFUnDA: Perfluoroundecanoic acid; MeFOSAA: 2-(N-methyl-perfluorooctane sulfonamido) acetic acid; NASEM sum: Sum of PFOA, PFOS, PFHxS, PFDA, PFNA, PFUnDA, and MeFOSAA

* For results below the LOD, we computed a value using LOD/√2 to calculate medians and geometric means. The LOD for all substances was 0.1 µg/L.

† The NHANES 95th percentiles are determined from NHANES survey years 2017–2018 for people aged ≥ 20 years.

Table C5. Summary of polybrominated diphenyl ether results (in ng/g lipid) in blood for all Maui County employees (n = 258)

Substance	Participant Results*					Reference Value	
	n (%) over LOD	n (%) ≥ mean	n (%) ≥ 95th	Median (range)	Geometric mean (GSD)	NHANES† mean	NHANES 95th percentile‡
BDE-17§	18 (7%)	NC	NC	< LOD (< LOD–0.9)	0.14 (1.48)	0.13	< LOD
BDE-28	152 (59%)	28 (11%)	1 (0.4%)	0.23 (< LOD–20.6)	0.29 (2.48)	0.86	8.20
BDE-47	196 (76%)	23 (9%)	1 (0.4%)	3.3 (< LOD–251.8)	3.68 (2.81)	16.70	163
BDE-85	36 (14%)	NC	NC	< LOD (< LOD–3.1)	0.15 (1.65)	0.35	4.10
BDE-99	114 (44%)	NC	NC	0.85 (< LOD–15.6)	1.12 (2.05)	3.60	41.6
BDE-100	219 (85%)	19 (7%)	1 (0.4%)	0.77 (< LOD–42.2)	0.80 (2.75)	3.63	36.6
BDE-153	258 (100%)	113 (44%)	11 (4%)	10.4 (1.6–229.1)	11.47 (2.58)	12.10	73.3
BDE-154	41 (16%)	NC	NC	< LOD (< LOD–2.2)	0.15 (1.62)	0.31	4.2
BDE-183	36 (14%)	NC	NC	< LOD (< LOD–1.3)	0.14 (1.50)	0.24	< LOD
BDE-209	147 (57%)	25 (10%)	NC	0.92 (< LOD–7.3)	1.01 (1.68)	2.13	NC
PBB-153§	241 (95%)	26 (10%)	0 (0%)	0.67 (< LOD–23.8)	0.71 (2.66)	2.94	34.6

Abbreviations: GSD: geometric standard deviation; LOD: limit of detection; NC: not calculated; ng/g lipid: nanograms per gram of lipid; NHANES: The National Health and Nutrition Examination Survey

Substances: BDE-17: 2,2´,4- Tribromodiphenyl ether. The LOD is 0.14 ng/g; BDE-28: 2,4,4´-Tribromodiphenyl ether. The LOD is 0.14 ng/g; BDE-47: 2,2´,4,4´-Tetrabromodiphenyl ether. The LOD is 1.2 ng/g; BDE-85: 2,2´,3,4,4´-Pentabromodiphenyl ether. The LOD is 0.14 ng/g; BDE-99: 2,2´,4,4´,5-Pentabromodiphenyl ether. The LOD is 0.75 ng/g; BDE-100: 2,2´,4,4´,6-Pentabromodiphenyl ether. The LOD is 0.19 ng/g; BDE-153: 2,2´,4,4´,5,5´-Hexabromodiphenyl ether. The LOD is 0.14 ng/g; BDE-154: 2,2´,4,4´,5,6´-Hexabromodiphenyl ether. The LOD is 0.14 ng/g; BDE-183: 2,2´,3,4,4´,5´,6-Heptabromodiphenyl ether. The LOD is 0.14 ng/g; BDE-209: Decabromodiphenyl ether. The LOD is 0.71 ng/g; PBB 153: 2,2´,4,4´,5,5´-Hexabromobiphenyl. The LOD is 0.14 ng/g.

* For results below the LOD, we computed a value using LOD/√2 to calculate medians and geometric means.

† The means are calculated from NHANES 2015–2016 for ≥ 20 years.

‡ The NHANES unadjusted 95th percentiles are determined from NHANES survey years 2003–2004 for people aged ≥ 20 years.

§ Due to interfering substances, only 257 samples were tested for BDE-17 and 254 samples were tested for PBB-153.

Table C6. Summary of organophosphate ester in urine (µg/L for uncorrected, µg/g creatinine for corrected) results for all Maui County employees (n = 256)

Substance	Participant Results*				Reference Value†	
	n (%) ≥ LOD	Median (range) Geometric mean [GSD] (Uncorrected)	Median (range) Geometric mean [GSD] (Corrected)	n (%) ≥ Uncorrected RV n (%) ≥ Corrected RV	NHANES 95th percentile (µg/L) (Uncorrected)	NHANES 95th percentile (µg/g cr) (Corrected)
BCEtP	187 (73%)	0.19 (< LOD–7.12) 0.21 [2.73]	0.22 (< LOD–13.03) 0.22 [2.98]	4 (2%) 3 (1%)	2.63	2.15
BCPP	158 (63%)	0.13 (< LOD–6.26) 0.16 [2.52]	0.15 (< LOD–7.67) 0.17 [2.51]	12 (5%) 9 (4%)	1.11	0.881
BDCPP	246 (96%)	0.90 (< LOD–22.70) 0.91 [3.09]	0.94 (< LOD–14.35) 0.97 [2.42]	11 (4%) 4 (2%)	6.94	4.48
DbuP	54 (21%)	< LOD (< LOD–0.92) 0.08 [1.46]	< LOD (< LOD–0.64) 0.08 [1.97]	NC	0.86	0.729
DPhP	243 (95%)	0.58 (< LOD–14.10) 0.60 [3.03]	0.60 (< LOD–6.77) 0.65 [2.29]	13 (5%) 2 (1%)	4.99	4.08
TBBA	0 (0%)	< LOD (All < LOD) All < LOD	< LOD (All < LOD) All < LOD	NC	0.063	0.177
iPPPP	36 (14%)	< LOD (< LOD–0.25) 0.04 [1.49]	< LOD (< LOD–0.31) 0.04 [1.97]	NC	0.103	0.177
tBPP	21 (8%)	< LOD (< LOD–0.69) 0.04 [1.39]	< LOD (< LOD–0.29) 0.04 [1.98]	NC	0.1	0.186

Abbreviations: GSD: geometric standard deviation; LOD: limit of detection; NC: not calculated; NHANES: The National Health and Nutrition Examination Survey; RV: reference value; µg/L: micrograms per liter; µg/g cr: micrograms per gram creatinine

Substances: BCEtP: Bis(2-chloroethyl) phosphate is a metabolite of tris(2-chloroethyl) phosphate. LOD is 0.1 µg; BCPP: Bis(1-chloro-2-propyll) phosphate is a metabolite of tris(1-chloro-2-propyl) phosphate. LOD is 0.1 µg. n = 251 for this analyte; BDCPP: Bis(1,3-dichloro-2-propyl) phosphate is a metabolite of tris(1,3-dichloro-2-propyl) phosphate. LOD is 0.1 µg; DbuP: Di-n-butyl phosphate is a metabolite of Tributyl phosphate. LOD is 0.1 µg; DPhP: Diphenyl phosphate is a metabolite of triphenyl phosphate, isopropylphenyl triphenyl phosphate, isopropylphenyl diphenyl phosphate, t-butylphenyl diphenyl phosphate, and 2-ethylhexyl diphenyl phosphate. LOD is 0.1 µg; TBBA: 2,3,4,5-tetrabromobenzoic acid is a metabolite of 2-ethylhexyl-2,3,4,5-tetrabromobenzoate. LOD is 0.05 µg; iPPPP: 2-[(isopropyl)phenyl]phenyl hydrogen phosphate is a metabolite of isopropylphenyl diphenyl phosphate. LOD is 0.05 µg; tBPPP: 4-[(tert-butyl)phenyl]phenyl hydrogen phosphate is a metabolite of tertbutylphenyl diphenyl phosphate. LOD is 0.05 µg.

* For results below the LOD, we computed a value using LOD/√2 to calculate medians and geometric means.

† The NHANES 95th percentiles are determined from NHANES survey years 2017–2018 for people aged ≥ 20 years (both creatinine corrected and uncorrected).

Table C7. Summary of inorganic elements results in blood (n = 257) and urine (n = 256) for all Maui County employees

Source*	Substance	Firefighters	Police Department Employees	Ocean Safety Officers	Other Maui County Employees	Reference Value		
		n tested [Median]† (Range) n (%) ≥ RV	n tested [Median]† (Range) n (%) ≥ RV	n tested [Median]† (Range) n (%) ≥ RV	n tested [Median]† (Range) n (%) ≥ RV	OSHA medical removal limit	ACGIH BEI	NHANES 95th percentile‡
Blood	Cadmium (µg/L)	177 [0.14] (< LOD–0.52)¶ 0 (0%)	39 [0.16] (0.08–0.58) 0 (0%)	19 [0.17] (0.076–0.48) 0 (0%)	22 [0.22] (0.08–0.79) 0 (0%)	5	5	—
	Lead (µg/dL)	177 [0.60] (0.28–2.24) 0 (0%)	39 [0.57] (0.28–1.39) 0 (0%)	19 [0.62] (0.27–1.0) 0 (0%)	22 [0.69] (0.29–1.80) 0 (0%)	60	20	—
	Manganese (µg/L)	177 [8.70] (3.99–23.4) 7 (4%)	39 [11.15] (5.75–16.3) 2 (5%)	19 [9.7] (6.5–16.2) 1 (5%)	22 [9.4] (3.3–22.6) 2 (9%)	—	—	16.0
	Selenium (µg/L)	177 [197] (133–344) 17 (10%)	39 [203] (167–297) 5 (13%)	19 [206] (161–239) 2 (11%)	22 [210.6] (168–296) 4 (18%)	—	—	234

Table C7 Continued. Summary of inorganic elements results in blood (n = 257) and urine (n = 256) for all Maui County employees

Source*	Substance	Firefighters	Police Department Employees	Ocean Safety Officers	Other Maui County Employees	Reference Value		
		n tested [Median]† (Range) n (%) ≥ RV	n tested [Median]† (Range) n (%) ≥ RV	n tested [Median]† (Range) n (%) ≥ RV	n tested [Median]† (Range) n (%) ≥ RV	OSHA medical removal limit	ACGIH BEI	NHANES 95th percentile‡
Urine	Total arsenic (µg/g cr)	167 [22.5] (3.1–513.0) N/A	39 [15.9] (2.2–585.0) N/A	19 [20.4] (6.1–98.6) N/A	22 [37.7] (10.7–906.0) N/A	—	—	—
	Inorganic-related arsenic species (µg/g cr)§	108 [8.39] (2.76–51.50) 16 (10%)	19 [10.0] (3.0–19.8) 2 (6%)	12 [8.5] (4.1–13.9) 0 (0%)	20 [10.4] (3.0–173.0) 5 (23%)	—	15	—
	Chromium (µg/L)	176 [< LOD] (< LOD–3.96)¶ 8 (5%)	39 [< LOD] (< LOD–0.89) 1 (3%)	19 [< LOD] (< LOD–0.47) 0 (0%)	22 [0.19] (< LOD–2.30) 5 (23%)	—	0.7	—
	Nickel (µg/L)	176 [1.07] (< LOD–9.64)¶ 8 (5%)	39 [1.26] (< LOD–3.98) 1 (3%)	19 [0.94] (0.22–5.27) 1 (5%)	22 [1.29] (0.52–3.50) 0 (0%)	—	—	3.95

Abbreviations: ACGIH: American Conference of Governmental Industrial Hygienists; BEI: Biological Exposure Indices; LOD: limit of detection; N/A: not applicable; NHANES: The National Health and Nutrition Examination Survey; OSHA: Occupational Safety and Health Administration; RV: reference value; µg/dL: micrograms per deciliter; µg/g cr: micrograms per gram creatinine; µg/L: micrograms per liter

* Blood and urine samples were collected as random spot samples.

† For results below the LOD, we computed a value using LOD/√2 to calculate medians.

‡ The NHANES 95th percentiles are determined from NHANES survey years 2017–2018 for people aged ≥ 20 years.

§ Inorganic-related arsenic species values were determined only when total arsenic values were at or above 15 µg/g cr. They were calculated as the sum of arsenous (III) acid, arsenic (V) acid, dimethylarsinic acid, and monomethylarsonic acid.

¶ LOD values: cadmium: 0.065 µg/L; chromium: 0.19 µg/L; nickel: 0.31 µg/L.

Table C8. Summary of PFAS results in blood (µg/L) for Maui County employees (n = 258)

	Participant Results*												Reference Value	
	Firefighters (n = 178)			Police Department Employees (n = 39)			Ocean Safety Officers (n = 19)			Other Maui County Employees (n = 22)				
Substance	n (%) ≥ LOD	Median (Range)	n (%) ≥ RV	n (%) ≥ LOD	Median (Range)	n (%) ≥ RV	n (%) ≥ LOD	Median (Range)	n (%) ≥ RV	n (%) ≥ LOD	Median (Range)	n (%) ≥ RV	NHANES 95th percentile†	NASEM sum PFAS
PFOA	178 (100%)	1.3 (0.37–3.5)	0 (0%)	39 (100%)	1.1 (0.47–2.8)	0 (0%)	19 (100%)	1.3 (0.4–2.1)	0 (0%)	22 (100%)	1.0 (0.1–3.1)	0 (0%)	3.9	—
n-PFOA	178 (100%)	1.2 (0.3–3.4)	0 (0%)	39 (100%)	1.0 (0.4–2.7)	0 (0%)	19 (100%)	1.2 (0.3–2.0)	0 (0%)	21 (95%)	0.95 (< LOD–3.0)	0 (0%)	3.8	—
Sb-PFOA	0 (0%)	< LOD (All < LOD)	NC	0 (0%)	< LOD (All < LOD)	NC	0 (0%)	< LOD (All < LOD)	NC	0 (0%)	< LOD (All < LOD)	NC	2.0	—
PFOS	178 (100%)	3.1 (0.27–11)	0 (0%)	39 (100%)	2.5 (0.7–7.6)	0 (0%)	19 (100%)	2.4 (0.7–4.3)	0 (0%)	22 (100%)	3.3 (0.4–9.8)	0 (0%)	15.1	—
n-PFOS	178 (100%)	2.3 (0.5–8.4)	0 (0%)	39 (100%)	1.7 (0.5–6.6)	0 (0%)	19 (100%)	1.7 (0.5–3.3)	0 (0%)	22 (100%)	2.5 (0.3–7.2)	0 (0%)	11.0	—
Sm-PFOS	176 (99%)	0.8 (< LOD–3.3)	0 (0%)	39 (100%)	0.8 (0.2–2.5)	0 (0%)	19 (100%)	0.6 (0.2–1.8)	0 (0%)	22 (100%)	0.75 (0.1–2.6)	0 (0%)	4.6	—

Table C8 Continued. Summary of PFAS results in blood (µg/L) for Maui County employees (n = 258)

	Participant Results*												Reference Value	
	Firefighters (n = 178)			Police Department Employees (n = 39)			Ocean Safety Officers (n = 19)			Other Maui County Employees (n = 22)				
Substance	n (%) ≥ LOD	Median (Range)	n (%) ≥ RV	n (%) ≥ LOD	Median (Range)	n (%) ≥ RV	n (%) ≥ LOD	Median (Range)	n (%) ≥ RV	n (%) ≥ LOD	Median (Range)	n (%) ≥ RV	NHANES 95th percentile†	NASEM sum PFAS
PFHxS	176 (99%)	1.2 (< LOD–9.3)	7 (4%)	39 (100%)	0.9 (0.2–4.9)	2 (5%)	19 (100%)	0.9 (0.2–1.6)	0 (0%)	21 (95%)	0.95 (< LOD–2.8)	0 (0%)	3.8	—
PFDA	173 (97%)	0.2 (< LOD–0.90)	4 (2%)	38 (97%)	0.2 (LOD–0.9)	3 (8%)	16 (84%)	0.2 (< LOD–0.6)	1 (5%)	19 (86%)	0.25 (< LOD–0.7)	3 (14%)	0.6	—
PFNA	178 (100%)	0.4 (0.1–1.7)	2 (1%)	39 (100%)	0.4 (0.2–1.1)	0 (0%)	19 (100%)	0.4 (0.1–1.1)	0 (0%)	22 (100%)	0.5 (0.1–1.5)	1 (5%)	1.4	—
PFUnDA	173 (97%)	0.3 (< LOD–1.8)	11 (6%)	33 (85%)	0.2 (< LOD–1.8)	12 (31%)	18 (95%)	0.3 (< LOD–0.7)	4 (21%)	20 (91%)	0.35 (< LOD–1.30)	19 (86%)	0.4	—
MeFOSAA	6 (3%)	< LOD (< LOD–0.5)	NC	0 (0%)	< LOD (All < LOD)	NC	0 (0%)	< LOD (All < LOD)	NC	2 (9%)	< LOD (< LOD–0.4)	NC	0.6	—
NASEM sum	178 (100%)	7.0 (1.7–21.6)	1 (0.6%)	39 (100%)	5.7 (1.9–13.1)	0 (0%)	19 (100%)	5.9 (1.6–8.9)	0 (0%)	22 (100%)	6.90 (0.92–16.0)	0 (0%)	—	20

Abbreviations: LOD: limit of detection; NASEM: National Academies of Science, Engineering, and Medicine, NC: not calculated; NHANES: The National Health and Nutrition Examination Survey; PFAS: per- and polyfluoroalkyl substances; RV: reference value; µg/L: micrograms per liter

Substances: PFOA: Perfluorooctanoic acid; n-PFOA: Linear isomer of PFOA; Sb-PFOA: Sum of branched isomers of PFOA; PFOS: Perfluorooctane sulfonic acid; n-PFOS: linear isomer of PFOS; Sm-PFOS: Sum of monomethyl branched isomers of PFOS; PFHxS: Perfluorohexane sulfonic acid; PFDA: Perfluorodecanoic acid; PFNA: Perfluorononanoic acid; PFUnDA: Perfluoroundecanoic acid; MeFOSAA: 2-(n-methyl-perfluorooctane sulfonamido) acetic acid; NASEM sum: Sum of PFOA, PFOS, PFHxS, PFDA, PFNA, PFUnDA, and MeFOSAA

* For results below the LOD, we computed a value using LOD/√2 to calculate medians and geometric means. The LOD for all substances is 0.1 µg/L.

† The NHANES 95th percentiles are determined from NHANES survey years 2017–2018 for people aged ≥ 20 years.

Table C9. Summary of polybrominated diphenyl ether results in blood (ng/g lipid) for Maui County employees (n = 258)

	Participant Results*												Reference Value
	Firefighters (n = 178)			Police Department Employees (n = 39)			Ocean Safety Officers (n = 19)			Other Maui County Employees (n = 22)			
Substance	n (%) ≥ LOD	Median (Range)	n (%) ≥ RV	n (%) ≥ LOD	Median (Range)	n (%) ≥ RV	n (%) ≥ LOD	Median (Range)	n (%) ≥ RV	n (%) ≥ LOD	Median (Range)	n (%) ≥ RV	NHANES 95th percentile†
BDE-17‡	12 (7%)	< LOD (< LOD–0.54)	NC	3 (8%)	< LOD (< LOD–0.82)	NC	0 (0%)	< LOD (All < LOD)	NC	2 (10%)	< LOD (< LOD–0.92)	NC	< LOD
BDE-28	103 (58%)	0.22 (< LOD–5.0)	0 (0%)	21 (54%)	0.18 (< LOD–20.6)	1 (3%)	10 (56%)	0.30 (< LOD–2.4)	0 (0%)	16 (73%)	0.43 (< LOD–6.8)	0 (0%)	8.20
BDE-47	139 (78%)	3.6 (< LOD–85.6)	0 (0%)	25 (64%)	1.9 (< LOD–251.8)	1 (3%)	14 (74%)	3.2 (< LOD–51.6)	0 (0%)	19 (85%)	3.6 (< LOD–45.6)	0 (0%)	163
BDE-85	23 (13%)	< LOD (< LOD–0.84)	NC	6 (15%)	< LOD (< LOD–3.1)	NC	3 (16%)	< LOD (< LOD–0.88)	NC	4 (20%)	< LOD (< LOD–0.92)	NC	4.10
BDE-99	84 (47%)	0.92 (< LOD–13.76)	NC	13 (33%)	< LOD (< LOD–15.6)	NC	7 (37%)	0.85 (< LOD–8.1)	NC	10 (45%)	0.85 (< LOD–4.8)	NC	41.6
BDE-100	151 (85%)	0.77 (< LOD–11.5)	0 (0%)	30 (77%)	0.60 (< LOD–42.2)	1 (3%)	17 (89%)	0.62 (< LOD–17.2)	0 (0%)	21 (95%)	1.4 (< LOD–4.6)	0 (0%)	36.6
BDE-153	178 (100%)	10.5 (2.2–229.1)	10 (6%)	39 (100%)	6.9 (1.6–73.2)	0 (0%)	19 (100%)	13.2 (1.75–42.3)	0 (0%)	22 (100%)	9.2 (1.9–47.9)	0 (0%)	73.3
BDE-154	25 (14%)	< LOD (< LOD–0.65)	NC	7 (18%)	< LOD (< LOD–2.2)	NC	3 (16%)	< LOD (< LOD–1.2)	NC	7 (32%)	< LOD (< LOD–0.92)	NC	4.2

Table C9 Continued. Summary of polybrominated diphenyl ether results in blood (ng/g lipid) for Maui County employees (n = 258)

	Participant Results*												Reference Value
	Firefighters (n = 178)			Police Department Employees (n = 39)			Ocean Safety Officers (n = 19)			Other Maui County Employees (n = 22)			
Substance	n (%) ≥ LOD	Median (Range)	n (%) ≥ RV	n (%) ≥ LOD	Median (Range)	n (%) ≥ RV	n (%) ≥ LOD	Median (Range)	n (%) ≥ RV	n (%) ≥ LOD	Median (Range)	n (%) ≥ RV	NHANES 95th percentile†
BDE-183	20 (11%)	< LOD (< LOD–0.60)	NC	6 (15%)	< LOD (< LOD–1.3)	NC	4 (21%)	< LOD (< LOD–0.25)	NC	7 (32%)	< LOD (< LOD–0.92)	NC	< LOD
BDE-209	102 (57%)	0.92 (< LOD–7.3)	NC	15 (38%)	0.71 (< LOD–3.23)	NC	13 (68%)	0.99 (< LOD–4.3)	NC	17 (77%)	1.2 (< LOD–5.1)	NC	NC
PBB-153‡	170 (98%)	0.69 (< LOD–20.5)	0 (0%)	32 (84%)	0.51 (< LOD–3.9)	0 (0%)	19 (100%)	0.77 (0.23–23.8)	0 (0%)	19 (86%)	0.78 (< LOD–4.1)	0 (0%)	34.6

Abbreviations: LOD: limit of detection; NC: not calculated; ng/g lipid: nanograms per gram of lipid; NHANES: The National Health and Nutrition Examination Survey; RV: reference value

Substances: BDE-17: 2,2´,4- Tribromodiphenyl ether. The LOD is 0.14 ng/g; BDE-28: 2,4,4´-Tribromodiphenyl ether. The LOD is 0.14 ng/g; BDE-47: 2,2´,4,4´-Tetrabromodiphenyl ether. The LOD is 1.2 ng/g; BDE-85: 2,2´,3,4,4´-Pentabromodiphenyl ether. The LOD is 0.14 ng/g; BDE-99: 2,2´,4,4´,5-Pentabromodiphenyl ether. The LOD is 0.75 ng/g; BDE-100: 2,2´,4,4´,6-Pentabromodiphenyl ether. The LOD is 0.19 ng/g; BDE-153: 2,2´,4,4´,5,5´-Hexabromodiphenyl ether. The LOD is 0.14 ng/g; BDE-154: 2,2´,4,4´,5,6´-Hexabromodiphenyl ether. The LOD is 0.14 ng/g; BDE-183: 2,2´,3,4,4´,5´,6-Heptabromodiphenyl ether. The LOD is 0.14 ng/g; BDE-209: Decabromodiphenyl ether. The LOD is 0.71 ng/g; PBB 153: 2,2´,4,4´,5,5´-Hexabromobiphenyl. The LOD is 0.14 ng/g.

* For results below the LOD, we computed a value using LOD/√2 to calculate medians and geometric means.

† The NHANES unadjusted 95th percentiles are determined from NHANES survey years 2003–2004 for people aged ≥ 20 years.

‡ Due to interfering substances, only 257 samples were tested for BDE-17 and 254 samples were tested for PBB-153.

Table C10. Summary of organophosphate ester in urine (µg/L) (uncorrected) results for Maui County employees (n = 257)

	Participant Results†								Reference Value
	Firefighters n = 176*		Police Department Employees n = 39		Ocean Safety Officers n = 19		Other Maui County Employees n = 22		
Substance	n (%) ≥ LOD	Median (Range) n (%) ≥ RV	n (%) ≥ LOD	Median (Range) n (%) ≥ RV	n (%) ≥ LOD	Median (Range) n (%) ≥ RV	n (%) ≥ LOD	Median (Range) n (%) ≥ RV	NHANES 95th percentile‡ (µg/L) (Uncorrected)
BCEtP	134 (76%)	0.18 (< LOD–7.12) 3 (2%)	29 (74%)	0.23 (< LOD–2.82) 1 (3%)	11 (59%)	0.16 (< LOD–2.4) 0 (0%)	20 (91%)	0.31 (< LOD–1.4) 0 (0%)	2.63
BCPP	120 (70%)	0.15 (< LOD–6.26) 9 (5%)	16 (41%)	< LOD (< LOD–0.69) NC	10 (55%)	0.11 (< LOD–1.2) 1 (5%)	16 (76%)	0.17 (< LOD–3.0) 2 (9%)	1.11
BDCPP	167 (95%)	0.86 (< LOD–22.7) 5 (3%)	39 (100%)	1.4 (0.18–11.8) 4 (10%)	15 (77%)	0.49 (< LOD–7.1) 1 (5%)	22 (100%)	1.4 (0.43–13.0) 1 (5%)	6.94
DbuP	76 (43%)	< LOD (< LOD–0.92) NC	1 (<1%)	< LOD (< LOD–0.14) NC	3 (14%)	< LOD (< LOD–0.42) NC	5 (23%)	< LOD (< LOD–0.27) NC	0.86
DPhP	171 (97%)	0.72 (< LOD–9.01) 11 (6%)	29 (74%)	0.30 (< LOD–9.39) 2 (3%)	18 (95%)	0.37 (< LOD–2.5) NC	22 (100%)	0.40 (0.17–14.1) 1 (5%)	4.99

Table C10 Continued. Summary of organophosphate ester in urine (µg/L) (uncorrected) results for Maui County employees (n = 257)

Substance	Participant Results†								Reference Value
	Firefighters n = 176*		Police Department Employees n = 39		Ocean Safety Officers n = 19		Other Maui County Employees n = 22		
	n (%) ≥ LOD	Median (Range) n (%) ≥ RV	n (%) ≥ LOD	Median (Range) n (%) ≥ RV	n (%) ≥ LOD	Median (Range) n (%) ≥ RV	n (%) ≥ LOD	Median (Range) n (%) ≥ RV	NHANES 95th percentile‡ (µg/L) (Uncorrected)
TBBA	0 (0%)	< LOD (All < LOD) NC	0 (0%)	< LOD (All < LOD) NC	0 (0%)	< LOD (All < LOD) NC	0 (0%)	< LOD (All < LOD) NC	0.063
iPPPP	33 (19%)	< LOD (< LOD–0.14) NC	5 (13%)	< LOD (< LOD–0.21) NC	0 (0%)	< LOD (All < LOD) NC	5 (23%)	< LOD (< LOD–0.08) NC	0.103
tBPP	21 (12%)	< LOD (< LOD–0.06) NC	0 (0%)	< LOD (All < LOD) NC	3 (16%)	< LOD (< LOD–0.20) NC	4 (18%)	< LOD (< LOD–0.69) NC	0.1

Abbreviations: LOD: limit of detection; NC: not calculated; NHANES: The National Health and Nutrition Examination Survey; µg/L: micrograms per liter; RV: reference value

Substances: BCEtP: Bis(2-chloroethyl) phosphate is a metabolite of tris(2-chloroethyl) phosphate. LOD is 0.1 µg; BCPP: Bis(1-chloro-2-propyll) phosphate is a metabolite of tris(1-chloro-2-propyl) phosphate. LOD is 0.1 µg. n = 251 for this analyte; BDCPP: Bis(1,3-dichloro-2-propyl) phosphate is a metabolite of tris(1,3-dichloro-2-propyl) phosphate. LOD is 0.1 µg; DbuP: Di-n-butyl phosphate is a metabolite of Tributyl phosphate. LOD is 0.1 µg; DPhP: Diphenyl phosphate is a metabolite of triphenyl phosphate, isopropylphenyl triphenyl phosphate, isopropylphenyl diphenyl phosphate, t-butylphenyl diphenyl phosphate and 2-ethylhexyl diphenyl phosphate. LOD is 0.1 µg; TBBA: 2,3,4,5-tetrabromobenzoic acid is a metabolite of 2-ethylhexyl-2,3,4,5-tetrabromobenzoate. LOD is 0.05 µg; iPPPP: 2-[(isopropyl)phenyl]phenyl hydrogen phosphate is a metabolite of isopropylphenyl diphenyl phosphate. LOD is 0.05 µg; tBPPP: 4-[(tert-butyl)phenyl]phenyl hydrogen phosphate is a metabolite of tertbutylphenyl diphenyl phosphate. LOD is 0.05 µg.

* n = 172 for BCPP

† For results below the LOD, we computed a value using LOD/√2 to calculate medians and geometric means.

‡ The NHANES 95th percentiles are determined from NHANES survey years 2017–2018 for people aged ≥ 20 years.

Table C11. Summary of inorganic elements results in blood and urine for Hawaiʻi National Guard Servicemembers (n = 28)

Source†	Substance (units)	Participant Results*			Reference Value		
		n (%) ≥ RV	Median (Range)	Geometric mean (GSD)	OSHA medical removal limit	NHANES 95th percentile‡	ACGIH BEI
Blood	Cadmium (µg/L)	0 (0%)	0.17 (0.08–0.75)	0.19 (1.86)	5	—	5
	Lead (µg/dL)	0 (0%)	0.59 (0.34–1.36)	0.62 (1.42)	60	—	20
	Manganese (µg/L)	2 (7%)	10.2 (4.5–19.3)	9.86 (1.39)	—	16.0	—
	Selenium (µg/L)	4 (14%)	192 (165–281)	197.29 (1.16)	—	234	—
Urine	Total arsenic (µg/g cr)	N/A	19.6 (5.1–369)	21.61 (3.14)	—	—	—
	Inorganic-related arsenic species (µg/g cr)§	2 (8%)	9.16 (3.54–17.7)	9.13 (1.61)	—	—	15
	Chromium (µg/L)	7 (25%)	0.3 (< LOD–25.1)	0.37 (3.24)	—	—	0.7
	Nickel (µg/L)	2 (7%)	1.3 (< LOD–5.3)	1.26 (2.09)	—	3.95	—

Abbreviations: ACGIH: American Conference of Governmental Hygienists; BEI: Biological Exposure Indices; GSD: geometric standard deviation; LOD: limit of detection; N/A: not applicable; NHANES: The National Health and Nutrition Examination Survey; OSHA: Occupational Safety and Health Administration; RV: reference value; µg/dL: micrograms per deciliter; µg/g cr: micrograms per gram creatinine; µg/L: micrograms per liter

* For results below the LOD, we computed a value using LOD/√2 to calculate medians and geometric means. LOD values: cadmium: 0.065 µg/L; lead: 0.049 µg/dL; manganese: 0.52 µg/L; selenium: 9.9 µg/L; total arsenic: 0.23 µg/g cr; chromium: 0.19 µg/L; nickel: 0.31 µg/L.

† Blood and urine samples were collected as random spot samples.

‡ The NHANES 95th percentiles are determined from NHANES survey years 2017–2018 for people aged ≥ 20 years.

§ Inorganic-related arsenic species values were determined only when total arsenic values were at or above 15 µg/g cr. They were calculated as the sum of arsenous (III) acid, arsenic (V) acid, dimethylarsinic acid, and monomethylarsonic acid. For total arsenic n = 26 and for inorganic arsenic n = 14.

Table C12. Summary of PFAS results (µg/L) in blood for Hawaiʻi National Guard Servicemembers (n = 28)

Substance	Participant Results				Reference Value	
	n (%) ≥ LOD	Median* (Range)	Geometric mean (GSD)	n (%) ≥ RV	NHANES† 95th percentile	NASEM sum PFAS
PFOA	28 (100%)	1.1 (0.47–2.0)	1.03 (1.43)	0 (0%)	3.9	—
n-PFOA	28 (100%)	1.0 (0.4–1.9)	0.95 (1.48)	0 (0%)	3.8	—
Sb-PFOA	0 (0%)	< LOD (All < LOD)	0.07 (1.00)	NC	2	—
PFOS	28 (100%)	2.3 (0.57–4.3)	2.24 (1.54)	0 (0%)	15.1	—
n-PFOS	28 (100%)	1.8 (0.5–3.7)	1.74 (1.51)	0 (0%)	11.0	—
Sm-PFOS	27 (96%)	0.55 (< LOD–1.5)	0.45 (1.95)	0 (0%)	4.6	—
PFHxS	28 (100%)	0.75 (0.2–3.1)	0.72 (2.00)	0 (0%)	3.8	—
PFDA	25 (89%)	0.2 (< LOD–0.5)	0.18 (1.78)	0 (0%)	0.6	—
PFNA	28 (100%)	0.4 (0.1–0.9)	0.40 (1.64)	0 (0%)	1.4	—
PFUnDA	26 (93%)	0.25 (< LOD–1.1)	0.25 (1.98)	9 (32%)	0.4	—
MeFOSAA	0 (0%)	< LOD (All < LOD)	0.07 (1.00)	NC	0.6	—
NASEM sum	28 (100%)	5.19 (1.9–9.5)	5.12 (1.46)	0 (0%)	—	20

Abbreviations: GSD: geometric standard deviation; LOD: limit of detection; NASEM: National Academies for Science, Engineering, and Medicine; NC: not calculated; NHANES: The National Health and Nutrition Examination Survey; PFAS: per- and polyfluoroalkyl substances; RV: reference value; µg/L: micrograms per liter

Substances: PFOA: Perfluorooctanoic acid; n-PFOA: Linear isomer of PFOA; Sb-PFOA: Sum of branched isomers of PFOA; PFOS: Perfluorooctane sulfonic acid; n-PFOS: Linear isomer of PFOS; Sm-PFOS: Sum of monomethyl branched isomers of PFOS; PFHxS: Perfluorohexane sulfonic acid; PFDA: Perfluorodecanoic acid; PFNA: Perfluorononanoic acid; PFUnDA: Perfluoroundecanoic acid; MeFOSAA: 2-(n-Methyl-perfluorooctane sulfonamido) acetic acid; NASEM sum: Sum of PFOA, PFOS, PFHxS, PFDA, PFNA, PFUnDA, and MeFOSAA

* For results below the LOD, we computed a value using LOD/√2 to calculate medians and geometric means. The LOD for all substances was 0.1 µg/L.

† The NHANES 95th percentiles are determined from NHANES survey years 2017–2018 for people aged ≥ 20 years.

Table C13. Summary of polybrominated diphenyl ether results in blood (ng/g lipid) for Hawai'i National Guard Servicemembers (n = 28)

Substance	Participant Results*				Reference Value	
	n (%) ≥ LOD	Median (Range)	n (%) ≥ mean n (%) ≥ 95th percentile	Geometric mean (GSD)	NHANES mean†	NHANES 95th percentile‡
BDE-17	2 (7%)	< LOD (< LOD–0.49)	NC	0.13 (1.40)	0.13	< LOD
BDE-28	20 (71%)	0.31 (< LOD–1.3)	3 (1%) 0 (0%)	0.29 (2.02)	0.86	8.2
BDE-47	23 (82%)	2.8 (< LOD–20.9)	1 (4%) 0 (0%)	3.12 (2.32)	16.69	163
BDE-85	0 (0%)	< LOD (All < LOD)	NC	0.12 (1.23)	0.35	4.1
BDE-99	5 (18%)	< LOD (< LOD–2.7)	NC	0.77 (1.53)	3.60	41.6
BDE-100	23 (82%)	0.61 (< LOD–3.6)	NC	0.58 (2.44)	3.63	36.6
BDE-153	28 (100%)	4.6 (1.2–26.0)	6 (21%) 0 (0%)	5.35 (2.39)	12.10	73.3
BDE-154	0%	< LOD (All < LOD)	NC	0.12 (1.23)	0.31	4.2
BDE-183	5 (18%)	< LOD (< LOD–0.22)	NC	0.14 (1.28)	0.24	< LOD
BDE-209	12 (43%)	0.85 (< LOD–3.9)	NC	0.92 (1.65)	2.13	NC
PBB-153	24 (86%)	0.45 (< LOD–3.5)	2 (2%) 0 (0%)	0.57 (2.94)	2.94	34.6

Abbreviations: GSD: geometric standard deviation; LOD: limit of detection; NC: not calculated; ng/g lipid: nanograms per gram of lipid; NHANES: The National Health and Nutrition Examination Survey; RV: reference value

Substances: BDE-17: is 2,2´,4-Tribromodiphenyl ether. The LOD is 0.14 ng/g; BDE-28: is 2,4,4´-Tribromodiphenyl ether. The LOD is 0.14 ng/g; BDE-47: is 2,2´,4,4´-Tetrabromodiphenyl ether. The LOD is 1.2 ng/g; BDE-85: is 2,2´,3,4,4´-Pentabromodiphenyl ether. The LOD is 0.14 ng/g; BDE-99: is 2,2´,4,4´,5-Pentabromodiphenyl ether. The LOD is 0.75 ng/g; BDE-100: is 2,2´,4,4´,6-Pentabromodiphenyl ether. The LOD is 0.19 ng/g; BDE-153: is 2,2´,4,4´,5,5´-Hexabromodiphenyl ether. The LOD is 0.14 ng/g; BDE-154: is 2,2´,4,4´,5,6´-Hexabromodiphenyl ether. The LOD is 0.14 ng/g; BDE-183: is 2,2´,3,4,4´,5´,6-Heptabromodiphenyl ether. The LOD is 0.14 ng/g; BDE-209: is Decabromodiphenyl ether. The LOD is 0.71 ng/g; PBB 153: is 2,2´,4,4´,5,5´-Hexabromobiphenyl. The LOD is 0.14 ng/g.

* For results below the LOD, we computed a value using LOD/√2 to calculate medians and geometric means.

† The means are calculated from NHANES 2015–2016 for ≥ 20 years.

‡ The National Health and Nutrition Examination Survey (NHANES) unadjusted 95th percentiles are determined from NHANES survey years 2003–2004 for people aged ≥ 20 years.

Table C14. Summary of organophosphate ester in urine results for Hawaiʻi National Guard Service members (n = 28)

Substance	Participant Results*						Reference Value	
	n (%) ≥ LOD	Median (Range) (μg/L) (Uncorrected)	Geometric mean GSD (μg/L) (Uncorrected)	Median (Range) (μg/g cr) (Corrected)	Geometric mean (GSD) (μg/g cr) (Corrected)	n (%) ≥ RV (Uncorrected) n (%) ≥ RV (Corrected)	NHANES 95th percentile† (μg/L) (Uncorrected)	NHANES 95th percentile† (μg/g cr) (Corrected)
BCEtP	21 (75%)	0.20 (< LOD–0.8)	0.19 (2.18)	0.18 (< LOD–0.96)	0.19 (2.56)	0 (0%) 0 (0%)	2.63	2.15
BCPP	12 (43%)	< LOD (< LOD–1.5)	0.13 (2.53)	< LOD (< LOD–2.74)	0.12 (2.81)	NC	1.11	0.88
BDCPP	26 (93%)	0.67 (< LOD–10.2)	0.79 (4.06)	0.81 (< LOD–9.74)	0.92 (3.25)	1 (4%) 1 (4%)	6.94	4.48
DBuP	1 (4%)	< LOD (< LOD–0.1)	0.07 (1.11)	< LOD (< LOD–0.07)	0.07 (1.81)	NC	0.86	0.71
DPhP	26 (93%)	0.43 (< LOD–2.7)	0.44 (2.68)	0.48 (< LOD–1.60)	0.51 (1.91)	0 (0%)	4.99	4.08
TBBA	0 (0%)	< LOD (All < LOD)	< LOD (All < LOD)	< LOD (All < LOD)	< LOD (All < LOD)	NC	0.063	0.18
iPPPP	0 (0%)	< LOD (All < LOD)	< LOD (All < LOD)	< LOD (All < LOD)	< LOD (All < LOD)	NC	0.103	0.18
tBPP	0 (0%)	< LOD (All < LOD)	< LOD (All < LOD)	< LOD (All < LOD)	< LOD (All < LOD)	NC	0.1	0.19

Abbreviations: GSD: geometric standard deviation; LOD: limit of detection; NC: not calculated; NHANES: The National Health and Nutrition Examination Survey; RV: reference value; μg/L: micrograms per liter

Substances: BCEtP: Bis(2-chloroethyl) phosphate is a metabolite of tris(2-chloroethyl) phosphate. LOD is 0.1 μg; BCPP: Bis(1-chloro-2-propyll) phosphate is a metabolite of tris(1-chloro-2-propyl) phosphate. LOD is 0.1 μg; BDCPP: Bis(1,3-dichloro-2-propyl) phosphate is a metabolite of tris(1,3-dichloro-2-propyl) phosphate. LOD is 0.1 μg; DBuP: Di-n-butyl phosphate is a metabolite of Tributyl phosphate. LOD is 0.1 μg; DPhP: Diphenyl phosphate is a metabolite of triphenyl phosphate, Isopropylphenyl triphenyl phosphate, isopropylphenyl diphenyl phosphate, t-butylphenyl diphenyl phosphate and 2-ethylhexyl diphenyl phosphate. LOD is 0.1 μg/L; TBBA: 2,3,4,5-tetrabromobenzoic acid is a metabolite of 2-ethylhexyl-2,3,4,5-tetrabromobenzoate. LOD is 0.05 μg/L; iPPPP: 2-[(isopropyl)phenyl]phenyl hydrogen phosphate is a metabolite of isopropylphenyl diphenyl phosphate. LOD is 0.05 μg/L; tBPPP: 4-[(tert-butyl)phenyl]phenyl hydrogen phosphate is a metabolite of tertbutylphenyl diphenyl phosphate. LOD is 0.05 μg/L.

* For results below the LOD, we computed a value using LOD/√2 to calculate medians and geometric means.

† The NHANES 95th percentiles are determined from NHANES survey years 2017–2018 for people aged ≥ 20 years (creatinine corrected and uncorrected).

Table C15. Median **manganese** concentrations (µg/L) for **all Maui County employees** (n = 257), stratified by age, seafood consumption, time spent in the impact zone, and job category

Characteristic	Median (IQR)*	*P* value†
Age (years)		
< 25	10.4 (9.1–11.7)	0.10
≥ 25–29	9.1 (7.8–10.7)	
≥ 30–39	9.0 (7.1–10.7)	
≥ 40–49	9.0 (7.4–11.5)	
≥ 50	9.7 (7.6–12.8)	
Eaten seafood in the last 3 days		
Yes	9.2 (7.6–11.4)	0.91
No	8.7 (7.2–11.5)	
Missing	8.0 (7.7–9.1)	
Cumulative time in the impact zone during August 8–12 (hours)		
0–11	8.9 (7.0–10.8)	0.65
12–23	9.6 (7.5–12.1)	
24–35	9.7 (7.9–11.1)	
36–47	9.0 (7.4–11.5)	
48–59	9.1 (8.0–11.9)	
≥ 60	9.3 (6.9–10.2)	
Job category		
Firefighter	8.7 (7.0–10.7)	0.01
Police Department Employee	11.2 (9.1–12.7)	
Ocean Safety Officer	9.7 (7.8–11.4)	
Other Maui County Employee	9.4 (7.9–12.2)	

Abbreviations: IQR: interquartile range; µg/L: micrograms per liter

* The manganese limit of detection (LOD) is 0.52 µg/L. For results below the LOD, we computed a value using LOD/√2 to calculate medians.

† *P* value determined based on analysis of variance of log-transformed values as a continuous variable.

Table C16. Median **manganese** concentrations (µg/L) of **Maui County Firefighters (n = 177)**, stratified by age, seafood consumption, time spent in the impact zone, and job tenure as a firefighter

Characteristic	Median (IQR)*	*P* value†
Age (years)		
< 25	11.3 (9.9–12.5)	0.06
≥ 25–29	8.9 (6.6–10.3)	
≥ 30–39	8.5 (6.9–10.6)	
≥ 40–49	8.2 (7.2–10.0)	
≥ 50	8.9 (7.0–12.3)	
Eaten seafood in the last 3 days		
Yes	8.9 (7.0–10.7)	0.87
No	8.2 (7.0–10.8)	
Missing	8.0 (7.7–9.1)	
Cumulative time in the impact zone during August 8–12 (hours)		
0–11	8.7 (6.9–10.8)	0.19
12–24	9.2 (6.9–11.4)	
24–35	9.1 (7.6–10.9)	
36–48	7.8 (6.9–9.9)	
48–59	8.9 (8.0–12.6)	
≥ 60	7.8 (6.4–9.7)	
Job tenure as a Firefighter (years)		
< 5	9.0 (6.8–11.2)	0.26
5–9	8.3 (7.1–10.4)	
10–19	8.1 (6.9–9.9)	
20–29	8.8 (7.3–12.5)	
≥ 30	9.7 (9.7–9.8)	

Abbreviations: IQR: interquartile range; µg/L: micrograms per liter

* The manganese limit of detection (LOD) is 0.52 µg/L. For results below the LOD, we computed a value using LOD/√2 to calculate medians.

† *P* value determined based on analysis of variance of log-transformed values as a continuous variable.

Table C17. Median **manganese** concentrations (µg/L) of **National Guard servicemembers (n = 28)**, stratified by age, seafood consumption, and whether individuals responded to the fire on each day of interest

Characteristic	Median (IQR)*	*P* value†
Age (years)		
< 40	10.6 (9.0–11.5)	0.63
≥ 40	9.5 (7.9–12.1)	
Eaten seafood in the last 3 days		
Yes	10.6 (9.2–11.6)	0.61
No	9.6 (8.5–11.4)	
Responded on		
August 8		
No	10.6 (9.1–11.5)	0.55
Yes	9.3 (7.7–11.5)	
August 9		
No	11.3 (9.3–11.5)	0.24
Yes	9.5 (7.8–10.6)	
August 10		
No	11.1 (8.8–11.5)	0.97
Yes	9.6 (8.7–11.5)	
August 11		
No	10.2 (9.1–11.5)	0.89
Yes	10.2 (8.3–11.8)	
August 12		
No	10.9 (9.6–11.4)	0.50
Yes	9.5 (7.5–12.4)	

Abbreviations: IQR: interquartile range; µg/L: micrograms per liter

* The manganese limit of detection (LOD) is 0.52 µg/L. For results below the LOD, we computed a value using LOD/√2 to calculate medians.

† *P* value determined based on analysis of variance of log-transformed values as a continuous variable.

Table C18. Median **selenium** concentrations (µg/L) for **all Maui County employees (n = 257)**, stratified by age, seafood consumption, time spent in the impact zone, and job category

Characteristic	Median (IQR)*	*P* value†
Age (years)		
< 25	205.6 (195.8–226.7)	0.36
≥ 25–29	193.1 (183.5–213.2)	
≥ 30–39	196.8 (181.9–213.4)	
≥ 40–49	200.7 (184.8–219.8)	
≥ 50	197.5 (182.6–212.8)	
Eaten seafood in the last 3 days		
Yes	201.6 (186.8–219.9)	0.01
No	194.4 (181.8–213.0)	
Missing	171.7 (165.5–172.8)	
Cumulative time in the impact zone during August 8–12 (hours)		
< 12	199.0 (185.9–218.9)	0.07
12–23	207.3 (186.9–221.0)	
24–35	193.6 (183.9–217.5)	
36–47	200.2 (181.8–213.2)	
48–59	190.9 (181.4–205.8)	
≥ 60	189.4 (177.7–205.5)	
Job category		
Firefighter	196.5 (182.0–214.8)	0.18
Police Department Employee	203.4 (188.7–214.0)	
Ocean Safety Officer	205.9 (182.3–215.2)	
Other Maui County Employee	210.6 (192.1–224.1)	

Abbreviations: IQR: interquartile range; µg/L: micrograms per liter

* The selenium limit of detection (LOD) is 9.9 µg/L. For results below the LOD, we computed a value using LOD/√2 to calculate medians.

† *P* value determined based on analysis of variance of log-transformed values as a continuous variable.

Table C19. Median **selenium** concentrations (µg/L) for **Maui County Firefighters (n = 177)**, stratified by age, seafood consumption, time spent in the impact zone, and job tenure as a firefighter

Characteristic	Median (IQR)*	*P* value†
Age (years)		
< 25	205.6 (196.6–226.7)	0.43
≥ 25–29	189.5 (182.5–211.5)	
≥ 30–39	195.5 (179.8–210.1)	
≥ 40–49	200.3 (184.0–219.8)	
≥ 50	191.7 (179.7–210.8)	
Eaten seafood in the last 3 days		
Yes	200.3 (184.2–220.5)	0.04
No	192.9 (181.7–211.8)	
Missing	171.7 (165.5–172.8)	
Cumulative time in the impact zone during August 8–12 (hours)		
< 11	200.4 (187.8–223.5)	0.02
12–23	207.9 (185.0–222.2)	
24–35	191.9 (180.5–207.2)	
36–47	187.1 (177.0–204.4)	
48–59	183.9 (179.3–201.6)	
≥ 60	188.9 (179.0–205.3)	
Job tenure as a Firefighter (years)		
< 5	189.0 (179.9–210.1)	0.31
5–9	207.3 (185.9–229.5)	
10–19	197.0 (184.2–204.2)	
20–29	194.9 (179.1–217.1)	
≥ 30	191.1 (186.1–196.9)	

Abbreviations: IQR: interquartile range; µg/L: micrograms per liter.

* The selenium limit of detection (LOD) is 9.9 µg/L. For results below the LOD, we computed a value using LOD/√2 to calculate medians.

† *P* value determined based on analysis of variance of log-transformed values as a continuous variable.

Table C20. Median **selenium** concentrations (µg/L) for **National Guard servicemembers (n = 28)**, stratified by age, seafood consumption, and whether individuals responded to the fire on each day of interest

Characteristic	Median (IQR)*	*P* value†
Age (years)		
< 40	189.1 (176.9–196.9)	0.17
≥ 40	210.8 (183.6–232.3)	
Eaten seafood in the last 3 days		
Yes	192.9 (173.9–212.5)	0.74
No	189.1 (180.1–204.1)	
Responded on		
August 8		
No	191.0 (176.1–212.9)	0.88
Yes	194.0 (186.4–206.5)	
August 9		
No	192.9 (177.2–207.8)	0.59
Yes	191.0 (184.5–210.8)	
August 10		
No	191.7 (184.5–198.5)	0.96
Yes	191.9 (176.5–212.9)	
August 11		
No	191.7 (187.3–201.6)	0.90
Yes	191.9 (174.8–212.1)	
August 12		
No	192.9 (188.0–203.2)	0.86
Yes	191.0 (172.8–211.6)	

Abbreviations: IQR: interquartile range; µg/L: micrograms per liter

* The selenium limit of detection (LOD) is 9.9 µg/L. For results below the LOD, we computed a value using LOD/√2 to calculate medians.

† *P* value determined based on analysis of variance of log-transformed values as a continuous variable.

Table C21. Median **inorganic-related arsenic species** concentrations (µg/g creatinine) for **all Maui County Employees** (n = 244) below and above the ACGIH BEI of 15 µg/g creatinine, stratified by age, seafood consumption, time spent in the impact zone, and job category

Characteristic	Below n (%)	Above n (%)	*P* value*	Median (IQR)†	*P* value‡
Age (years)					
< 25	11 (100%)	0 (0%)	0.14	7.7 (5.2–9.9)	0.04
≥ 25–29	22 (100%)	0 (0%)		7.8 (5.2–8.6)	
≥ 30–39	78 (90%)	9 (10%)		9.1 (5.8–14.3)	
≥ 40–49	67 (93%)	5 (7%)		7.8 (6.0–11.2)	
≥ 50	43 (83%)	9 (17%)		11.2 (7.6–15.1)	
Eaten seafood in the last 3 days					
Yes	134 (88%)	19 (12%)	0.02	9.2 (6.4–13.2)	0.07
No	85 (97%)	3 (3%)		7.7 (5.3–9.5)	
Missing	2 (67%)	1 (33%)		14.4 (11.5–18.1)	
Cumulative time in the impact zone during August 8–12 (hours)					
< 12	64 (91%)	6 (9%)	0.94	8.0 (5.9–10.1)	0.69
12–23	48 (92%)	4 (8%)		10.4 (7.0–12.6)	
24–35	41 (91%)	4 (9%)		8.6 (5.2–12.3)	
36–47	27 (90%)	3 (10%)		9.0 (6.4–13.8)	
48–59	22 (88%)	3 (12%)		13.2 (5.4–15.2)	
≥ 60	19 (87%)	3 (13%)		8.4 (6.3–11.8)	
Job category					
Firefighter	151 (90%)	16 (10%)	0.09	8.4 (5.8–12.5)	0.21
Police Department Employee	34 (94%)	2 (6%)		10.9 (6.0–12.5)	
Ocean Safety Officer	19 (100%)	0 (0%)		8.5 (6.9–9.7)	
Other Maui County Employee	17 (77%)	5 (23%)		10.4 (7.1–15.9)	

Abbreviations: ACGIH: American Conference of Governmental Industrial Hygienists; BEI: Biological Exposure Indices; IQR: interquartile range; µg/g creatinine: micrograms per gram creatinine

* *P* value determined by Fisher's exact test.

† The total arsenic limit of detection (LOD) is 0.23 micrograms per liter. For results below the LOD, we computed a value using LOD/√2 to calculate medians. The Above/Below analysis has an n of the whole sample but the median of inorganic arsenic has an n of only the participants who had inorganic arsenic testing performed.

‡ *P* value determined based on analysis of variance of log-transformed values as a continuous variable.

Table C22. Median **inorganic-related arsenic species** concentrations (µg/g creatinine) for **Maui County Firefighters** (n = 167) below and above the ACGIH BEI of 15 µg/g creatinine, stratified by age, seafood consumption, time spent in the impact zone, and job tenure as a firefighter

Characteristic	Below n (%)	Above n (%)	*P* value*	Median (IQR)†	*P* value‡
Age (years)					
< 25	7 (100%)	0 (0%)	0.29	7.7 (5.9–9.7)	0.10
≥ 25–29	15 (100%)	0 (0%)		6.9 (5.1–8.1)	
≥ 30–39	54 (89%)	7 (11%)		9.1 (5.7–14.6)	
≥ 40–49	47 (94%)	3 (7%)		7.8 (6.1–11.2)	
≥ 50	28 (82%)	6 (18%)		10.3 (7.3–15.6)	
Eaten seafood in the last 3 days					
Yes	97 (88%)	13 (12%)	0.08	8.4 (6.2–12.5)	0.18
No	52 (96%)	2 (4%)		7.6 (5.4–8.7)	
Missing	2 (67%)	1 (33%)		14.4 (11.5–18.1)	
Cumulative time in the impact zone during August 8–12 (hours)					
0–11	43 (90%)	5 (10%)	0.69	7.8 (5.8–11.9)	0.82
12–23	31 (94%)	2 (6%)		10.8 (7.9–12.6)	
24–35	32 (91%)	3 (9%)		8.3 (5.2–12.0)	
36–47	20 (95%)	1 (5%)		8.4 (6.0–11.0)	
48–59	12 (86%)	2 (14%)		6.1 (4.6–14.6)	
≥ 60	13 (81%)	3 (19%)		8.4 (5.8–10.5)	
Job tenure as a Firefighter (years)					
< 5	44 (92%)	4 (8%)	0.64	7.9 (5.5–9.9)	0.73
5–9	31 (92%)	3 (8%)		8.4 (5.9–12.3)	
10–19	38 (90%)	4 (10%)		8.4 (5.3–13.5)	
20–29	36 (90%)	4 (10%)		8.4 (7.0–12.6)	
≥ 30	2 (67%)	1 (33%)		9.9 (7.8–12.7)	

Abbreviations: ACGIH: American Conference of Governmental Industrial Hygienists; BEI: Biological Exposure Indices; IQR: interquartile range; µg/g creatinine: micrograms per gram creatinine

* *P* value determined by Fisher's exact test.

† The total arsenic limit of detection (LOD) is 0.23 micrograms per liter. For results below the LOD, we computed a value using LOD/√2 to calculate medians. The Above/Below analysis has an n of the whole sample but the median of inorganic arsenic has an n of only the participants who had inorganic arsenic testing performed.

‡ *P* value determined based on analysis of variance of log-transformed values as a continuous variable.

Table C23. Median **inorganic-related arsenic species** concentrations (µg/g creatinine) for **National Guard servicemembers** (n = 16) below and above the ACGIH BEI of 15 µg/g creatinine, stratified by age, seafood consumption, and whether individuals responded to the fire on each day of interest

Characteristic	Below n (%)	Above n (%)	*P* value*	Median (IQR)†	*P* value‡
Age (years)					
< 40	15 (100%)	0 (0%)	0.17	8.7 (7.8–10.3)	0.89
≥ 40	9 (82%)	2 (18%)		11.3 (5.6–16.5)	
Eaten seafood in the last 3 days					
Yes	11 (92%)	1 (8%)	1.0	9.4 (7.8–12.9)	0.92
No	13 (93%)	1 (7%)		9.0 (5.7–13.4)	
Responded on:					
August 8					
No	16 (89%)	2 (11%)	1.0	8.6 (6.1–13.9)	0.75
Yes	8 (100%)	0 (0%)		9.2 (8.7–10.2)	
August 9					
No	12 (92%)	1 (8%)	1.0	7.8 (5.4–10.5)	0.17
Yes	12 (92%)	1 (8%)		11.0 (9.1–13.3)	
August 10					
No	6 (100%)	0 (0%)	1.0	6.8 (5.0–8.4)	0.06
Yes	18 (90%)	2 (10%)		11.0 (8.1–14.0)	
August 11					
No	8 (100%)	0 (0%)	1.0	7.6 (5.7–8.1)	0.04
Yes	16 (89%)	2 (11%)		12.9 (9.0–14.2)	
August 12					
No	9 (100%)	0 (0%)	0.53	6.6 (5.4–7.7)	0.07
Yes	15 (88%)	2 (12%)		11.1 (9.1–14.0)	

Abbreviations: ACGIH: American Conference of Governmental Industrial Hygienists; BEI: Biological Exposure Indices; IQR: interquartile range; µg/g: micrograms per gram creatinine

* *P* value determined by Fisher's exact test.

† The total arsenic limit of detection (LOD) is 0.23 micrograms per liter. For results below the LOD, we computed a value using LOD/√2 to calculate medians. The Above/Below analysis has an n of the whole sample but the median of inorganic arsenic has an n of only the participants who had inorganic arsenic testing performed.

‡ *P* value determined based on analysis of variance of log-transformed values as a continuous variable.

Table C24. Proportion of **Maui County Employees** (n = 256) below and above the ACGIH BEI of 0.7 µg/L for **chromium***, stratified by age, seafood consumption, time spent in the impact zone, and job category

Characteristic	Below n (%)	Above n (%)	*P* value†
Age (years)			
< 25	11 (100%)	0 (0%)	0.17
≥ 25–29	20 (87%)	3 (13%)	
≥ 30–39	89 (96%)	4 (4%)	
≥ 40–49	75 (97%)	2 (3%)	
≥ 50	47 (90%)	5 (10%)	
Eaten seafood in the last 3 days			
Yes	151 (94%)	10 (6%)	0.75
No	88 (96%)	4 (4%)	
Missing	3 (100%)	0 (0%)	
Cumulative time in the impact zone during August 8–12 (hours)			
0–11	70 (97%)	2 (3%)	0.04
12–23	53 (96%)	2 (4%)	
24–35	40 (83%)	8 (17%)	
36–47	30 (97%)	1 (3%)	
48–59	26 (96%)	1 (4%)	
≥ 60	23 (100%)	0 (0%)	
Job category			
Firefighter	168 (95%)	8 (5%)	0.01
Police Department Employee	38 (97%)	1 (3%)	
Ocean Safety Officer	19 (100%)	0 (0%)	
Other Maui County Employee	17 (77%)	5 (23%)	

Abbreviations: ACGIH: American Conference of Governmental Industrial Hygienists; BEI: Biological Exposure Indices; µg/L: micrograms per liter

* The chromium limit of detection (LOD) is 0.19 µg/L. For results below the LOD, we computed a value using LOD/√2 to calculate medians.

† *P* value determined by Fisher's exact test.

Table C25. Proportion of **Maui County Firefighters** (n = 176) below and above the ACGIH BEI of 0.7 µg/L for **chromium***, stratified by age, seafood consumption, time spent in the impact zone, and job tenure as a firefighter

Characteristic	Below n (%)	Above n (%)	*P* value†
Age (years)			
< 25	7 (100%)	0 (0%)	0.60
≥ 25–29	15 (94%)	1 (6%)	
≥ 30–39	63 (95%)	3 (5%)	
≥ 40–49	52 (98%)	1 (2%)	
≥ 50	31 (91%)	3 (9%)	
Eaten seafood in the last 3 days			
Yes	108 (94%)	7 (6%)	0.40
No	57 (98%)	1 (2%)	
Missing	3 (100%)	0 (0%)	
Cumulative time in the impact zone during August 8–12 (hours)			
0–11	49 (98%)	1 (2%)	0.08
12–23	36 (100%)	0 (0%)	
24–35	33 (87%)	5 (13%)	
36–47	20 (95%)	1 (5%)	
48–59	14 (93%)	1 (7%)	
≥ 60	16 (100%)	0 (0%)	
Job tenure as a Firefighter (years)			
< 5	47 (92%)	4 (8%)	0.53
5–9	36 (100%)	0 (0%)	
10–19	44 (96%)	2 (4%)	
20–29	38 (95%)	2 (5%)	
≥ 30	3 (100%)	0 (0%)	

Abbreviations: ACGIH: American Conference of Governmental Industrial Hygienists; BEI: Biological Exposure Indices; µg/L: micrograms per liter

* The chromium limit of detection (LOD) is 0.19 µg/L. For results below the LOD, we computed a value using LOD/√2 to calculate medians.

† *P* value determined by Fisher's exact test.

Table C26. Proportion of **National Guard servicemembers (n = 28)** below and above the ACGIH BEI of 0.7 µg/L for **chromium***, stratified by age, seafood consumption, and whether individuals responded to the fire on each day of interest

Characteristic	Below n (%)	Above n (%)	*P* value†
Age (years)			
< 40	14 (82%)	3 (18%)	0.50
≥ 40	7 (64%)	4 (36%)	
Eaten seafood in the last 3 days			
Yes	11 (85%)	2 (15%)	0.512
No	13 (87%)	2 (13%)	
Responded on:			
August 8			
No	16 (80%)	4 (20%)	0.63
Yes	5 (63%)	3 (38%)	
August 9			
No	13 (87%)	2 (13%)	0.27
Yes	8 (62%)	5 (38%)	
August 10			
No	5 (63%)	3 (38%)	0.63
Yes	16 (80%)	4 (20%)	
August 11			
No	7 (70%)	3 (30%)	1
Yes	14 (78%)	4 (22%)	
August 12			
No	6 (67%)	3 (33%)	0.82
Yes	15 (79%)	4 (21%)	

Abbreviations: ACGIH: American Conference of Governmental Industrial Hygienists; BEI: Biological Exposure Indices; µg/L: micrograms per liter

* The chromium limit of detection (LOD) is 0.19 µg/L. For results below the LOD, we computed a value using LOD/√2 to calculate medians. The total percentage below and above the ACGIH BEI of 0.7 µg/L for chromium may not add to 100% because of rounding.

† *P* value determined by Fisher's exact test.

Table C27. Median **nickel** concentrations (µg/L) for **all Maui County employees (n = 256)**, stratified by age, seafood consumption, time spent in the impact zone, and job category

Characteristic	Median (IQR)*	*P* value†
Age (years)		
< 25	1.1 (0.8–1.3)	0.48
≥ 25–29	1.0 (0.5–1.5)	
≥ 30–39	1.1 (0.7–1.5)	
≥ 40–49	1.1 (0.7–1.7)	
≥ 50	1.4 (0.7–2.1)	
Eaten seafood in the last 3 days		
Yes	1.2 (0.7–1.6)	0.41
No	1.1 (0.7–1.6)	
Missing	0.4 (0.3–0.9)	
Cumulative time in the impact zone during August 8–12 (hours)		
0–11	1.0 (0.6–1.4)	0.27
12–23	1.3 (0.9–1.7)	
24–35	1.2 (0.7–1.7)	
36–47	1.2 (0.5–1.8)	
48–59	1.2 (0.6–1.6)	
≥ 60	1.0 (0.6–1.2)	
Job category		
Firefighter	1.1 (0.7–1.6)	0.52
Police Department Employee	1.3 (0.8–1.5)	
Other Maui County Employee	1.3 (1.0–1.7)	
Ocean Safety Officer	0.9 (0.5–1.2)	

Abbreviations: IQR: interquartile range; µg/L: micrograms per liter

* The nickel limit of detection (LOD) is 0.31 µg/L. For results below the LOD, we computed a value using LOD/√2 to calculate medians.

† *P* value determined based on analysis of variance of log-transformed values as a continuous variable.

Table C28. Median **nickel** concentrations (µg/L) for **Maui County Firefighters (n = 176)**, stratified by age, seafood consumption, time spent in the impact zone, and job tenure as a firefighter

Characteristic	Median (IQR)*	*P* value†
Age (years)		
< 25	0.8 (0.7–1.3)	0.79
≥ 25–29	1.0 (0.6–1.6)	
≥ 30–39	1.1 (0.7–1.5)	
≥ 40–49	1.0 (0.7–1.6)	
≥ 50	1.4 (0.7–2.1)	
Eaten seafood in the last 3 days		
Yes	1.2 (0.7–1.6)	0.43
No	1.0 (0.7–1.4)	
Missing	0.4 (0.3–0.9)	
Cumulative time in the impact zone during August 8–12 (hours)		
0–11	0.9 (0.6–1.6)	0.64
12–23	1.3 (0.9–1.6)	
24–35	1.0 (0.6–2.0)	
36–47	1.2 (0.8–1.7)	
48–59	1.1 (0.6–1.5)	
≥ 60	0.9 (0.6–1.1)	
Job tenure as a Firefighter (years)		
< 5	1.0 (0.6–1.6)	0.79
5–9	1.1 (0.5–1.6)	
10–19	1.0 (0.7–1.5)	
20–29	1.2 (0.7–2.0)	
≥ 30	0.8 (0.8–1.6)	

Abbreviations: IQR: interquartile range; µg/L: micrograms per liter

* The nickel limit of detection (LOD) is 0.31 µg/L. For results below the LOD, we computed a value using LOD/√2 to calculate medians.

† *P* value determined based on analysis of variance of log-transformed values as a continuous variable.

Table C29. Median **nickel** concentrations (µg/L) for **National Guard servicemembers (n = 28)**, stratified by age, seafood consumption, and whether individuals responded to the fire on each day of interest

Characteristic	Median (IQR)*	*P* value†
Age (years)		
< 40	1.0 (0.8–1.9)	0.07
≥ 40	1.6 (1.1–2.6)	
Eaten seafood in the last 3 days		
Yes	1.0 (0.8–1.4)	0.34
No	1.6 (1.1–2.2)	
Responded on:		
August 8		
No	1.2 (0.8–2.3)	0.79
Yes	1.4 (1.0–1.7)	
August 9		
No	1.2 (0.8–2.1)	0.61
Yes	1.4 (1.0–2.2)	
August 10		
No	0.8 (0.5–1.1)	0.01
Yes	1.5 (1.0–2.3)	
August 11		
No	0.9 (0.6–1.2)	0.01
Yes	1.6 (1.1–2.3)	
August 12		
No	1.2 (0.9–1.5)	0.95
Yes	1.4 (0.9–2.2)	

Abbreviations: IQR: interquartile range; µg/L: micrograms per liter

* The nickel limit of detection (LOD) is 0.31 µg/L. For results below the LOD, we computed a value using LOD/√2 to calculate medians.

† *P* value determined based on analysis of variance of log-transformed values as a continuous variable.

Table C30. Median **per- and polyfluoroalkyl substances (PFAS)** concentrations (µg/L) for **all Maui County Employees (n = 258)**, stratified by age, seafood consumption, time spent in the impact zone, and job category

Characteristic	N	PFDA Median* (IQR)	*P* value†	PFNA Median* (IQR)	*P* value†	PFHxS Median* (IQR)	*P* value†	PFUnDA Median* (IQR)	*P* value†	PFOS Median* (IQR)	*P* value†	PFOA Median* (IQR)	*P* value†
Age (years)													
< 25	11	0.2 (0.1–0.4)	0.53	0.4 (0.2–0.6)	0.06	0.8 (0.6–0.9)	0.22	0.4 (0.2–0.5)	0.14	2.3 (1.5–3.2)	< 0.01	1.1 (0.9–1.5)	0.33
≥ 25–29	23	0.2 (0.1–0.3)		0.4 (0.3–0.5)		0.8 (0.7–1.4)		0.3 (0.2–0.4)		2.5 (2.3–3.3)		1.4 (1.0–1.5)	
≥ 30–39	94	0.2 (0.2–0.3)		0.4 (0.3–0.5)		1.0 (0.7–1.5)		0.3 (0.2–0.4)		2.8 (2.2–3.4)		1.2 (0.9–1.5)	
≥ 40–49	78	0.2 (0.2–0.4)		0.4 (0.4–0.7)		1.2 (0.7–1.6)		0.3 (0.2–0.5)		3.7 (2.4–4.5)		1.2 (1.0–1.8)	
≥ 50	52	0.2 (0.2–0.3)		0.5 (0.3–0.7)		1.2 (0.8–1.8)		0.3 (0.2–0.5)		3.5 (2.7–5.5)		1.4 (1.0–2.1)	
Eaten seafood in the last 3 days													
Yes	162	0.2 (0.2–0.3)	< 0.01	0.5 (0.4–0.7)	0.01	1.0 (0.7–1.5)	0.43	0.3 (0.2–0.5)	< 0.01	3.1 (2.3–4.3)	0.86	1.3 (1.0–1.6)	0.50
No	93	0.2 (0.1–0.3)		0.4 (0.3–0.5)		1.2 (0.7–1.6)		0.2 (0.1–0.4)		2.9 (2.3–4.3)		1.2 (0.9–1.6)	
Missing	3	0.2 (0.1–0.3)		0.6 (0.4–0.6)		1.9 (1.3–1.9)		0.1 (0.1–0.3)		3.5 (3.1–3.9)		1.0 (0.9–1.6)	
Cumulative time in the impact zone during August 8–12 (hours)													
0–11	74	0.2 (0.1–0.3)	0.46	0.4 (0.3–0.6)	0.45	1.0 (0.7–1.4)	0.12	0.3 (0.2–0.5)	0.76	2.8 (2.2–4.1)	0.28	1.2 (0.9–1.5)	0.29
12–23	55	0.2 (0.2–0.3)		0.5 (0.4–0.7)		1.1 (0.8–1.4)		0.3 (0.2–0.4)		3.2 (2.7–4.6)		1.3 (1.0–1.7)	

Table C30 Continued. Median **per- and polyfluoroalkyl substances (PFAS)** concentrations (µg/L) for **all Maui County Employees (n = 258)**, stratified by age, seafood consumption, time spent in the impact zone, and job category

Characteristic	N	PFDA Median* (IQR)	*P* value†	PFNA Median* (IQR)	*P* value†	PFHxS Median* (IQR)	*P* value†	PFUnDA Median* (IQR)	*P* value†	PFOS Median* (IQR)	*P* value†	PFOA Median* (IQR)	*P* value†
Cumulative time in the impact zone during August 8–12 (hours) continued													
24–35	48	0.2 (0.2–0.3)		0.4 (0.3–0.5)		1.3 (0.8–1.7)		0.3 (0.2–0.4)		2.9 (2.3–4.2)		1.3 (0.9–1.6)	
36–47	31	0.2 (0.2–0.3)		0.4 (0.4–0.5)		1.3 (0.7–1.7)		0.3 (0.2–0.5)		3.3 (2.3–5.0)		1.3 (1.0–1.8)	
48–59	27	0.2 (0.2–0.3)		0.4 (0.4–0.5)		0.9 (0.6–1.2)		0.3 (0.2–0.4)		2.8 (2.1–3.7)		1.3 (1.1–1.6)	
≥ 60	23	0.2 (0.1–0.3)		0.5 (0.4–0.6)		1.0 (0.8–1.7)		0.3 (0.1–0.5)		3.0 (2.3–4.2)		1.2 (0.9–1.6)	
Job category													
Firefighter	178	0.2 (0.2–0.3)	0.43	0.4 (0.3–0.6)	0.19	1.2 (0.8–1.7)	< 0.01	0.3 (0.2–0.5)	0.11	3.1 (2.4–4.5)	0.01	1.3 (1.0–1.7)	0.14
Police Department Employee	39	0.2 (0.1–0.3)		0.4 (0.3–0.5)		0.9 (0.5–1.2)		0.2 (0.1–0.4)		2.5 (1.9–3.8)		1.1 (0.9–1.5)	
Ocean Safety Officer	19	0.2 (0.1–0.3)		0.4 (0.2–0.5)		0.9 (0.8–1.2)		0.3 (0.2–0.5)		2.4 (1.7–3.3)		1.3 (0.9–1.5)	
Other Maui County Employee	22	0.2 (0.2–0.4)		0.5 (0.4–0.9)		0.9 (0.6–1.1)		0.3 (0.2–0.7)		3.3 (2.2–5.0)		1.0 (0.8–1.8)	

Abbreviations: IQR: interquartile range; PFDA: Perfluorodecanoic acid; PFHxS: Perfluorohexane sulfonic acid; PFNA: Perfluorononanoic acid; PFOA: Perfluorooctanoic acid; PFOS: Perfluorooctane sulfonic acid; PFUnDA: Perfluoroundecanoic acid; µg/L: micrograms per liter

* For results below the limit of detection (LOD), we computed a value using LOD/√2 to calculate medians.

† *P* value determined based on analysis of variance of log-transformed values as a continuous variable.

Table C31. Median **per- and polyfluoroalkyl substances (PFAS)** concentrations (µg/L) for **all Maui County Firefighters (n = 178)**, stratified by age, seafood consumption, time spent in the impact zone, and job tenure as a firefighter

Characteristic	N	PFDA Median* (IQR)	*P* value†	PFNA Median* (IQR)	*P* value†	PFHxS Median* (IQR)	*P* value†	PFUnDA Median* (IQR)	*P* value†	PFOS Median* (IQR)	*P* value†	PFOA Median* (IQR)	*P* value†
Age (years)													
< 25	7	0.4 (0.2–0.5)	0.27	0.6 (0.4–0.8)	0.06	0.8 (0.7–0.8)	0.09	0.4 (0.3–0.6)	0.16	3.1 (2.3–3.3)	< 0.01	1.5 (1.2–1.6)	0.04
≥ 25–29	16	0.2 (0.2–0.3)		0.4 (0.3–0.5)		0.8 (0.7–1.5)		0.3 (0.2–0.4)		2.5 (2.4–3.2)		1.4 (1.0–1.6)	
≥ 30–39	67	0.2 (0.2–0.3)		0.4 (0.3–0.5)		1.0 (0.7–1.5)		0.3 (0.2–0.5)		2.8 (2.2–3.5)		1.2 (0.9–1.4)	
≥ 40–49	54	0.2 (0.2–0.4)		0.4 (0.4–0.7)		1.3 (1.0–1.7)		0.3 (0.2–0.5)		3.8 (2.7–4.7)		1.2 (1.0–1.8)	
≥ 50	34	0.2 (0.2–0.3)		0.5 (0.3–0.7)		1.6 (1.1–1.9)		0.3 (0.2–0.4)		3.8 (2.9–5.6)		1.6 (1.3–2.1)	
Eaten seafood in the last 3 days													
Yes	116	0.2 (0.2–0.3)	0.01	0.5 (0.4–0.7)	< 0.01	1.2 (0.8–1.7)	0.81	0.3 (0.3–0.5)	< 0.01	3.2 (2.5–4.6)	0.49	1.3 (1.1–1.7)	0.44
No	59	0.2 (0.1–0.3)		0.4 (0.3–0.5)		1.2 (0.7–1.7)		0.2 (0.2–0.3)		2.9 (2.4–4.2)		1.2 (0.9–1.6)	
Missing	3	0.2 (0.1–0.3)		0.6 (0.4–0.6)		1.9 (1.3–1.9)		0.1 (0.1–0.3)		3.5 (3.1–3.9)		1.0 (0.9–1.6)	
Cumulative time in the impact zone during August 8–12 (hours)													
0–11	52	0.2 (0.2–0.3)	0.31	0.4 (0.3–0.6)	0.70	1.0 (0.7–1.6)	0.40	0.3 (0.2–0.4)	0.20	3.0 (2.4–4.3)	0.92	1.3 (0.1–1.7)	0.70
12–23	36	0.2 (0.2–0.3)		0.5 (0.4–0.7)		1.1 (0.8–1.6)		0.3 (0.2–0.4)		3.1 (2.7–4.4)		1.3 (1.0–1.6)	

Table C31 Continued. Median **per- and polyfluoroalkyl substances (PFAS)** concentrations (µg/L) for **all Maui County Firefighters (n = 178)**, stratified by age, seafood consumption, time spent in the impact zone, and job tenure as a firefighter

Characteristic	N	PFDA Median* (IQR)	*P* value†	PFNA Median* (IQR)	*P* value†	PFHxS Median* (IQR)	*P* value†	PFUnDA Median* (IQR)	*P* value†	PFOS Median* (IQR)	*P* value†	PFOA Median* (IQR)	*P* value†
Cumulative time in the impact zone during August 8–12 (hours) continued													
24–35	38	0.2 (0.2–0.3)		0.4 (0.3–0.5)		1.3 (0.9–1.7)		0.3 (0.2–0.4)		3.0 (2.4–4.3)		1.3 (1.0–1.5)	
36–47	21	0.2 (0.2–0.3)		0.5 (0.4–0.6)		1.5 (0.9–1.8)		0.3 (0.2–0.5)		3.7 (2.5–4.7)		1.3 (1.0–1.9)	
48–59	15	0.2 (0.2–0.3)		0.4 (0.4–0.4)		1.1 (0.6–1.6)		0.3 (0.2–0.4)		2.9 (2.4–4.2)		1.4 (1.2–1.6)	
≥ 60	16	0.3 (0.2–0.4)		0.5 (0.4–0.6)		1.0 (0.8–1.7)		0.4 (0.3–0.6)		3.6 (2.4–4.3)		1.3 (1.0–1.6)	
Job tenure as a Firefighter (firefighters only; years)													
<5	51	0.2 (0.2–0.3)	0.39	0.4 (0.3–0.5)	0.04	0.8 (0.6–1.4)	0.01	0.3 (0.2–0.4)	0.23	2.5 (2.2–3.1)	< 0. 01	1.0 (1.0–1.0)	0.03
5–9	37	0.3 (0.2–0.4)		0.5 (0.4–0.6)		1.1 (0.8–1.7)		0.4 (0.2–0.5)		3.3 (2.5–4.5)		1.2 (1.0–1.5)	
10–19	47	0.2 (0.2–0.3)		0.4 (0.4–0.6)		1.3 (1.0–1.8)		0.3 (0.2–0.4)		3.3 (2.7–4.6)		1.2 (0.9–1.5)	
20–29	40	0.2 (0.1–0.3)		0.5 (0.3–0.7)		1.4 (1.1–1.8)		0.3 (0.2–0.4)		3.9 (2.8–4.8)		1.0 (0.8–1.3)	
≥ 30	3	0.3 (0.3–0.3)		0.6 (0.5–0.8)		2.6 (1.7–2.7)		0.5 (0.4–0.5)		7.2 (5.0–8.9)		1.1 (0.7–2.0)	

Abbreviations: IQR: interquartile range; PFDA: Perfluorodecanoic acid; PFHxS: Perfluorohexane sulfonic acid; PFNA: Perfluorononanoic acid; PFOA: Perfluorooctanoic acid; PFOS: Perfluorooctane sulfonic acid; PFUnDA: Perfluoroundecanoic acid; µg/L: micrograms per liter

* For results below the limit of detection (LOD), we computed a value using LOD/√2 to calculate medians.

† *P* value determined based on analysis of variance of log-transformed values as a continuous variable.

Table C32. Median **per- and polyfluoroalkyl substances (PFAS)** concentrations (µg/L) for **all National Guard servicemembers (n = 28)**, stratified by age, seafood consumption, and whether individuals responded to the fire on each day of interest

Characteristic	N	PFDA Median* (IQR)	*P* value†	PFNA Median* (IQR)	*P* value†	PFHxS Median* (IQR)	*P* value†	PFUnDA Median* (IQR)	*P* value†	PFOS Median* (IQR)	*P* value†	PFOA Median* (IQR)	*P* value†
Age (years)													
< 40 years	17	0.2 (0.2–0.3)	0.32	0.4 (0.3–0.6)	0.53	0.6 (0.4–0.9)	0.24	0.3 (0.2–0.4)	0.27	2.3 (1.7–2.5)	0.35	1.0 (0.9–1.3)	0.39
≥ 40 years	11	0.1 (0.1–0.3)		0.4 (0.2–0.6)		0.8 (0.5–1.3)		0.2 (0.1–0.4)		2.8 (2.0–3.5)		1.2 (0.8–1.4)	
Eaten seafood in the last 3 days													
Yes	13	0.2 (0.1–0.2)	0.58	0.4 (0.3–0.6)	0.60	0.6 (0.4–0.9)	0.22	0.2 (0.2–0.3)	0.97	2.3 (1.7–2.6)	0.68	1.1 (0.7–1.3)	0.25
No	15	0.2 (0.1–0.3)		0.4 (0.3–0.5)		0.8 (0.5–1.4)		0.3 (0.1–0.5)		2.5 (1.8–3.2)		1.1 (0.9–1.4)	
Responded on:													
August 8													
No	20	0.2 (0.1–0.3)	0.27	0.3 (0.3–0.4)	0.10	0.5 (0.4–1.0)	0.13	0.2 (0.2–0.4)	0.22	2.0 (1.7–2.5)	0.03	1.0 (0.7–1.3)	0.22
Yes	8	0.2 (0.2–0.3)		0.6 (0.4–0.6)		0.8 (0.7–1.3)		0.3 (0.2–0.5)		3.1 (2.5–3.7)		1.2 (1.0–1.4)	
August 9													
No	15	0.2 (0.1–0.2)	0.16	0.3 (0.3–0.4)	0.52	0.5 (0.3–0.8)	0.02	0.2 (0.1–0.3)	0.24	2.3 (1.7–2.6)	0.13	1.0 (0.7–1.1)	0.03
Yes	13	0.2 (0.2–0.3)		0.4 (0.4–0.6)		0.9 (0.7–1.4)		0.3 (0.2–0.5)		2.6 (1.8–3.4)		1.3 (1.1–1.4)	

Table C32 Continued. Median **per- and polyfluoroalkyl substances (PFAS)** concentrations (µg/L) for **all National Guard servicemembers (n = 28)**, stratified by age, seafood consumption, and whether individuals responded to the fire on each day of interest

Characteristic	N	PFDA Median* (IQR)	*P* value†	PFNA Median* (IQR)	*P* value†	PFHxS Median* (IQR)	*P* value†	PFUnDA Median* (IQR)	*P* value†	PFOS Median* (IQR)	*P* value†	PFOA Median* (IQR)	*P* value†
August 10													
No	8	0.2 (0.1–0.3)	0.97	0.3 (0.3–0.5)	0.88	0.6 (0.4–0.9)	0.78	0.2 (0.2–0.4)	0.85	1.9 (1.8–2.3)	0.23	1.0 (0.7–1.1)	0.69
Yes	20	0.2 (0.1–0.3)		0.4 (0.3–0.6)		0.7 (0.5–1.3)		0.2 (0.2–0.4)		2.7 (1.7–3.4)		1.1 (0.9–1.4)	
August 11													
No	10	0.2 (0.1–0.3)	0.85	0.3 (0.3–0.5)	0.73	0.5 (0.3–0.9)	0.34	0.2 (0.2–0.4)	0.86	1.8 (1.6–2.2)	0.07	1.0 (0.7–1.1)	0.20
Yes	18	0.2 (0.1–0.3)		0.4 (0.3–0.6)		0.8 (0.5–1.3)		0.2 (0.2–0.5)		2.8 (2.1–3.4)		1.1 (1.0–1.4)	
August 12													
No	9	0.2 (0.2–0.3)	0.28	0.4 (0.3–0.5)	0.62	0.5 (0.5–0.8)	0.70	0.3 (0.2–0.4)	0.57	2.3 (1.7–2.3)	0.46	1.0 (0.7–1.1)	0.32
Yes	19	0.2 (0.1–0.3)		0.4 (0.3–0.6)		0.8 (0.4–1.3)		0.2 (0.1–0.4)		2.6 (1.8–3.4)		1.1 (0.9–1.4)	

Abbreviations: IQR: interquartile range; PFDA: Perfluorodecanoic acid; PFHxS: Perfluorohexane sulfonic acid; PFNA: Perfluorononanoic acid; PFOA: Perfluorooctanoic acid; PFOS: Perfluorooctane sulfonic acid; PFUnDA: Perfluoroundecanoic acid; µg/L: micrograms per liter

* For results below the limit of detection (LOD), we computed a value using LOD/√2 to calculate medians.

† *P* value determined based on analysis of variance of log-transformed values as a continuous variable.

Table C33. Median **polybrominated diphenyl ether (PBDE)** concentrations (ng/g lipid) for **all Maui County Employees (n = 258)**, stratified by age, seafood consumption, time spent in the impact zone, and job category

Characteristic	N	BDE-28 Median* (IQR)	*P* value†	BDE-47 Median* (IQR)	*P* value†	BDE-100 Median* (IQR)	*P* value†	BDE-153 Median* (IQR)	*P* value†	BDE-209 Median* (IQR)	*P* value†	PBB-153 Median* (IQR)	*P* value†
Age (years)													
< 25	11	0.5 (0.3–0.7)	< 0.01	6.5 (5.0–9.4)	< 0.01	1.0 (0.6–1.8)	0.01	7.7 (5.1–8.7)	0.046	1.6 (1.1–2.2)	< 0.01	0.2 (0.2–0.3)	< 0.01
≥ 25–29	23	0.2 (0.1–0.4)		3.2 (1.6–4.4)		0.6 (0.4–1.2)		9.7 (5.3–18.7)		0.8 (0.7–0.9)		0.3 (0.2–0.6)	
≥30–39	94	0.2 (0.1–0.3)		2.7 (1.4–5.4)		0.6 (0.3–1.1)		9.8 (5.5–17.3)		0.8 (0.7–1.2)		0.4 (0.3–0.7)	
≥ 40–49	78	0.2 (0.1–0.4)		3.5 (1.4–5.6)		0.7 (0.4–1.5)		11.0 (6.4–24.7)		0.8 (0.7–1.2)		0.9 (0.6–1.3)	
≥ 50	52	0.3 (0.2–0.9)		5.2 (2.1–10.2)		1.2 (0.6–1.8)		13.4 (5.8–25.6)		1.1 (0.8–1.5)		1.6 (1.2–2.7)	
Eaten seafood in the last 3 days													
Yes	162	0.2 (0.2–0.5)	0.56	3.5 (1.7–7.4)	0.40	0.8 (0.5–1.6)	0.28	10.6 (5.5–18.7)	0.22	1.0 (0.7–1.4)	0.28	0.6 (0.3–1.2)	0.51
No	93	0.2 (0.1–0.4)		2.7 (1.4–6.0)		0.6 (0.3–1.3)		9.7 (6.0–18.6)		0.8 (0.7–1.1)		0.7 (0.4–1.3)	
Missing	3	0.2 (0.2–0.2)		4.0 (3.8–4.7)		1.0 (0.7–1.4)		27.2 (18.6–40.7)		0.8 (0.8–1.0)		0.9 (0.8–1.1)	
Cumulative time in the impact zone during August 8–12 (hours)													
0–11	74	0.3 (0.2–0.5)	0.42	3.7 (1.7–6.9)	0.83	0.9 (0.5–1.6)	0.71	11.5 (6.3–19.4)	0.61	1.0 (0.7–1.4)	0.32	0.7 (0.4–1.2)	0.36
12–23	55	0.3 (0.1–0.5)		3.7 (1.8–6.5)		0.8 (0.5–1.6)		10.9 (6.6–20.0)		1.0 (0.8–1.3)		0.8 (0.4–1.4)	
24–35	48	0.2 (0.1–0.3)		3.0 (1.6–4.9)		0.7 (0.4–1.2)		9.9 (5.9–20.3)		0.8 (0.7–1.5)		0.5 (0.3–1.4)	

Table C33 Continued. Median **polybrominated diphenyl ether (PBDE)** concentrations (ng/g lipid) for **all Maui County Employees (n = 258)**, stratified by age, seafood consumption, time spent in the impact zone, and job category

Characteristic	N	BDE-28 Median* (IQR)	*P* value†	BDE-47 Median* (IQR)	*P* value†	BDE-100 Median* (IQR)	*P* value†	BDE-153 Median* (IQR)	*P* value†	BDE-209 Median* (IQR)	*P* value†	PBB-153 Median* (IQR)	*P* value†
Cumulative time in the impact zone during August 8–12 (hours) continued													
36–47	31	0.3 (0.1–0.5)		2.7 (1.7–6.7)		0.6 (0.4–1.7)		8.8 (5.4–13.5)		0.8 (0.7–1.1)		0.6 (0.4–1.1)	
48–59	27	0.2 (0.1–0.4)		2.9 (1.8–6.8)		0.8 (0.4–1.8)		6.0 (4.3–16.9)		0.8 (0.7–1.3)		0.7 (0.3–1.5)	
≥ 60	23	0.2 (0.1–0.2)		1.9 (1.2–4.4)		0.8 (0.2–1.3)		12.7 (6.6–25.6)		0.8 (0.7–1.0)		0.7 (0.3–1.3)	
Job category													
Firefighter	178	0.2 (0.1–0.4)	0.28	3.6 (1.8–6.3)	0.57	0.8 (0.4–1.3)	0.28	10.5 (6.1–21.4)	0.10	0.9 (0.7–1.3)	0.01	0.7 (0.4–1.2)	0.13
Police Department Employee	39	0.2 (0.1–0.4)		1.9 (1.2–4.9)		0.6 (0.2–1.7)		6.8 (4.5–14.8)		0.7 (0.6–0.9)		0.5 (0.2–1.0)	
Ocean Safety Officer	19	0.3 (0.1–0.4)		3.2 (1.6–6.3)		0.6 (0.3–1.3)		13.2 (7.4–18.0)		1.0 (0.8–1.2)		0.8 (0.4–1.0)	
Other Maui County Employee	22	0.4 (0.2–0.7)		3.6 (1.6–7.7)		1.4 (0.7–2.2)		9.1 (5.8–16.9)		1.2 (1.0–1.5)		0.8 (0.3–1.7)	

Abbreviations: BDE-28: 2,4,4´-Tribromodiphenyl ether; BDE-47: 2,2´,4,4´-Tetrabromodiphenyl ether; BDE-100: 2,2´,4,4´,6-Pentabromodiphenyl ether; BDE-153: 2,2´,4,4´,5,5´-Hexabromodiphenyl ether; BDE-209: Decabromodiphenyl ether; PBB-153: 2,2´,4,4´,5,5´-Hexabromobiphenyl; IQR: interquartile range; ng/g lipid: nanograms per gram lipid

* For results below the limit of detection (LOD), we computed a value using LOD/√2 to calculate medians. Limit of detection (LOD) values: BDE-28: 0.14 ng/g; BDE-47: 1.2 ng/g; BDE-100: 0.19 ng/g; BDE-153: 0.14 ng/g; BDE-209: 0.71 ng/g; PBB-153: 0.14 ng/g.

† *P* value determined based on analysis of variance of log-transformed values as a continuous variable.

Table C34. Median **polybrominated diphenyl ether (PBDE)** concentrations (ng/g lipid) for **all Maui County Firefighters (n = 178)**, stratified by age, seafood consumption, time spent in the impact zone, and job tenure as a firefighter

Characteristic	N	BDE-28 Median* (IQR)	*P* value†	BDE-47 Median* (IQR)	*P* value†	BDE-100 Median* (IQR)	*P* value†	BDE-153 Median* (IQR)	*P* value†	BDE-209 Median* (IQR)	*P* value†	PBB-153 Median* (IQR)	*P* value†
Age (years)													
< 25	7	0.6 (0.4–1.0)	< 0.01	9.0 (5.2–15.2)	0.01	1.7 (0.8–2.4)	0.03	7.7 (5.8–8.7)	0.19	2.0 (1.0–2.5)	0.07	0.3 (0.2–0.3)	< 0.01
≥ 25–29	16	0.2 (0.2–0.4)		3.3 (1.6–4.6)		0.7 (0.4–1.3)		11.5 (6.4–21.5)		0.8 (0.7–1.0)		0.3 (0.2–0.6)	
≥ 30–39	67	0.2 (0.1–0.3)		2.9 (1.7–5.4)		0.7 (0.3–1.1)		10.4 (6.0–18.9)		0.9 (0.7–1.2)		0.5 (0.3–0.7)	
≥ 40–49	54	0.2 (0.1–0.4)		3.6 (1.6–5.2)		0.7 (0.4–1.2)		10.0 (6.5–26.6)		0.9 (0.8–1.2)		0.9 (0.6–1.3)	
≥ 50	34	0.3 (0.2–0.9)		5.7 (2.4–10.5)		1.0 (0.5–1.8)		13.9 (5.7–37.4)		1.0 (0.7–1.7)		1.6 (1.3–2.5)	
Eaten seafood in the last 3 days													
Yes	116	0.2 (0.2–0.4)	0.81	3.5 (2.0–6.3)	0.86	0.8 (0.5–1.4)	0.55	10.9 (6.3–23.9)	0.13	1.0 (0.8–1.3)	0.77	0.7 (0.4–1.2)	0.92
No	59	0.2 (0.1–0.5)		3.3 (1.4–6.8)		0.6 (0.3–1.3)		9.1 (5.9–18.7)		0.8 (0.7–1.2)		0.7 (0.4–1.1)	
Missing	3	0.2 (0.2–0.2)		4.0 (3.8–4.7)		1.0 (0.7–1.4)		27.2 (18.6–40.7)		0.8 (0.8–1.0)		0.9 (0.8–1.1)	
Cumulative time in the impact zone during August 8–12 (hours)													
0–11	52	0.2 (0.1–0.5)	0.48	3.7 (1.7–8.0)	0.77	0.8 (0.4–1.6)	0.88	9.9 (5.6–28.0)	0.972	0.9 (0.7–1.4)	0.82	0.7 (0.8–1.2)	0.71
12–23	36	0.3 (0.1–0.5)		4.0 (2.2–5.9)		0.8 (0.6–1.3)		10.9 (7.4–21.3)		1.0 (0.8–1.2)		0.8 (0.4–1.3)	
24–35	38	0.2 (0.1–0.3)		3.0 (1.9–4.5)		0.7 (0.5–1.1)		12.5 (6.6–21.1)		0.8 (0.7–1.1)		0.6 (0.3–1.1)	

Table C34 Continued. Median **polybrominated diphenyl ether (PBDE)** concentrations (ng/g lipid) for **all Maui County Firefighters (n = 178)**, stratified by age, seafood consumption, time spent in the impact zone, and job tenure as a firefighter

Characteristic	N	BDE-28 Median* (IQR)	*P* value†	BDE-47 Median* (IQR)	*P* value†	BDE-100 Median* (IQR)	*P* value†	BDE-153 Median* (IQR)	*P* value†	BDE-209 Median* (IQR)	*P* value†	PBB-153 Median* (IQR)	*P* value†
Cumulative time in the impact zone during August 8–12 (hours) continued													
36–47	21	0.3 (0.2–0.5)		3.6 (2.2–9.2)		0.6 (0.5–1.7)		9.3 (6.1–15.6)		0.9 (0.7–1.1)		0.6 (0.4–1.0)	
48–59	15	0.2 (0.1–0.3)		2.9 (1.9–6.4)		0.8 (0.4–1.1)		7.1 (4.3–15.8)		1.1 (0.8–1.3)		0.7 (0.4–1.5)	
≥ 60	16	0.2 (0.2–0.3)		3.1 (1.4–5.0)		1.0 (0.3–1.3)		11.7 (6.7–27.6)		0.8 (0.7–1.1)		0.8 (0.5–1.5)	
Job tenure as a Firefighter (firefighters only; years)													
< 5	51	0.2 (0.1–0.4)	0.01	2.7 (1.5–4.4)	0.01	0.6 (0.3–1.2)	0.02	9.4 (5.2–16.8)	0.163	0.8 (0.7–1.4)	0.37	0.4 (0.3–0.6)	< 0.01
5–9	37	0.3 (0.2–0.5)		3.6 (1.8–8.7)		1.0 (0.4–2.0)		9.3 (6.2–26.9)		0.9 (0.8–1.1)		0.4 (0.3–0.6)	
10–19	47	0.2 (0.1–0.3)		3.6 (1.8–5.2)		0.7 (0.4–1.0)		10.4 (6.1–20.5)		1.0 (0.7–1.6)		1.0 (0.6–1.4)	
20–29	40	0.3 (0.2–0.9)		5.3 (2.4–9.4)		1.0 (0.5–1.7)		14.0 (6.5–30.9)		0.9 (0.8–1.2)		1.4 (1.0–1.9)	
≥ 30	3	0.2 (0.1–5)		5.5 (4.0–8.8)		1.0 (0.8–1.7)		13.0 (11.9–22.8)		2.0 (1.1–2.2)		1.6 (1.6–2.1)	

Abbreviations: BDE-28: 2,4,4´-Tribromodiphenyl ether; BDE-47: 2,2´,4,4´-Tetrabromodiphenyl ether; BDE-100: 2,2´,4,4´,6-Pentabromodiphenyl ether; BDE-153: 2,2´,4,4´,5,5´-Hexabromodiphenyl ether; BDE-209: Decabromodiphenyl ether; PBB-153: 2,2´,4,4´,5,5´-Hexabromobiphenyl; IQR: interquartile range; ng/g lipid: nanograms per gram of lipid

* For results below the limit of detection (LOD), we computed a value using LOD/√2 to calculate medians. Limit of detection (LOD) values: BDE-28: 0.14 ng/g; BDE-47: 1.2 ng/g; BDE-100: 0.19 ng/g; BDE-153: 0.14 ng/g; BDE-209: 0.71 ng/g; PBB-153: 0.14 ng/g.

† *P* value determined based on analysis of variance of log-transformed values as a continuous variable.

Table C35. Median **polybrominated diphenyl ether (PBDE)** concentrations (ng/g lipid) for **all National Guard servicemembers (n = 28)**, stratified by age, seafood consumption, and whether individuals responded to the fire on each day of interest

Characteristic	N	BDE-28 Median* (IQR)	*P* value†	BDE-47 Median* (IQR)	*P* value†	BDE-100 Median* (IQR)	*P* value†	BDE-153 Median* (IQR)	*P* value†	BDE-209 Median* (IQR)	*P* value†	PBB-153 Median* (IQR)	*P* value†
Age (years)													
< 40 years	17	0.3 (0.1–0.5)	0.61	2.8 (1.9–5.2)	0.55	0.6 (0.3–1.2)	0.97	4.4 (2.4–8.9)	0.24	0.8 (0.7–0.9)	0.14	0.3 (0.2–0.5)	< 0.05
≥ 40 years	11	0.2 (0.2–0.3)		2.7 (1.4–5.5)		0.6 (0.3–1.0)		6.9 (3.8–13.8)		1.0 (0.6–1.6)		1.6 (0.7–2.6)	
Eaten seafood in the last 3 days													
Yes	13	0.3 (0.1–0.4)	0.97	3.6 (1.9–5.1)	0.55	0.6 (0.3–1.2)	0.77	3.7 (2.3–6.9)	0.08	0.8 (0.7–0.9)	0.45	0.4 (0.2–0.8)	0.21
No	15	0.2 (0.2–0.5)		2.7 (1.4–5.6)		0.6 (0.3–0.9)		7.1 (4.2–11.7)		0.9 (0.6–1.3)		0.6 (0.3–1.8)	
Responded on:													
August 8													
No	20	0.3 (0.1–0.6)	0.84	2.7 (1.6–5.3)	0.94	0.7 (0.3–1.2)	0.54	5.7 (2.4–10.3)	0.94	0.8 (0.6–1.0)	0.05	0.6 (0.2–1.7)	0.28
Yes	8	0.3 (0.2–0.3)		4.0 (2.3–5.3)		0.5 (0.4–0.7)		4.2 (3.4–8.7)		1.1 (0.6–2.2)		0.4 (0.3–0.5)	
August 9													
No	15	0.3 (0.2–0.7)	0.48	2.7 (1.8–6.0)	0.66	0.8 (0.3–1.4)	0.40	4.4 (2.4–8.9)	0.37	0.8 (0.6–1.0)	0.12	0.5 (0.2–1.7)	0.91
Yes	13	0.3 (0.2–0.4)		4.2 (1.5–5.2)		0.5 (0.4–0.8)		4.8 (3.7–12.4)		0.8 (0.7–2.0)		0.4 (0.3–0.8)	

Table C35 Continued. Median **polybrominated diphenyl ether (PBDE)** concentrations (ng/g lipid) for **all National Guard servicemembers (n = 28)**, stratified by age, seafood consumption, and whether individuals responded to the fire on each day of interest

Characteristic	N	BDE-28 Median* (IQR)	*P* value†	BDE-47 Median* (IQR)	*P* value†	BDE-100 Median* (IQR)	*P* value†	BDE-153 Median* (IQR)	*P* value†	BDE-209 Median* (IQR)	*P* value†	PBB-153 Median* (IQR)	*P* value†
August 10													
No	8	0.3 (0.2–0.4)	0.98	3.2 (2.5–5.5)	0.56	0.6 (0.4–1.3)	0.47	7.8 (5.3–11.4)	0.44	0.9 (0.8–1.0)	0.75	0.2 (0.2–0.4)	0.06
Yes	20	0.3 (0.2–0.4)		2.7 (1.5–5.3)		0.6 (0.2–1.0)		4.3 (2.4–9.3)		0.8 (0.6–1.3)		0.6 (0.3–1.8)	
August 11													
No	10	0.3 (0.2–0.6)	0.37	3.9 (2.7–6.5)	0.11	0.7 (0.4–1.5)	0.24	6.9 (2.9–10.4)	0.97	0.9 (0.7–1.0)	0.55	0.2 (0.2–0.3)	0.01
Yes	18	0.3 (0.1–0.4)		2.7 (1.4–5.1)		0.6 (0.2–1.0)		4.3 (2.7–9.8)		0.8 (0.6–1.3)		0.7 (0.4–2.2)	
August 12													
No	9	0.3 (0.2–0.7)	0.28	3.6 (2.8–7.1)	0.40	0.5 (0.4–1.3)	0.81	4.2 (2.3–6.9)	0.16	0.8 (0.7–0.9)	0.27	0.2 (0.2–0.5)	0.15
Yes	19	0.2 (0.2–0.4)		2.7 (1.5–5.2)		0.6 (0.3–1.0)		6.9 (3.8–12.6)		0.8 (0.6–1.3)		0.6 (0.3–1.6)	

Abbreviations: BDE-28: 2,4,4´-Tribromodiphenyl ether; BDE-47: 2,2´,4,4´-Tetrabromodiphenyl ether; BDE-100: 2,2´,4,4´,6-Pentabromodiphenyl ether; BDE-153: 2,2´,4,4´,5,5´-Hexabromodiphenyl ether; BDE-209: Decabromodiphenyl ether; PBB-153: 2,2´,4,4´,5,5´-Hexabromobiphenyl; IQR: interquartile range; ng/g lipid: nanograms per gram of lipid

LOD values: BDE-28: 0.14 ng/g; BDE-47: 1.2 ng/g; BDE-100: 0.19 ng/g; BDE-153: 0.14 ng/g; BDE-209: 0.71 ng/g; PBB-153: 0.14 ng/g.

* For results below the limit of detection (LOD), we computed a value using LOD/√2 to calculate medians.

† *P* value determined based on analysis of variance of log-transformed values as a continuous variable.

Table C36. Median **organophosphate ester** concentrations (μg/L) for all **Maui County Employees (n = 256)**, stratified by age, time spent in the impact zone, and job category

Characteristic	N	BCEtP*	*P* value†	BCPP*	*P* value†	BDCPP*	*P* value†	DPhP*	*P* value†
Age (years)									
< 25	11	0.2 (0.1–0.6)	0.46	0.2 (0.1–0.3)	0.49	1.2 (0.6–1.9)	0.67	1.1 (0.8–2.0)	0.25
≥ 25–29	23	0.1 (0.1–0.4)		0.1 (0.1–0.4)		0.9 (0.4–2.0)		0.5 (0.2–1.8)	
≥ 30–39	94	0.2 (0.1–0.3)		0.1 (0.1–0.2)		0.9 (0.5–1.7)		0.6 (0.3–1.1)	
≥ 40–49	78	0.2 (0.1–0.4)		0.1 (0.1–0.3)		1.0 (0.4–1.9)		0.6 (0.3–1.2)	
≥ 50	52	0.2 (0.1–0.4)		0.1 (0.1–0.4)		0.8 (0.5–1.6)		0.5 (0.2–0.9)	
Cumulative time in the impact zone during August 8–12 (hours)									
0–11	74	0.2 (0.1–0.4)	0.45	0.1 (0.1–0.3)	0.37	0.8 (0.4–1.4)	0.14	0.5 (0.2–1.1)	0.10
12–23	55	0.3 (0.1–0.5)		0.2 (0.1–0.3)		1.0 (0.6–2.3)		0.7 (0.4–1.2)	
24–35	48	0.1 (0.1–0.4)		0.2 (0.1–0.4)		1.1 (0.5–3.1)		1.0 (0.3–2.0)	
36–47	31	0.2 (0.1–0.3)		0.1 (0.1–0.2)		0.7 (0.4–1.6)		0.4 (0.3–1.2)	
48–59	27	0.1 (0.1–0.3)		0.1 (0.1–0.2)		0.8 (0.5–1.5)		0.5 (0.2–0.7)	
≥ 60	23	0.1 (0.1–0.3)		0.1 (0.1–0.3)		0.7 (0.5–1.4)		0.6 (0.3–0.8)	
Job category									
Firefighter	176	0.2 (0.1–0.3)	0.51	0.2 (0.1–0.3)	0.02	0.9 (0.5–1.5)	< 0.01	0.7 (0.4–1.3)	< 0.01
Police Department Employee	39	0.2 (0.1–0.5)		0.1 (0.1–0.1)		1.4 (0.6–2.9)		0.3 (0.2–1.0)	
Ocean Safety Officer	19	0.2 (0.1–0.3)		0.1 (0.1–0.2)		0.5 (0.2–0.9)		0.4 (0.2–0.7)	
Other Maui County Employee	22	0.3 (0.1–0.4)		0.2 (0.1–0.2)		1.4 (0.9–2.4)		0.4 (0.4–0.5)	

Abbreviations: BCEtP: Bis(2-chloroethyl) phosphate; BCPP: Bis(1-chloro-2-propyl) phosphate; BDCPP: Bis(1,3-dichloro-2-propyl) phosphate; DPhP: Diphenyl phosphate; IQR: interquartile range; μg/L: micrograms per liter

LOD values: BCEtP: 0.1 μg; BCPP: 0.1 μg; BDCPP: 0.1 μg; DPhP: 0.1 μg.

* For results below the limit of detection (LOD), we computed a value using LOD/√2 to calculate medians.

† *P* value determined based on analysis of variance of log-transformed values as a continuous variable.

Table C37. Median **organophosphate ester (OPE)** concentrations (µg/L) for all **Maui County Firefighters (n = 176)**, stratified by age, time spent in the impact zone, and job tenure as a firefighter

Characteristic	N	BCEtP*	*P* value†	BCPP*	*P* value†	BDCPP*	*P* value†	DPhP*	*P* value†
Age (years)									
< 25	7	0.1 (0.1–0.4)	0.46	0.2 (0.1–0.3)	0.75	1.7 (0.9–2.6)	0.49	1.2 (1.1–3.5)	0.12
≥ 25–29	16	0.1 (0.1–0.3)		0.2 (0.1–0.4)		0.9 (0.6–1.3)		0.7 (0.3–1.8)	
≥ 30–39	66	0.2 (0.1–0.3)		0.1 (0.1–0.2)		0.8 (0.4–1.4)		0.7 (0.4–1.3)	
≥ 40–49	53	0.2 (0.1–0.3)		0.2 (0.1–0.3)		1.0 (0.4–1.4)		0.6 (0.4–1.2)	
≥ 50	34	0.2 (0.1–0.4)		0.2 (0.1–0.5)		0.7 (0.5–1.2)		0.6 (0.3–1.2)	
Cumulative time in the impact zone during August 8–12 (hours)									
0–11	52	0.2 (0.1–0.3)	0.38	0.2 (0.1–0.3)	0.40	0.9 (0.4–1.5)	0.23	0.6 (0.4–1.2)	0.51
12–23	36	0.3 (0.1–0.5)		0.2 (0.1–0.3)		0.8 (0.5–1.8)		0.7 (0.5–1.2)	
24–35	38	0.1 (0.1–0.3)		0.1 (0.1–0.4)		1.1 (0.5–1.5)		1.0 (0.4–2.0)	
36–47	21	0.3 (0.2–0.4)		0.2 (0.2–0.2)		1.1 (0.5–1.9)		1.0 (0.4–1.7)	
48–59	15	0.1 (0.1–0.3)		0.1 (0.1–0.2)		0.5 (0.2–1.0)		0.5 (0.3–0.7)	
≥ 60	16	0.1 (0.1–0.3)		0.1 (0.1–0.3)		0.7 (0.4–1.0)		0.6 (0.4–0.8)	
Job tenure as a Firefighter (years)									
<5	51	0.2 (0.1–0.4)	0.61	0.2 (0.1–0.3)	0.13	1.1 (0.4–1.8)	0.68	0.8 (0.5–1.7)	0.05
5–9	37	0.2 (0.1–0.3)		0.1 (0.1–0.2)		0.8 (0.5–1.1)		0.8 (0.5–1.7)	
10–19	47	0.2 (0.1–0.3)		0.1 (0.1–0.2)		0.9 (0.4–2.1)		0.6 (0.3–1.2)	
20–29	40	0.2 (0.1–0.4)		0.2 (0.1–0.4)		0.7 (0.5–1.3)		0.7 (0.4–1.2)	
≥ 30	3	0.3 (0.1–0.4)		0.7 (0.2–1.2)		0.5 (0.4–0.5)		0.2 (0.1–0.3)	

Abbreviations: BCEtP: Bis(2-chloroethyl) phosphate; BCPP: Bis(1-chloro-2-propyl) phosphate; BDCPP: Bis(1,3-dichloro-2-propyl) phosphate; DPhP: Diphenyl phosphate; IQR: interquartile range; µg/L: micrograms per liter

Limit of detection (LOD) values: BCEtP: 0.1 µg; BCPP: 0.1 µg; BDCPP: 0.1 µg; DPhP: 0.1 µg.

* For results below the limit of detection (LOD), we computed a value using LOD/√2 to calculate medians.

† *P* value determined based on analysis of variance of log-transformed values as a continuous variable.

Table C38. Median **organophosphate ester** concentrations (µg/L) for all **National Guard servicemembers (n = 28)**, stratified by age and whether individuals responded to the fire on each day of interest

Characteristic	N	BCEtP*	*P* value†	BCPP*	*P* value†	BDCPP*	*P* value†	DPhP*	*P* value†
Age (years)									
< 40	17	0.2 (0.1–0.3)	0.98	0.1 (0.1–0.3)	0.04	0.8 (0.2–2.1)	0.97	0.4 (0.3–0.9)	0.94
≥ 40	11	0.2 (0.1–0.3)		0.1 (0.1–0.1)		0.5 (0.2–2.6)		0.4 (0.2–0.9)	
Responded on:									
August 8									
No	20	0.2 (0.1–0.3)	0.72	0.1 (0.1–0.2)	0.36	0.5 (0.2–1.9)	0.23	0.5 (0.2–0.9)	0.38
Yes	8	0.2 (0.1–0.3)		0.1 (0.1–0.1)		2.2 (0.5–4.1)		0.4 (0.4–0.6)	
August 9									
No	15	0.2 (0.1–0.3)	0.56	0.1 (0.1–0.2)	0.45	0.7 (0.4–1.7)	0.7	0.4 (0.2–0.7)	0.20
Yes	13	0.2 (0.1–0.2)		0.1 (0.1–0.1)		0.7 (0.2–3.4)		0.4 (0.4–1.4)	
August 10									
No	8	0.2 (0.2–0.3)	0.37	0.1 (0.1–0.2)	0.95	0.8 (0.2–2.2)	0.98	0.7 (0.3–1.2)	0.81
Yes	20	0.2 (0.1–0.3)		0.1 (0.1–0.1)		0.7 (0.2–2.3)		0.4 (0.2–0.6)	
August 11									
No	10	0.2 (0.1–0.3)	0.90	0.1 (0.1–0.3)	0.35	0.8 (0.2–2.0)	0.92	0.7 (0.3–1.3)	0.45
Yes	18	0.2 (0.1–0.3)		0.1 (0.1–0.3)		0.7 (0.3–2.9)		0.4 (0.2–0.6)	
August 12									
No	9	0.2 (0.1–0.5)	0.54	0.1 (0.1–0.2)	0.83	1.9 (0.8–2.1)	0.12	0.6 (0.3–1.2)	0.19
Yes	19	0.2 (0.1–0.3)		0.1 (0.1–0.1)		0.5 (0.2–2.1)		0.4 (0.1–0.6)	

Abbreviations: BCEtP: Bis(2-chloroethyl) phosphate; BCPP: Bis(1-chloro-2-propyl) phosphate; BDCPP: Bis(1,3-dichloro-2propyl) phosphate; DPhP: Diphenyl phosphate; IQR: interquartile range; µg/L: micrograms per liter

Limit of detection (LOD) values: BCEtP: 0.1 µg; BCPP: 0.1 µg; BDCPP: 0.1 µg; DPhP: 0.1 µg.

* For results below the limit of detection (LOD), we computed a value using LOD/√2 to calculate medians.

† *P* value determined based on analysis of variance of log-transformed values as a continuous variable.

Section D: Occupational Exposure Limits and Health Effects of Exposure

NIOSH investigators refer to mandatory (legally enforceable) and recommended OELs for chemical, physical, and biological agents when evaluating workplace hazards. OELs are developed by federal agencies and safety and health organizations to prevent adverse health effects from workplace exposures. Generally, OELs suggest levels of exposure that most employees may be exposed to for up to 10 hours per day, 40 hours per week, for a working lifetime, without experiencing adverse health effects.

However, not all employees will be protected if their exposures are maintained below these levels. Some may have adverse health effects because of individual susceptibility, a preexisting medical condition, or a hypersensitivity (allergy). In addition, some hazardous substances act in combination with other exposures, with the general environment, or with medications or personal habits of the employee to produce adverse health effects. Most OELs address airborne exposures, but some substances can be absorbed directly through the skin and mucous membranes. In some cases, airborne exposure limits are established based on scientific studies that correlate certain levels of airborne substances with corresponding biomarker levels in exposed individuals. By monitoring biomarkers of exposure, it is possible to determine if employers are complying with the recommended airborne exposure limits and if they may be at risk for adverse health effects due to excessive exposure. Biomonitoring programs can be used to measure biomarkers of exposure in populations and assess compliance with airborne exposure limits. This information can help inform regulatory decisions, workplace safety measures, and public health interventions aimed at reducing exposures and protecting human health.

In the United States, OELs have been established by federal agencies, professional organizations, state and local governments, and other entities. Some OELs are legally enforceable limits; others are recommendations.

- OSHA, an agency of the U.S. Department of Labor, publishes limits for some substances in employees' blood called medical removal limits. When an employee has a blood level above the medical removal limit for a certain substance, the employee must be removed from work until their level is lower. These legal limits are enforceable in workplaces covered under the Occupational Safety and Health Act of 1970.
- NIOSH recommended exposure limits (RELs) are recommendations based on a critical review of the scientific and technical information and the adequacy of methods to identify and control the hazard. NIOSH RELs are published in the *NIOSH Pocket Guide to Chemical Hazards* [NIOSH 2007]. NIOSH also recommends risk management practices (e.g., engineering controls, safe work practices, employee education/training, PPE, and exposure and medical monitoring) to minimize the risk of exposure and adverse health effects.
- Another set of OELs commonly used and cited in the United States includes the threshold limit values (TLVs) and biological exposure indices (BEIs), which are recommended by ACGIH. The ACGIH TLVs and BEIs are developed by committee members of this professional organization from a review of the published,

peer-reviewed literature. TLVs and BEIs are not consensus standards. They are considered voluntary exposure guidelines for use by industrial hygienists and others trained in this discipline "to assist in the control of health hazards" [ACGIH 2023].

Outside the United States, OELs have been established by various agencies and organizations and include legal and recommended limits. The Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung (Institute for Occupational Safety and Health of the German Social Accident Insurance) maintains a database of international OELs from European Union member states, Canada (Québec), Japan, Switzerland, and the United States. The database, available at https://www.dguv.de/ifa/gestis/gestis-stoffdatenbank/index-2.jsp, contains international limits for more than 2,000 hazardous substances and is updated periodically.

OSHA requires an employer to furnish employees a place of employment free from recognized hazards that cause or are likely to cause death or serious physical harm (Occupational Safety and Health Act of 1970; Public Law 91–596, sec. 5[a][1]). This is true in the absence of a specific OEL. It also is important to keep in mind that OELs may not reflect current health-based information.

When multiple OELs exist for a substance or agent, NIOSH investigators generally encourage employers to use the lowest OEL when making risk assessment and risk management decisions.

We compared substances without OELs to NHANES results. NHANES is a program of studies designed to assess the health and nutritional status of adults and children in the United States, including environmental exposures to chemicals. NHANES results can be considered representative of the general population. Because of this, we used NHANES 95th percentiles as reference values to compare participant results to. A 95th percentile is the value where 95% of results are under it and 5% of results are over it.

In this evaluation, we only performed biologic testing of blood and urine samples. We did not perform air sampling. However, information about air-based OELs is included in the following section because air sampling OELs are closely related to corresponding biologic monitoring OELs. For example, performing air sampling for lead and comparing results to air-based OELs can help determine if biological monitoring is needed.

Lead

Inorganic lead is a naturally occurring, soft metal that has been mined and used in industry since ancient times. It comes in many forms (e.g., lead acetate, lead chloride, lead chromate, lead nitrate, lead oxide, lead phosphate, and lead sulfate). Lead is considered toxic to all organ systems and serves no useful purpose in the body.

Occupational exposure to inorganic lead occurs via inhalation of lead-containing dust and fume and ingestion of lead particles from contact with lead-contaminated surfaces. Exposure may also occur through transfer of lead to the mouth from contaminated hands or cigarettes when careful attention to hygiene, particularly hand washing, is not practiced. In addition to the inhalation and ingestion routes of exposure, lead can be absorbed through the skin, particularly through damaged skin [Filon et al. 2006; Stauber et al. 1994; Sun et al. 2002].

Occupational Exposure Limits for Lead in Air

In the United States, employers in general industry are required by law to follow the OSHA lead standard [29 CFR 1910.1025]. This standard was established in 1978 and has not yet been updated to reflect the current scientific knowledge regarding the health effects of lead exposure. Under the OSHA standard, the PEL for airborne exposure to lead is 50 $\mu g/m^3$ of air for an 8-hour TWA, with an action level of 30 $\mu g/m^3$ (also an 8-hour TWA). In 2013, the California Department of Public Health (CDPH) recommended that California OSHA lower the PEL for lead from 0.5 to 2.1 $\mu g/m^3$ (8-hour TWA) [Billingsley 2013]. In 2024, the California OSHA Standards Board voted to reduce the California OSHA PEL from 50 $\mu g/m^3$ to 10 $\mu g/m^3$ and the action level from 30 $\mu g/m^3$ to 2 $\mu g/m^3$.

Other guidelines for lead exposure, which are not legally enforceable, are often followed in the United States. Like the OSHA lead standard, these guidelines have also not been updated. The NIOSH REL and ACGIH TLV for lead are 50 $\mu g/m^3$ as an 8-hour work shift [ACGIH 2023; NIOSH 2007].

Blood Lead Levels

In most cases, an individual's blood lead level (BLL) is a good indication of recent exposure to lead because the half-life of lead (the time interval it takes for the quantity in the body to be reduced by half its initial value) is 1–2 months [CDC 2013; Lauwerys and Hoet 2001; Moline and Landrigan 2004]. Most lead in the body is stored in the bones, with a half-life of years to decades. Measuring bone lead, however, is primarily done only for research. Elevated zinc protoporphyrin levels have also been used as an indicator of chronic lead intoxication. However, other factors, such as iron deficiency, can cause an elevated zinc protoporphyrin level, so monitoring the BLL over time is more specific for evaluating chronic occupational lead exposure.

The OSHA lead standard mandates medical removal for an employee with a single BLL of $\geq$ 60 $\mu g/dL$, or three BLLs averaging $\geq$ 50 $\mu g/dL$, and permits return to work once the employee's BLL decreases to $<$ 40 $\mu g/dL$ [29 CFR 1910.1025]. ACGIH recommends that employee BLLs be controlled to below 20 $\mu g/dL$, and also designates lead as an animal carcinogen [ACGIH 2021]. CDC recommends removal of pregnant women from lead-exposed work areas when BLLs are $\geq$ 10 $\mu g/dL$ [CDC 2010; CDPH 2009]. In 2013, CDPH recommended that California OSHA keep BLLs below the range of 5 to 10 $\mu g/dL$ [Billingsley 2013; CDPH 2024]. In 2015, NIOSH designated 5 $\mu g/dL$ of whole blood, in a venous blood sample, as the reference BLL for adults [CDC 2023a].

Health Effects of Lead

The OSHA PEL, NIOSH REL, and ACGIH TLV may prevent overt symptoms of lead poisoning, but they do not protect workers from lead's contributions to conditions such as hypertension, renal dysfunction, or reproductive and cognitive effects [Brown-Williams et al. 2009; Holland and Cawthon 2016; Institute of Medicine 2013; Schwartz and Hu 2007; Schwartz and Stewart 2007]. Generally, acute lead poisoning with symptoms has been documented in persons having BLLs above 70 $\mu g/dL$. These BLLs are rare today in the United States, largely as a result of workplace controls put in place to comply with current OELs. When present, acute lead poisoning can cause a myriad of adverse health effects including abdominal pain, hemolytic anemia, and neuropathy. Lead poisoning has, in very rare cases, progressed to encephalopathy and coma [Moline and Landrigan 2004].

People with chronic lead poisoning, which is more likely at current OELs, may not have symptoms or they may have nonspecific symptoms that may not be recognized as being associated with lead exposure. These symptoms include headache, joint and muscle aches, weakness, fatigue, irritability, depression, constipation, anorexia, and abdominal discomfort [Moline and Landrigan 2004].

The National Toxicology Program (NTP) released a monograph on the health effects of low-level lead exposure [NTP 2012]. For adults, the NTP concluded the following about the evidence regarding health effects of lead (Table D1).

Table D1. Evidence regarding health effects of lead in adults

Health area	NTP conclusion	Principal health effects	Blood lead evidence
Neurological	Sufficient	Increased incidence of essential tremor	Yes, < 10 µg/dL
	Limited	Psychiatric effects, decreased hearing, decreased cognitive function, increased incidence of amyotrophic lateral sclerosis	Yes, < 10 µg/dL
	Limited	Increased incidence of essential tremor	Yes, < 5 µg/dL
Immune	Inadequate		Unclear
Cardiovascular	Sufficient	Increased blood pressure and increased risk of hypertension	Yes, < 10 µg/dL
	Limited	Increased cardiovascular-related mortality and electrocardiography abnormalities	Yes, < 10 µg/dL
Renal	Sufficient	Decreased glomerular filtration rate	Yes, < 5 µg/dL
Reproductive	Sufficient	Women: reduced fetal growth	Yes, < 5 µg/dL
	Sufficient	Men: adverse changes in sperm parameters and increased time to pregnancy	Yes, ≥ 15–20 µg/dL
	Limited	Women: increase in spontaneous abortion and preterm birth	Yes, < 10 µg/dL
	Limited	Men: decreased fertility	Yes, ≥ 10 µg/dL
	Limited	Men: spontaneous abortion	Yes, ≥ 31 µg/dL
	Inadequate	Women and Men: stillbirth, endocrine effects, birth defects	Unclear

Various organizations have assessed the relationship between lead exposure and cancer. According to the Agency for Toxic Substances and Disease Registry [ATSDR 2020] and the NTP [NTP 2021a], inorganic lead compounds are reasonably anticipated to cause cancer in humans. The International Agency for Research on Cancer (IARC) classifies inorganic lead as probably carcinogenic to humans [IARC 2006].

Cadmium

Cadmium is a metal used in batteries, pigments, plastic stabilizers, metal coatings, and television phosphors [ACGIH 2001]. Employees may inhale cadmium particulate when sanding, grinding, or scraping cadmium-metal alloys or cadmium-containing paints or in ash and debris containing cadmium

[ACGIH 2001]. In addition to inhalation, cadmium may be absorbed via ingestion. Non-occupational sources of cadmium exposure include cigarette smoke and dietary intake [ACGIH 2001].

Early symptoms of cadmium exposure may include mild irritation of the upper respiratory tract, a sensation of constriction of the throat, a metallic taste, and/or cough. Short-term exposure effects of cadmium inhalation include cough, chest pain, sweating, chills, shortness of breath, and weakness [Thun et al. 1991]. Short-term exposure effects of ingestion may include nausea, vomiting, diarrhea, and abdominal cramps [Thun et al. 1991]. Long-term exposure effects may include loss of the sense of smell, ulceration of the nose, emphysema, kidney damage, mild anemia, and an increased risk of cancer of the lung, and possibly of the prostate [ATSDR 2012a].

The OSHA PEL for cadmium is 5 $\mu g/m^3$ as an 8-hour TWA and the OSHA medical removal limit for cadmium in blood is 5 µg/L. The OSHA cadmium standard also has requirements for preplacement examinations and medical surveillance for employees depending on the frequency and severity of their cadmium exposures [29 CFR 1910.1027]. The ACGIH TLV for cadmium is 10 $\mu g/m^3$ for total particulate and 2 $\mu g/m^3$ an 8-hour TWA [ACGIH 2024a]. NIOSH considers cadmium to be an occupational carcinogen but has not set a quantitative recommended exposure limit. NIOSH is revising its cadmium limit and, in the meantime, urges employers to assess the conditions under which their workers may be exposed to cadmium and take all reasonable precautions to reduce these exposures to the fullest extent feasible.

Manganese

Manganese (Mn) metal is a silver-gray colored, lustrous, brittle element [NIOSH 2007]. It forms compounds in multiple oxidation states, but compounds containing the Mn(II), Mn(III), and Mn(IV) oxidation states are most commonly found in the environment [ATSDR 2012b].

Although some manganese intake is essential for human health, exposure to high levels of manganese is toxic. Work-related inhalation of manganese is the primary source of toxic manganese exposure. Airborne manganese consists primarily of insoluble oxides in particulate form. The most common manifestations of manganese overexposure are neurologic in nature and begin insidiously with feelings of weakness and lethargy. As exposure continues, symptoms such as tremor, speech impairment, and incoordination may occur. A characteristic sign of chronic manganese intoxication is the complete absence of facial expression. In some cases, overexposure to manganese can lead to psychiatric disturbances. Although manganese intoxication resembles Parkinsonism, it can be distinguished clinically and by pathology [ATSDR 2012b].

Subclinical neurological health effects, such as decreased performance on neurobehavioral tests, have also been noted in workers exposed to lower levels of manganese [ATSDR 2012b]. However, results of studies evaluating associations between low manganese exposure levels and neurologic deficits are mixed. For example, a study of manganese alloy plant workers found that manganese-exposed workers had increased hand tremor compared with unexposed controls [Bast-Pettersen et al. 2004]. Other studies have shown poorer performance on neurobehavioral tests, such as finger tapping, digit span, and visual reaction time, among manganese-exposed workers [Lucchini et al. 1995; Roels et al. 1992]. Conversely, other studies have not found an association between low-level occupational manganese exposure and neurologic health effects [Deschamps et al. 2001]. Interpreting abnormal neurobehavioral tests from workplace exposure to low levels of manganese is difficult, and abnormalities found in asymptomatic workers do not necessarily imply progression to disease [Santamaria et al. 2007].

Airborne occupational exposure limits include the NIOSH REL, NIOSH short-term exposure limit (STEL), OSHA ceiling limit, and the California OSHA PEL. The NIOSH REL for manganese and its compounds is 1 mg/m^3, and the NIOSH STEL is 3 mg/m^3 [NIOSH 2007]. Federal OSHA does not have a PEL for manganese for full-shift exposures but does have a ceiling limit of 5 mg/m^3, which should not be exceeded at any time [29 CFR 1910.1000, Table Z-1]. California OSHA established a PEL at 0.2 mg/m^3 and the ACGIH TLV 0.02 mg/m^3 as respirable particulate matter and 0.1 mg/m^3 as the inhalable fraction [ACGIH 2024a; OSHA 2023].

A review of the literature suggests that persons without occupational exposure to manganese often have blood manganese levels of 4–15 µg/L and urine manganese levels of 1–8 µg/L. Several studies have shown higher blood and urine manganese levels in groups of workers who are chronically exposed to airborne manganese at work [ATSDR 2012b]. One study found correlations between blood and urine manganese concentrations and airborne manganese cumulative exposure indices [Lucchini et al. 1995]. However, other evidence suggests that blood and urine manganese levels may not be reliable for tracking individual exposure to inhaled manganese [ATSDR 2012b; Smith et al. 2007]. Manganese levels in hair are variable depending on hair color and use of dyes [ATSDR 2012b] and should not be used to follow exposure. Magnetic resonance imaging (MRI) can demonstrate areas of manganese accumulation in the brain [ATSDR 2012b] but using MRI to follow exposure over time is impractical. There are no established OELs in the United States for levels of manganese in the urine.

Selenium

Selenium is a naturally occurring element that is commonly found in rocks and soil. Elemental selenium is primarily formed as a byproduct of copper refining. Selenium is also found in organic compounds and as part of compounds with minerals. Selenium is widely used in the glass industry; it is also used in the preparation of some pharmaceuticals, rubber production, and diagnostic radiology. Selenium can be found in some pigments, photographic exposure meters, rectifiers, soil additives, nutritional feed for poultry and livestock, pesticides, dietary supplements, and anti-dandruff shampoo [ATSDR 2003].

Selenium is an essential trace element necessary for many physiological processes in the body [Kieliszek et al. 2022; Lei et al. 2022]. However, excess selenium can lead to acute or chronic toxicity. In acute selenium toxicity, nausea, vomiting, diarrhea, and abdominal pain are common [ATSDR 2003; Nuttall 2006]. Selenosis, or chronic selenium toxicity, manifests as hair and nail changes or loss, tooth discoloration and decay, and neurological symptoms [ATSDR 2003; Nuttall 2006]. Individuals with acute or chronic toxicity can have garlic breath [Nuttall 2006]. A systematic review and meta-analysis identified that selenium exposure is associated with a slightly higher risk of developing type 2 diabetes [Vinceti et al. 2018].

The OSHA PEL for selenium compounds is 0.2 mg/m^3 for an 8-hour TWA [29 CFR 1910.1000, Table Z-1]. The NIOSH REL for selenium compounds is 0.2 mg/m^3 for up to a 10-hour TWA [NIOSH 2007]. The immediately dangerous to life or health (IDLH) concentration of selenium compounds is 1 mg/m^3. The ACGIH TLV for an 8-hour TWA is 0.2 mg/m^3 [ACGIH 2023, 2024].

Arsenic

Arsenic is a naturally occurring element that is found in the earth's crust. Inorganic arsenic refers to arsenic that is combined with other elements such as oxygen, chlorine, and sulfur. Organic arsenic refers to compounds with a carbon-arsenic bond [ATSDR 2016].

Inorganic arsenic compounds have been extensively used to preserve wood, mainly in the form of copper chromated arsenate (CCA) to make "pressure-treated lumber." New use of CCA has been phased out of wood products for residential uses, but wood treated prior to this date and existing structures made with CCA-treated wood were not phased out. Inorganic arsenic compounds had been used as pesticides, mainly on cotton fields and in orchards, but can no longer be used in agriculture. Organic arsenic compounds are used as pesticides, mainly on cotton fields and in orchards [ATSDR 2016].

The main route of exposure for most people is likely through food and drinking water. Seafood, especially shellfish, can accumulate arsenic, mostly in an organic form called arsenobetaine that is much less harmful to health [ATSDR 2016]. Rice, rice-based foods, and hijiki (a type of seaweed) contain inorganic arsenic [Biomonitoring California 2018; Yokoi and Konomi 2012]. Occupational exposure to arsenic can be significant in industries such as nonferrous smelting, wood preservation, glass manufacturing, electronics, pesticide production and application, and cotton production, via inhalation and skin contact [ATSDR 2016].

Inorganic arsenic has been used as a human poison since ancient times. Health effects associated with inorganic arsenic exposure include gastrointestinal symptoms, skin changes such as "corns" or "warts," decreased production of red and white blood cells, and a "pins and needles" sensation in the hands and feet. Breathing in high levels of inorganic arsenic can lead to sore throat and lung irritation [ATSDR 2016]. Arsenic has been recognized as a human carcinogen by IARC [IARC 2012] and the NTP [NTP 2021b]. Less is known about the health effects of organic arsenic in humans; studies in animals show that some organic arsenic compounds are less toxic than inorganic forms [ATSDR 2016].

In the United States, employers in general industry are required by law to follow the OSHA inorganic arsenic standard [29 CFR 1910.1018]. The OSHA PEL for inorganic arsenic (in air) is 10 $\mu g/m^3$ as an 8-hour TWA [29 CFR 1910.1018(c)]. Employers are required to provide medical examinations to employees exposed above the OSHA action level of 5 $\mu g/m^3$ for an 8-hour TWA for at least 30 days per year or for more than 10 years; employers are also required to perform more frequent monitoring of airborne concentrations of arsenic. NIOSH designates inorganic arsenic as an occupational carcinogen. The NIOSH REL is a 15-minute ceiling value of 0.002 mg/m^3. The ACGIH TLV for inorganic arsenic is 0.01 mg/m^3, "intended to minimize the potential for adverse effects on the skin, liver, peripheral vasculature, upper respiratory tract, and lungs, including cancer" [ACGIH 2024b]. The ACGIH BEI for inorganic arsenic plus methylated species is 15 µg/g creatinine for urine samples collected at the end of the work shift, end of the work week. This BEI is based on the 95th percentile concentration in the general population [ACGIH 2024b].

Chromium and Hexavalent Chromium

Chromium metal is a hard, blue-white to steel-gray colored, lustrous, brittle element [NIOSH 2007]. In the environment, it exists primarily in two valence states, trivalent chromium or Cr(III) and hexavalent chromium or Cr(VI) [EPA 2000].

Although chromium is an essential trace element in humans, Cr(VI) is extremely toxic and designated as a human carcinogen [IARC 2012; NIOSH 2013; OSHA 2006]. Cr(VI) is associated with lung cancer and nasal and sinus cancer; nonmalignant respiratory effects include irritated, ulcerated, or perforated nasal septa. The median airborne concentration of Cr(VI) in a study of U.S. workers, some of whom had nasal ulceration, was 20 $\mu g/m^3$, and the median time from employment to first diagnosis of nasal ulceration was less than a month [Gibb et al. 2000]. The purpose of the NIOSH REL for Cr(VI) compounds is to reduce occupationally exposed workers' risk of lung cancer associated with Cr(VI) compounds over a 45-year working lifetime. NIOSH further recommends reducing exposures to Cr(VI) compounds to below the REL to address the residual lung cancer risk that remains in those exposed to Cr(VI) compounds at the REL. Reducing airborne occupational exposures to Cr(VI) compounds will also reduce the nonmalignant respiratory effects of Cr(VI) compounds [NIOSH 2013].

Dermal exposures to Cr(VI) can result in skin irritation, ulcers, skin sensitization, and allergic contact dermatitis. NIOSH recommends preventing workplace dermal exposure to Cr(VI) to reduce the risk of adverse dermal effects [NIOSH 2013].

NIOSH RELs for chromium include the NIOSH REL for chromium metal, divalent chromium or Cr(II), and Cr(III) compounds of 500 $\mu g/m^3$. The NIOSH REL for all Cr(VI) compounds is 0.2 $\mu g/m^3$ [NIOSH 2007]. OSHA PELs for chromium and chromium compounds include the OSHA PEL for chromium metal and insoluble salts of 1,000 $\mu g/m^3$ [29 CFR 1910.1000, Table Z-1], the OSHA PEL for Cr(II) and Cr(III) compounds of 500 $\mu g/m^3$ [29 CFR 1910.1000, Table Z-1], and the OSHA PEL for Cr(VI) of 5 $\mu g/m^3$ [29 CFR 1910.1026]. The ACGIH TLV is 0.2 $\mu g/m^3$ TWA and 0.5 $\mu g/m^3$ STEL for Cr(VI) inhalable particulate matter [ACGIH 2023] to minimize the potential for respiratory tract irritation, asthma, and cancer.

Urinary chromium levels are a measure of total chromium exposure. Total chromium is used as a marker of exposure even in situations where Cr(VI) is the primary concern. A review of the literature suggests that persons without occupational exposure to chromium or Cr(VI) often have urine chromium levels of 0.22–1.8 µg/L of urine [ATSDR 2012c]. The ACGIH BEI for Cr(VI) of 0.7 µg/L is based on the total chromium in a urine sample collected at the end of the shift at the end of the workweek. This BEI is based on the 95th percentile concentration in the general population. OSHA does not have a legal requirement for levels of urine chromium [ACGIH 2023].

Nickel

Nickel metal is a hard, lustrous, silvery-white colored element. It is used in alloys, nickel plating, ceramic coloring, and batteries. Nickel is particularly useful in alloys because of the corrosion and heat resistance, hardness, and strength that it provides [ATSDR 2023d].

Although trace amounts of nickel are essential for human health, overexposure to nickel can have harmful effects. Allergic reactions from direct skin contact with nickel, such as development of a rash at the site of the nickel contact, are the most common harmful health effect in humans. More serious harmful health effects have been noted among working populations who are chronically overexposed to nickel. Inhalation of nickel-containing dust and fumes may cause asthma attacks in workers who are sensitized to nickel or may lead to chronic bronchitis or reduced lung function over time [ATSDR

2023d]. Nickel is also considered a cancer-causing agent, with chronic overexposures to insoluble nickel compounds leading to nasal, sinus, and lung cancers [ATSDR 2023d; IARC 2012].

The NIOSH REL for nickel, based on its designation as a potential occupational lung carcinogen, is 0.015 mg/m^3 [NIOSH 2007]. The OSHA PEL for nickel metal and insoluble and soluble nickel compounds is 1 mg/m^3 [29 CFR 1910.1000, Table Z-1]. The ACGIH TLV for insoluble compounds (i.e., nickel sulfide and nickel oxide) of nickel is 0.2 mg/m^3, for soluble nickel compounds and nickel subsulfide is 0.1 mg/m^3, and for elemental nickel is 1.5 mg/m^3 [ACGIH 2024a]. All the TLVs for nickel are applicable to the inhalable fraction of employee exposures to particulates.

PFAS

PFAS are a group of thousands of human-made chemicals that have been used in industry and consumer products since the 1940s [EPA 2023b; NIOSH 2022]. Their useful properties have made them central ingredients in coatings, materials, and textiles that are non-stick or resistant to heat, oil, stains, and water. Some PFAS are more widely used and studied than others; the most studied and well-known are perfluorooctanoic acid (PFOA), perfluorooctanesulfonic acid (PFOS).

Many PFAS are highly persistent in the environment and are removed very slowly from the body, and therefore can build up in people, animals, and the environment over time. Because of this and widespread use in consumer products and manufacturing, PFAS are present in water, soil, air, and food. Studies suggest that most people in the United States and in other industrialized countries have measurable amounts of PFAS in their blood [ATSDR 2022a]. In the general U.S. adult population, most exposures occur through drinking contaminated water, using consumer products containing PFAS, eating food that contains PFAS, or accidentally swallowing contaminated soil or dust. In occupational settings, inhalation is the most likely exposure route. Workers may also be exposed to PFAS by getting them on their skin and by swallowing them [ATSDR 2022a]. Specifically, during and after fires, first responders may be exposed to PFAS through use of firefighting foams that contain PFAS (e.g., AFFF); through dust containing PFAS (e.g., from combustion of stain-resistant upholstery or carpeting); and, potentially through contact with gear used to protect them from heat-related hazards during emergency response (e.g., turnout or bunker gear) [NIOSH 2022].

Research studies have reported a variety of health outcomes associated with exposures to PFAS, including that high levels of certain PFAS may lead to increased cholesterol levels, changes in liver enzymes, small decreases in infant birth weights, decreased vaccine response in children, increased risk of high blood pressure or preeclampsia in pregnant women, and increased risk of kidney or testicular cancer [ATSDR 2022b; NASEM 2022]. Recently, IARC updated their classification of PFOA to “carcinogenic to humans” (Group 1) and PFOS as “possibly carcinogenic to humans” (Group 2B) [Zahm et al. 2023].

While studies have shown that PFAS exposure is associated with a range of health effects, at this time there is insufficient toxicological and epidemiological data to fully inform OELs. The ACGIH has established TLVs for three PFAS in air: perfluoroisobutylene, perfluorobutyl ethylene, and ammonium perfluorooctanoate (a form of PFOA) [ACGIH 2024a]. However, air monitoring methods for PFAS are limited. Instead, most studies of occupational PFAS exposure rely on biological measures of workers’

PFAS exposure using serum blood and urine testing. PFAS can stay in the body for varying lengths of time ranging from days to years depending on its chemical structure [Christensen and Calkins 2023]. Finding a measurable amount of PFAS in serum or urine means that a person has had past or recent exposure to PFAS [NASEM 2022].

In the absence of biological OELs for PFAS, scientists rely on alternative comparisons to understand workers' PFAS exposure and determine the need for clinical follow-up. In the United States, the NHANES, an ongoing study conducted by the CDC, measures a selected number of PFAS in the blood and urine of people across the country; PFAS concentrations found among adults participating in NHANES represent average levels of exposure in the United States. PFAS have been measured in NHANES participants for more than 20 years and generally show a decreasing trend, meaning that concentrations measured in more recent years are lower than previous NHANES years. Scientists can compare concentrations of PFAS found in the blood and urine of workers to the concentrations found in NHANES to understand if groups of workers have been exposed to higher levels of PFAS than are found in the general U.S. population. Here, we measured PFAS that have been the most studied, were measured in NHANES, and have relatively long half-lives, meaning they stay in the body for a long time. We compared levels of PFAS found in workers' serum to the 95th percentile of PFAS among adults aged 20 years and older from the most recent data available from NHANES (2017–2018).

Previous studies have shown that first responders have elevated serum PFAS levels in comparison to reference populations [Christensen and Calkins 2023]. PFOS, PFHxS, and PFNA have been the most consistently elevated PFAS among firefighters. However, variability in PFAS exposure and serum PFAS levels exists based on how long a person has worked as a first responder, the PFAS-containing products they use or come into contact with, and the type of job tasks they do.

NASEM recently published Guidance on PFAS Exposure, Testing, and Clinical Follow-up, which includes recommendations for clinicians regarding advising patients about environmental exposure reduction, blood testing for those with likely elevated exposures, and clinical follow-up based on serum thresholds [NASEM 2022]. The guidelines rely on the sum of selected PFAS in serum (n-PFOA, sb-PFOA, n-PFOS, sm-PFOS, PFHxS, PFDA, PFNA, PFUnDA, and MeFOSAA) and recommend for persons with a serum PFAS level ≥ 20 µg/L that in addition to standard of care health screenings, clinicians should consider additional targeted screening for other disorders [NASEM 2022].

Flame-Retardant Chemicals (PBDEs and OPEs)

Polybrominated Diphenyl Ethers (PBDEs)

Flame retardants have been added to retail products and construction materials to inhibit, suppress, or delay the production of flames and impede the spread of fire since the 1970's. In 1975, California Technical Bulletin 117 required that upholstered furniture filling, which is usually polyurethane foam, meet an open flame test. Manufacturers added chemical flame retardants to foam to meet this standard. While the standard only applied in California, manufacturers sold Technical Bill 117-compliant products across North America to avoid having double inventory and to minimize liability. Polybrominated diphenyl ethers (PBDEs) were phased out of manufactured products in the United States from 2004 to 2013 [EPA 2012, 2015]. PBDEs were further restricted in 2017 by the Stockholm Convention [United Nations Environmental Programme 2017]. The phase out of PBDEs prompted manufacturers to switch to OPE flame retardants or other non-PBDE brominated flame retardants. California updated the California Technical Bill 117 in 2014 (TB117-2013) to reduce the requirement to a smoldering test reducing the amount or need for flame retardants in many materials. The TB117-2013 also required labeling in California prompting manufactures to remove flame retardants, if possible. These developments prompted rapid changes in flame retardants during the last few decades.

Although PBDEs have been phased out of most new materials, they were very widely used in building materials and furnishing and would still be present today in many U.S. buildings and furnishings. PBDEs are persistent in the environment and accumulate in humans and animals [Sacks and Lohmann 2012; Sjödin et al. 2020]. PBDEs with lower molecular weights (e.g., penta-BDE) have long half-lives (e.g., years), while the PBDE with the lowest molecular weight (BDE-209) has a half-life of approximately 15 days [Sjödin et al. 2020; Thuresson et al. 2006].

PBDEs have a molecular structure like thyroid hormones [McDonald 2002]. Some human epidemiologic studies have shown an association between exposure to PBDEs and changes in male reproductive hormones, semen quality, thyroid homeostasis, and hormone levels and fertility in women; cryptorchidism (undescended testicle); low birth weight and length; delayed motor skills; and decreased IQ [Abdallah et al. 2015; Czerska et al. 2013; Dallaire et al. 2009; Dishaw et al. 2014; Grant et al. 2013]. The EPA [2008] has classified BDE-209 as having "suggestive evidence of carcinogenic potential" based on rat and mouse studies. In 2015, the National Toxicology Program listed a mixture of pentabromodipenyl ether as having clear evidence of carcinogenic activity [NTP 2015]. California Prop 65 listed the same mixture of penta-BDEs as potentially carcinogenic in 2017 [NTP 2016; OEHHA 2017]. PBB (polybrominated biphenyls) were banned in the United States in 1973 [EPA 2014; NIOSH 2018, 2019a,b].

There are no OELs for PBDEs in the United States. One way to determine if workers are exposed to an agent through the workplace is compare their levels to the general population. In the NHANES study, serum samples containing PBDEs were collected from the general population from 2014 to 2015. These pooled serum samples are the most recent and are used as a comparison with the data collected in this study [CDC 2023b, 2024].

Organophosphate Esters Flame Retardants (OPEs)

Organophosphate esters flame retardants that sometimes have been the replacements for PBDE flame retardants also are associated with adverse health effects. TCEP and TDCPP are listed under California Prop 65 as being potentially carcinogenic to humans. The German MAK Commission has labeled TCEP as a substance that causes cancer in man and assumed to make a significant contribution to cancer risk. Also, TCEP was evaluated by IARC but listed as "unclassifiable as to carcinogenicity in humans [ACGIH 2023]." TBBPA is considered probably carcinogen to humans by IARC in 2016 and is considered a carcinogen according to California Prop 65 in 2017 [IARC 2018]. Also, TBBPA was given a skin notation by the German MAK Commission noting that there is a "danger of cutaneous absorption" [ACGIH 2023; OEHHA 2017]. TCEP exposure in animals has been associated with brain lesions, kidney tumors and decreased fertility. TDCPP was associated with liver, kidney, testes, and adrenal gland tumors in zebra fish [ATSDR 2015].

TDCPP has been found to alter ion homeostasis in human cell [Latronico et al. 2018]. TCEP and TCPP are also used in some polyurethane foam. Some phosphorus flame retardants have been associated with decreased fertility, reduced sperm motility, altered reproductive and thyroid hormones, and cancer in humans [Dishaw et al. 2014; Meeker and Stapleton 2010; Meeker et al. 2013a,b; van der Veen and de Boer 2012]. TPhP is listed by the ACGIH as "not classifiable as a human carcinogen" defined as an agent that has a cause for concern but data are lacking.

Exposure to flame retardants in indoor environments like homes, schools, and offices is thought to be mainly from ingestion of dust for the general population, primarily during the transfer of the flame retardants from hands to mouth, with dermal absorption the next most important route of exposure [Abdallah et al. 2015]. In contrast, a study estimated that inhalation exposure exceeded intake from ingestion of some chlorinated organophosphate flame retardants [Schreder et al. 2016]. Experimental data using human skin equivalent tissue demonstrate that absorption through skin increased as the number of bromine atoms decreased for PBDEs [Abdallah et al. 2015]. Animal studies show that TDCPP is easily absorbed through the skin and gastrointestinal tract [Nomeir et al. 1981], and recent studies of human ex vivo skin showed absorption of 28% for TCEP, 25% for TCPP, and 13% for TDCPP [Abdallah et al. 2016].

Some OELs exist for inhalation exposure for OPE flame retardants. TPhP has an OSHA PEL, NIOSH REL, and ACGIH TLV of 3 mg/m^3. There are no urine OELs for these OPE flame retardants. One way to determine if workers are exposed to an agent through the workplace is to compare their levels with the general population. The NHANES study collects urine from the general population, which is useful for comparison purposes. For the OPEs in this study, the most recent data collected from 2017 to 2020 are used as a comparison with the data collected in this study [CDC 2023b, 2024].

Section E: References

Background

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