New Castle County

Delaware | near New Castle Air National Guard Base

INFORMATION TO PROTECT OUR COMMUNITIES

Per- and Polyfluoroalkyl Substances (PFAS) Exposure Assessment

REPORT

National Center
for Environmental Health
Agency for Toxic Substances
and Disease Registry

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About ATSDR

The Agency for Toxic Substances and Disease Registry (ATSDR) is a federal public health agency of the U.S. Department of Health and Human Services (HHS). ATSDR works with other agencies and state, tribal and local governments to protect communities from harmful health effects related to exposure to natural and manmade hazardous substances. For more information about ATSDR, visit https://www.atsdr.cdc.gov/.

Abbreviations

9Cl-PF3ONS	9-Chlorohexadecafluoro-3-Oxanone-1-Sulfonic Acid
11Cl-PF3OUdS	11-Chloroeicosafluoro-3-Oxaundecane-1-Sulfonic Acid
AFFF	Aqueous Film Forming Foam, Also Known As “A Triple F”
ATSDR	Agency For Toxic Substances And Disease Registry
CDC	Centers For Disease Control And Prevention
DANG	Delaware Air National Guard
DNREC	Delaware Department Of Natural Resources And Environmental Control
DONA	4,8-Dioxa-3H-Perfluorononanoic Acid
EA	Exposure Assessment
EPA	U.S. Environmental Protection Agency
EtFOSAA	N-Ethyl Perfluorooctanesulfonamidoacetic Acid
FOD	Frequency Of Detection
FtS 4:2	Fluorotelomer Sulfonic Acid 4:2
FtS 6:2	Fluorotelomer Sulfonic Acid 6:2
FtS 8:2	Fluorotelomer Sulfonic Acid 8:2
HA	Health Advisory
HFPO-DA (GenX)	Hexafluoropropylene Oxide Dimer Acid
LOD	Limit Of Detection
MeFOSAA	N-Methyl Perfluorooctanesulfonamidoacetic Acid
MSC	Municipal Services Commission (City Of New Castle Water System)
µg/L, or ug/L	Micrograms Per Liter (Same As Parts Per Billion Or 1,000 Parts Per Trillion)
ng/g	Nanograms Per Gram (Same As Parts Per Billion Or Micrograms Per Kilogram)
NHANES	National Health And Nutrition Examination Survey
N-EtFOSA	N-Ethyl Perfluorooctanesulfonamide
N-EtFOSE	N-Ethyl Perfluorooctanesulfonamidoethanol
N-MeFOSA	N-Methyl Perfluorooctanesulfonamide
N-MeFOSE	N-Methyl Perfluorooctanesulfonamidoethanol
n-PFOA	Linear Isomer Of PFOA
n-PFOS	Linear Isomer Of PFOS
PFAS	Per- And Polyfluoroalkyl Substances
PFBA	Perfluorobutanoic Acid
PFBS	Perfluorobutane Sulfonic Acid
PFDA	Perfluorodecanoic Acid
PFDoA	Perfluorododecanoic Acid
PFDS	Perfluorodecane Sulfonic Acid
PFDoS	Perfluorododecanesulfonate
PFHpA	Perfluoroheptanoic Acid
PFHpS	Perfluoroheptane Sulfonic Acid
PFHxA	Perfluorohexanoic Acid
PFHxS	Perfluorohexane Sulfonic Acid

PFNA	Perfluorononanoic Acid
PFNS	Perfluorononane Sulfonic Acid
PFOA	Perfluorooctanoic Acid
PFOS	Perfluorooctane Sulfonic Acid
PFOSA	Perfluorooctanesulfonamide
PFPeA	Perfluoropentanoic Acid
PFPeS	Perfluoropentane Sulfonic Acid
PFTA	Perfluorotetradecanoic Acid
PFTrA	Perfluorotridecanoic Acid
PFUnA	Perfluoroundecanoic Acid
ppt	Parts Per Trillion (Same As 1 Nanogram Per Liter)
Sb-PFOA	Branched Isomers Of PFOA
Sm-PFOS	Branched Isomers Of PFOS
UCMR 3	Third Unregulated Contaminant Monitoring Rule

Executive Summary

Background and Purpose

PFAS (or per- and polyfluoroalkyl substances) are a family of synthetic chemicals that have been used in industry and consumer products since the 1950s. There are thousands of different PFAS. This assessment discusses some of the most commonly studied PFAS, including perfluorooctanoic acid (PFOA), Perfluorooctane Sulfonic Acid (PFOS), Perfluorohexane Sulfonic Acid (PFHxS), Perfluorononanoic Acid (PFNA), Perfluorodecanoic Acid (PFDA), Perfluoroundecanoic Acid (PFUnA), and N-Methyl Perfluorooctanesulfonamidoacetic Acid (MeFOSAA).

PFAS do not occur naturally but are widespread in the environment. They have been found in soil, water, air, and animal and plant life. Most PFAS (including PFOA, PFOS, PFHxS, and PFNA) are very resistant to breaking down or degrade into other PFAS that do not degrade further. Certain PFAS will therefore remain in the environment indefinitely. Major exposure routes for PFAS include drinking contaminated water and eating contaminated food, but exposure can also occur through other routes (i.e., ingestion of contaminated dust). Once PFAS enter people's bodies, some of them (including PFOA, PFOS, PFHxS, and PFNA) can remain in the blood for long periods. Most people in the United States have been exposed to PFAS. At least one PFAS was detected in more than 99% of NHANES samples collected for the 1999-2000 survey cycle.

The Centers for Disease Control and Prevention (CDC) and the Agency for Toxic Substances and Disease Registry (ATSDR) are conducting exposure assessments (EAs) in communities that were known to have PFAS in their drinking water and are near current or former military bases. This report shares results from in and around the City of New Castle in New Castle County, Delaware, near New Castle Air National Guard Base (the Base). When all EAs are complete, ATSDR will prepare a report describing the results across all sites.

Possibly as early as the 1970s, the Base used aqueous film forming foam (AFFF) containing PFAS for its firefighter training. Over time, the PFAS from the AFFF entered the ground, moved into the groundwater to offsite locations, and affected nearby municipal wells. In 2014, two drinking water systems serving the New Castle area, Artesian Water and Municipal Services Commission (MSC) of the City of New Castle, were found to contain PFAS levels exceeding the Environmental Protection Agency's (EPA) provisional health advisory (HA). Both water systems removed contaminated wells from service and upgraded their systems to reduce PFAS exposures, including installing granular activated carbon (GAC) filtration systems. Both systems mitigated PFAS concentrations to below the provisional HA in 2014. In 2016, one additional well in Artesian's system was found to exceed the (lower) 2016 EPA HA. Artesian took additional action to remove that well from service and reduce concentrations of PFAS in drinking water below the EPA HA. Final mitigation was achieved by MSC in August 2014 and by Artesian in July 2016. Based on the information ATSDR has reviewed, the Artesian and MSC public drinking water supplies currently meet or are below the EPA's 2016 HA for PFAS in drinking water. ATSDR does not recommend community members who get drinking water from the Artesian and MSC public water systems use alternative sources of water.

This EA assessed PFAS levels in the blood and urine of New Castle area residents living near New Castle Air National Guard Base. Test results were compared to PFAS levels in a nationally representative sample. Tap water and indoor dust samples from a subset of households were also analyzed for PFAS. These EA results will help participants and their communities better understand their PFAS exposure, allow ATSDR to provide recommendations to reduce exposure, and inform public health efforts related to protecting communities from sources of PFAS other than contaminated drinking water supplies.

ATSDR will use the data collected from this and other EAs to help inform future studies of PFAS water contamination.

Exposure Assessment Activities

ATSDR invited a randomly selected sample of New Castle County households to participate in this EA. To be eligible to participate, household residents must have (1) lived within the sampling frame and been served by the MSC drinking water system for at least 1 year before August 5, 2014, or by the Artesian Water system at least 1 year before July 18, 2016 (these residents have the greatest likelihood of past exposures to PFAS via the public drinking water supplies), (2) been greater than three years old at the time of sample collection, and (3) not been anemic or had a bleeding disorder that would prevent giving a blood sample. Results from randomly selected households allow ATSDR to estimate exposure for all community members, even those who were not tested.

In October 2019, 214 people (203 adults and 11 children) from 134 households participated in the EA sample collection event. ATSDR performed the following tasks:

- administered exposure history questionnaires to all participants
- collected blood and urine samples from most participants
- collected tap water and dust samples from the homes of 13 randomly selected participants
- tested 7 PFAS in blood, 14 in urine, 18 in water, and 33 in dust[1]
- measured PFHxS, PFOS, PFOA, PFNA, PFDA, and PFUnA across all media
- mailed individual biological and environmental results to participants in May 2020

This report summarizes community PFAS blood levels, measured in serum, for the group of New Castle County residents who participated in the EA. In this report, when we write blood levels of PFAS, we are referring to the measurement of PFAS in the serum fraction of the blood. This report also summarizes urine sample results from a subset of participants and presents results from the dust and tap water samples. Finally, the relationships between blood results and the environmental sampling data are explored. The New Castle County blood and urine data are compared to a nationally representative sample of the US population. Specifically, ATSDR compared New Castle County EA data to those collected by CDC as part of its National Health and Nutrition Examination Survey (NHANES). The NHANES survey collects blood and urine samples and tests them for chemicals, including PFAS, from a representative sample of the civilian non-institutionalized U.S. population. PFAS levels are also shown by age, race/ethnicity, sex, number of years living in the community, drinking water consumption patterns, and other exposure parameters.

The samples were collected and analyzed in strict accordance with ATSDR's *Exposure Assessment Protocol: Biological and Environmental Sampling of PFAS* (EA protocol) to ensure their quality. This EA was designed to estimate geometric mean concentrations of PFOS in blood for the sampling frame (all customers of the MSC water system and a small portion of customers from the Artesian Water system) population, with a precision goal of at least 15%. The precision is a measure of how wide the confidence interval is around the estimated geometric mean. ATSDR met this goal for PFOS, and precision for all other PFAS measured in this EA ranged from approximately 6% to 302%. ATSDR also calculated geometric means that were adjusted to the age distribution of the sampling frame population to correct for participation bias and to provide an estimate that is more generalizable to the sampling frame community. ATSDR also calculated geometric means that were adjusted to the national age distribution

[1] The laboratory reports branched and linear isomers of PFOA and PFOS in blood and urine. ATSDR reports on the sum of the individual isomer concentrations of PFOA and PFOS.

for comparison with the 2015–2016 NHANES survey. To assess possible relationships between blood levels and various demographic and exposure variables, ATSDR used statistical models. Univariate statistics were used to evaluate one variable at a time, mostly as a tool to examine the data broadly and find patterns within the data. Multivariate statistics and regression modeling were used to account for multiple variables simultaneously to control for potential confounding factors.

New Castle County Community-Wide Findings

Finding 1. Average blood levels of PFHxS, PFOS, PFOA, PFNA, and PFDA in the New Castle County EA site participants are higher than national levels.

Geometric means (i.e., averages) for PFHxS, PFOS, PFOA, PFNA, and PFDA blood levels were statistically higher ($p<0.05$) in New Castle County EA participants when compared to CDC's NHANES (2015–2016) testing, which was limited to people over 12 years old. The statistically higher blood PFAS levels were observed for both unadjusted geometric means for all EA participants and geometric means adjusted to the age distribution of the U.S. population from NHANES 2015–2016.

Of the PFAS analyzed in blood, PFHxS had the largest elevations when compared to national levels. The age-adjusted geometric mean blood PFHxS level among all New Castle County EA participants was 9.8 times higher than the national geometric mean. Blood PFHxS levels were above the national geometric mean for 99% of the New Castle County EA participants and above the NHANES 95th percentile for 86%. The age-adjusted geometric mean blood PFOS, PFOA, PFNA, and PFDA levels among New Castle County EA participants were 2.9, 2.4, 1.6, and 1.8 times higher, respectively.

PFUnA and MeFOSAA were detected in greater than 60% of samples, but ATSDR was unable to compare the geometric means calculated for these PFAS with NHANES because these PFAS were detected in fewer than 60% of NHANES samples.

Finding 2. Elevated blood levels of PFHxS, PFOS, and PFOA may be associated with past drinking water contamination.

Three PFAS (PFHxS, PFOS, and PFOA) with statistically elevated blood levels compared to national geometric means were detected in the MSC system as early as 2009 and in the Artesian Water system as early as 2014. We do not know if PFAS contamination began earlier, because data are not available before 2009 for the MSC system and 2014 for the Artesian Water system. The maximum concentrations observed in active drinking water wells in the MSC system were 1,400 parts per trillion (ppt) for PFHxS, 2,300 ppt for PFOS, and 440 ppt for PFOA. In the Artesian Water system, the maximum concentrations observed in active drinking water wells were 680 ppt for PFHxS, 1,800 ppt for PFOS, and 140 ppt for PFOA. In 2014, the MSC water supply system mitigated the contamination. The Artesian water supply system took similar action in 2014. In 2016, an additional well was found to be contaminated above the 2016 EPA HA so final mitigation in the Artesian system was not completed until 2016. However, these PFAS have long biological half-lives (2.1 to 35 years). Therefore, even though drinking water PFAS exposures in New Castle County were reduced in 2014 and 2016, past drinking water exposures were a likely contributing factor to the EA participants' elevated blood PFAS levels, observed 3 to 5 years later. PFHxS has the longest estimated half-life (up to 35 years) of the three compounds, which may be why it exceeded the NHANES 2015-2016 geometric mean by the largest margin.

PFHxS, PFOS, and PFOA were highly correlated in New Castle County EA participants' blood (Pearson correlation coefficient, *r* between 0.83 and 0.94). This means that, typically, residents who had elevated blood PFHxS levels also had elevated blood PFOS and blood PFOA levels. This correlation suggests a common exposure source, such as the public water supplies, though other sources of exposure may also have contributed to the observed blood levels.

Additional observations support the finding that past exposure to contaminated drinking water may have contributed to the elevated blood levels.

- First, in univariate and multivariate models, a consistent predictor of participant blood PFHxS, PFOS, and PFOA levels was how long the resident had lived in New Castle County during the past 20 years. Those who lived in the area longest had the highest PFHxS, PFOS, and PFOA blood levels—and also likely drank the contaminated water for the longest period.
- Second, in univariate and multivariate analyses, adults who used at least one filter or treatment device had statistically lower PFHxS, PFOS, and PFOA blood levels when compared to those who did not have a filter.

ATSDR also considered differences in participants' public water systems. In multivariate analyses, participants who lived in the MSC service area had significantly higher blood PFHxS (247%), PFOS (148%), and PFOA (25%) levels than participants who lived in the Artesian Water service area. The differences between the water systems were consistent with the degree of historical contamination (i.e., higher historical PFAS levels in MSC public water and higher blood PFAS levels in residents served by MSC).

In contrast, while blood levels of PFNA and PFDA in New Castle County EA participants were statistically elevated compared to the U.S. population, few drinking water related variables were associated with these PFAS in the blood of participants.

Finding 3. Sex, kidney disease, and cleaning frequency were associated with some PFAS blood levels.

PFAS blood levels varied with different demographic and exposure characteristics of the participant population. The following statistically significant relationships in the New Castle County EA data set were observed in adult participants (and are consistent with those reported in other non-ATSDR PFAS studies):

- Males had statistically higher blood levels of PFOS than females. Specifically, multivariate models found blood levels in adult males to be 28% higher than adult females for PFOS.
- Adult participants who reported a history of kidney disease had PFHxS blood levels that were 56% higher in multivariate models than those who did not report kidney disease. Only 6% (n=13) of adult participants reported a history of kidney disease, so these results should be interpreted with caution.
- Adult participants who reported cleaning their homes three times per week or more had PFHxS and PFOS blood levels that were 42% and 34% lower than adult participants who reported cleaning their homes a few times per month or less.

Most associations in children (<18 years) could not be evaluated because of the small number of child participants (n=11). However, blood levels of PFHxS and PFOS increased with self-reported water consumption levels at school; this finding should be interpreted with caution due to the small number of children who participated in the EA. The final report on all EA sites will include a more robust analysis of children.

Finding 4. Only one PFAS was detected in urine and at low concentrations.

ATSDR analyzed 22 (10%) of the urine samples collected. Only perfluorobutanoic acid (PFBA) was detected; it was detected in 59% of the 22 samples that were analyzed. ATSDR did not analyze all participants' urine samples because none of the species were detected in more than 60% of the samples analyzed.

Finding 5. All New Castle County tap water samples collected during the EA in 2019 met the EPA's HA for PFAS in drinking water.

This is based on 13 unfiltered and 7 filtered tap water samples collected in 13 households (3 serviced by Artesian Water and 10 serviced by MSC) during the EA.

Finding 6. Patterns and levels of dust contamination measured in participating EA households are comparable to those reported in selected U.S. studies.

Among the PFAS detected most frequently in household dust samples, PFBA, PFOA, and PFOS were measured at the highest concentrations. No nationally representative comparison values are available, but geometric mean and median concentrations for PFAS measured in dust collected in a small subset of participating households (n=13) were within the range of levels reported in a few published studies looking at other U.S. communities (with or without PFAS contamination). None of the PFAS measured in this EA's household dust samples were statistically correlated with the same PFAS measured in participants' blood. The final aggregate report on all EA sites will include a more robust comparison of PFAS measured in dust and blood.

Limitations

There are several limitations associated with this assessment.

- The random sampling recruitment method used for this EA was designed to measure blood PFAS concentrations that were generalizable to all New Castle County residents who were customers of the MSC water system and a small portion of customers from the Artesian Water system. However, the EA participant sample may not be fully representative of the community. Only 5% of the households from the random sample participated in the EA sample collection event, and participant characteristics were different than those of the area's overall population. Participants were older and less likely to be Black. ATSDR addressed some of these differences by calculating geometric mean estimates that were adjusted to the age distribution of the community.
- Measurement of blood, urine, and environmental PFAS concentrations in EA participants may improve the understanding of exposure in this community but will not provide discrete information about all sources of exposure. Additionally, identifying every potential confounding exposure is not possible.
- There are challenges in measurement of trace levels of PFBA in urine, including selectivity of the analytical instrumentation and potential for external contamination. Therefore, we advise caution when interpreting the PFBA results in urine.
- Multivariate regression models did explain a moderate portion of the variability in participants' blood PFHxS and PFOS levels (R-squared or R^2, a measure of model goodness-of-fit, ranged between 0.41 and 0.49, in the "all adult" models), but explained a smaller portion of blood PFOA levels ($R^2 = 0.22$). This means that other factors not identified could influence the relationships reported in this assessment (see "Statistical Analysis" section for details).
- This study did not directly assess tap water consumption prior to the reduction of PFAS from the two public water supplies.
- This EA was not designed to investigate health outcomes. Without additional information about exposure-response relationships, the results of this EA cannot be used to assess current or past health problems or predict the future occurrence of disease. PFAS found in a person's blood or urine means that exposure has occurred. The presence of PFAS in blood or urine does not tell us

how, where, when, or for how long a person was exposed to PFAS. Exposure to PFAS does not mean adverse health effects will result, either now or in the future.

- The dust results are exploratory and should be interpreted with caution. They are based on a limited set of samples, and in some cases those samples are based on a small sample amount.

Recommendations

This PFAS EA provides evidence that past exposures to PFAS in drinking water have impacted the levels of PFAS in people's bodies. These PFAS are eliminated from the body over a long period of time. This allowed ATSDR to measure PFAS even though exposures through drinking water were mitigated, or lowered, years ago.

Although the exposure contribution from PFAS in drinking water in Artesian Water and MSC systems has been mitigated, there are actions community members and local officials can take to further reduce exposures to PFAS and protect public health.

Based on the PFAS drinking water test results from the Artesian and MSC water systems, ATSDR does not recommend an alternate source of drinking water at this time.

1. What Artesian Water and MSC can/should do:
    a. Operators of the two public water systems should continue to monitor concentrations of PFAS in drinking water delivered to the New Castle County community to ensure that concentrations of PFAS remain below the EPA's HA for specific PFAS in drinking water. Results of PFAS monitoring should be shared with community members through appropriate communication channels (Consumer Confidence Reports for Artesian Water, https://www.artesianwater.com/my-bills-services/water-quality-reports/; Consumer Confidence Reports for MSC, https://newcastlemsc.delaware.gov/consumer-confidence-reports/).
    b. All treatment systems to remove PFAS from the drinking water in the Artesian Water and MSC systems should be maintained appropriately to ensure that PFAS concentrations remain below the EPA's HA for specific PFAS in drinking water.
2. What community members can/should do:
    a. Become familiar with Consumer Confidence Reports (Artesian Water, https://www.artesianwater.com/my-bills-services/water-quality-reports/; MSC, https://newcastlemsc.delaware.gov/consumer-confidence-reports/) for information on each system's water quality.
    b. Nursing mothers should continue breastfeeding. Based on current science, the known benefits of breastfeeding outweigh the potential risks for infants exposed to PFAS in breast milk.
    c. When possible, eliminate or decrease potential exposure to PFAS in consumer products such as stain-resistant products and food packaging materials. To learn more visit: https://www.fda.gov/food/chemical-contaminants-food/questions-and-answers-pfas-food
    d. Pay attention to advisories about food consumption, such as local fish advisories.
    e. Discuss any health concerns or symptoms with your health care provider. Share results of PFAS blood testing with your health care provider and make them aware of ATSDR resources for clinicians (https://www.atsdr.cdc.gov/pfas/resources/info-for-health-professionals.html). Follow the advice of your health care provider and the recommendations for checkups, vaccinations, and health screening tests.

f. At this time, ATSDR does not have plans to conduct additional blood testing for PFAS nor recommend PFAS EA participants get individually retested for PFAS in blood.

   - The biological half-lives of many of the PFAS measured in people's blood are long. PFHxS, in particular, has one of the longest half-lives–some estimates range in the decades. This means that PFAS blood levels are not expected to change significantly in the near-term, even if exposure stops. Additionally, it is unclear what an individual's PFAS test results mean in terms of possible health effects.

   For the general population, blood tests for PFAS are most useful when they are part of a scientific investigation like the EA. Test results tell you how much of each PFAS is in your blood, but it is unclear what the results mean in terms of possible health effects. In addition, blood testing for PFAS is not a routine test offered by most doctors or health departments. If you are concerned about the effect of PFAS on your health, talk to your health care provider and make them aware of ATSDR resources for clinicians (https://www.atsdr.cdc.gov/pfas/resources/info-for-health-professionals.html).

g. Follow the advice of your child's health care provider and the recommendations for well child checkups, vaccinations, and recommended health screening tests. Consult https://health.gov/myhealthfinder to help identify those vaccinations and tests.

h. For additional information about environmental exposures and children's health, contact the Pediatric Environmental Health Specialty Units, a nationwide network of experts in reproductive and children's environmental health (https://www.pehsu.net/).

For More Information

If you have questions or comments or want more information on the New Castle County EA site, call 800-CDC-INFO or email pfas@cdc.gov. For more information on the work CDC/ATSDR is doing to address PFAS exposure, visit ATSDR's PFAS website: https://www.atsdr.cdc.gov/pfas/. For other EA or PFAS-related questions, email pfas@cdc.gov.

Background and Purpose

The Centers for Disease Control and Prevention (CDC) and the Agency for Toxic Substances and Disease Registry (ATSDR) are conducting exposure assessments (EAs) in communities near current or former military bases that are known to have had per- and polyfluoroalkyl substances (PFAS) in their drinking water. One of these communities is in and around the City of New Castle in New Castle County, Delaware. This report summarizes the findings of the New Castle County EA. When all EAs are complete, ATSDR will prepare a report describing the results across all sites.

EA participants were recruited among New Castle County residents living near the New Castle Air Force Base who received drinking water from the Municipal Services Commission (MSC) or Artesian Water public water systems that had PFAS levels above state or federal guidelines. For more information and a map of the area see the "Methods" section of the report.

The EA involved collecting responses to exposure history questionnaires, biological samples (blood and urine), and environmental samples (tap water and household dust). ATSDR collected biological samples and administered questionnaires at the New Castle Visitor Center at 30 Market Street in New Castle between October 16 and October 27, 2019. During the same time frame, ATSDR also took water and dust samples in a subset of randomly chosen participant homes.

The results of the EA

- tell us the amount of PFAS in the blood and urine of individual participants and the New Castle County community and how these levels compare to the general U.S. population,
- tell us the amount of PFAS in the urine of a subset of individual participants and the EA community and how these levels compare to the general U.S. population,
- provide a better understanding of environmental factors that affect PFAS exposure,
- provide information that may be used to stop or reduce PFAS exposure,
- produce information that public health professionals can use to help communities affected by PFAS, and
- inform future studies looking at the effect of PFAS exposure on human health.

The EA does not look at what types of health problems are associated with exposure and is not meant to determine if PFAS levels in blood or urine are risk factors for illness now or later in life. Additionally, the EA does not tell us exactly how or where people were exposed or when or how long PFAS exposure lasted.

ATSDR's *Exposure Assessment Protocol: Biological and Environmental Sampling of PFAS,* termed the PFAS EA Protocol [ATSDR 2019a], provides additional background, describes the criteria for selecting communities for the EAs, and highlights the procedures ATSDR used in conducting the EAs.

What Are PFAS?

Human exposure to PFAS is a growing environmental health concern. PFAS are synthetic chemicals used in many industries and consumer products since the 1950s. They have been used in nonstick cookware; water-repellent clothing; stain-resistant fabrics and carpets; cosmetics; firefighting foams; and products that resist grease, water, and oil [Buck et al. 2011; Gluge et al. 2020; Wang et al. 2017]. Exposure to PFAS has been associated with increased cholesterol, decreased vaccine response in children, changes in liver enzymes, small decreases in infant birth weights, increased risk of high blood pressure or pre-eclampsia in pregnant women, and increased risk of kidney and testicular cancer [ATSDR 2021].

There are thousands of different PFAS. This assessment discusses some of the most commonly studied PFAS, which include perfluorooctanoic acid (PFOA), perfluorooctane sulfonic acid (PFOS), perfluorohexane sulfonic acid (PFHxS), perfluorononanoic acid (PFNA), perfluorodecanoic acid (PFDA), and perfluoroundecanoic acid (PFUnA). The manufacture and import of PFOA, precursor chemicals that can break down to PFOA, and related higher homologue chemicals, have been mostly phased out in the United States. However, existing stocks of PFOA might still be used, and there might be PFOA in some imported articles. PFOS manufacture in the United States has not been reported to the EPA since 2002, however, there are some limited ongoing uses of PFOS. These PFAS with long perfluoroalkyl chains are no longer produced in the United States because of concerns over long biological half-lives. Other countries may still manufacture and use them, but U.S. manufacturers have replaced these compounds with shorter chained PFAS which typically have shorter biological half-lives. Some of the PFAS discussed in this report, such as N-methyl perfluorooctanesulfonamidoacetic acid (MeFOSAA), are considered precursors that can degrade in the environment or in people to other PFAS [ATSDR 2021; Gluge et al. 2020; Wang et al. 2017].

PFAS do not occur naturally but are widespread in the environment. PFAS can be released into the environment during their production, use, or disposal. PFAS have been found in air, water, soil, sediment, animal and plant life, and air. Most PFAS (including PFOA, PFOS, PFHxS, and PFNA) are either very resistant to breaking down or degrade into other PFAS that do not degrade further. Certain PFAS will therefore remain in the environment indefinitely. Most people in the United States have been exposed to PFAS. At least one PFAS was detected in more than 99% of NHANES samples (1999-2000 survey cycle) [Calafat et al. 2007a]. Exposure can occur via contaminated drinking water for which ingestion is believed to be the primary exposure route. Studies have shown that showering, bathing, and swimming in water containing PFAS at levels seen in New Castle and Wilmington Manor (a census designated place adjacent to the City of New Castle) are not expected to be an important contributor to PFAS exposure relative to the contribution from drinking water [Sunderland 2019].

ATSDR's PFAS EAs focused on communities with known exposures via contaminated drinking water. However, residents may have had additional exposures to PFAS, such as from the following [Sunderland 2019]:

- eating food packaged in materials containing PFAS (e.g., popcorn bags, fast food containers, pizza boxes)
- eating fish or shellfish caught in PFAS-contaminated waters
- using consumer products, such as stain-resistant carpeting and water-repellent clothing
- eating garden vegetables grown with PFAS-contaminated water or soil
- accidentally swallowing PFAS-contaminated soil
- drinking infant formula mixed with PFAS-contaminated water
- consuming breastmilk from women exposed to PFAS
- gestational exposure to PFAS
- working in industries that manufacture, process, or use products containing PFAS
- background exposure to PFAS due to their ubiquitous nature

ATSDR asked study participants about these types of potential exposures to evaluate whether these exposures might influence PFAS levels in the EA communities.

After PFAS enter the human body, some PFAS can remain there for a long time. Some studies estimate that the half-life of PFHxS is between 4.7 and 35 years [ATSDR 2021]. Half-life estimates range from 3.3 to 27 years for PFOS and from 2.1 to 10.1 years for PFOA [ATSDR 2021].

The body of science about PFAS exposure and health effects is growing rapidly. Some, but not all, scientific studies have shown that exposure to certain PFAS may be linked to harmful health effects. While this EA does not examine specific health outcomes associated with PFAS exposure, EA findings might help inform future studies on how PFAS exposure affects human health.

Why New Castle County?

New Castle County was one of several sites located near military installations with identified PFAS drinking water contamination from use of products such as aqueous film forming foam (AFFF). When selecting EA sites, ATSDR considered the extent of PFOA and PFOS contamination in drinking water supplies, the duration over which exposure may have occurred, and the number of potentially affected residents.[2]

PFAS and precursors that degrade to other compounds measured in this EA were used in historical AFFF formulations. Two types of PFAS-containing AFFF were manufactured before 2016 [ITRC 2020]. Both formulations contained PFAS or PFAS precursors, the use of which resulted in the release of PFOS, PFHxS, PFOA, and PFHxA into the environment. Possibly as early as the 1970s, the Delaware Air National Guard Base used AFFF containing PFAS for its firefighter training. Over time, the PFAS from the AFFF moved off site in groundwater and contaminated nearby public drinking water supply wells.

The Delaware Air National Guard (DANG) identified non-PFAS contamination in public drinking water wells near the Base and the New Castle Airport. In 2014, the Delaware Department of Natural Resources and Environmental Control (DNREC), in coordination with the U.S. Environmental Protection Agency (EPA), conducted a site inspection of the New Castle Airport and Base area and began monitoring groundwater for PFAS. DNREC identified the Base and the airport as potential PFAS release areas [DANG 2018].

When PFAS first entered the Artesian Water and the Municipal Services Commission (MSC) public water systems serving residents in New Castle County is not known. These substances were first detected in the MSC water system in 2009, which is the first time that MSC water was tested for PFAS. MSC collected samples, sent them to three different laboratories, and received conflicting results. MSC decided to revisit the PFAS contamination issue in 5 years. In 2013 and 2014, Artesian Water conducted testing to fulfill requirements of the U.S. EPA's Third Unregulated Contaminant Monitoring Rule (UCMR 3). The rule required testing for six PFAS. On June 2, 2014, EPA notified Artesian Water that the levels measured in a treatment plant (Wilmington Manor 3) during UCMR 3 were above EPA's provisional health advisory at the time, which was 400 parts per trillion (ppt) for PFOA and 200 ppt for PFOS. Artesian Water immediately removed the Wilmington Manor 3 from service and notified customers [Artesian 2014].

Artesian Water also notified MSC, a neighboring water utility, of PFAS contamination detected in the area. MSC retested their water sources and detected PFAS above EPA's provisional health advisory. The highest sampling result from an active well in the MSC system was 1,400 parts per trillion ppt for PFHxS, 2,300 ppt for PFOS, and 440 ppt for PFOA. MSC inactivated all groundwater wells on August 5, 2014, and began purchasing water from Artesian Water. On December 16, 2014, MSC began using its groundwater wells again after a granular activated carbon (GAC) filtration system was installed.

In May 2016, EPA issued a lifetime health advisory for the sum of PFOA and PFOS levels in drinking water (70 ppt). PFAS levels previously observed in other water sources in the Artesian Water system were above this health advisory. Artesian Water removed additional wells from service and installed GAC

[2] PFHxS data were not available for all sites evaluated so were not considered in the site selection process even though water contaminated by AFFF often has higher concentrations of PFHxS than PFOA or PFOS.

filtration systems. The final contaminated water source was taken offline on July 18, 2016. The highest sampling results from an active well was 680 ppt for PFHxS, 1,800 ppt for PFOS, and 140 ppt for PFOA. In 2017, the DNREC confirmed that the GAC filtration systems had reduced levels of two specific PFAS, PFOS and PFOA, below the EPA health advisory.

The information available to ATSDR indicates that in 2019, Artesian Water's and MSC's drinking water met or were below the EPA's HA for PFAS in drinking water.

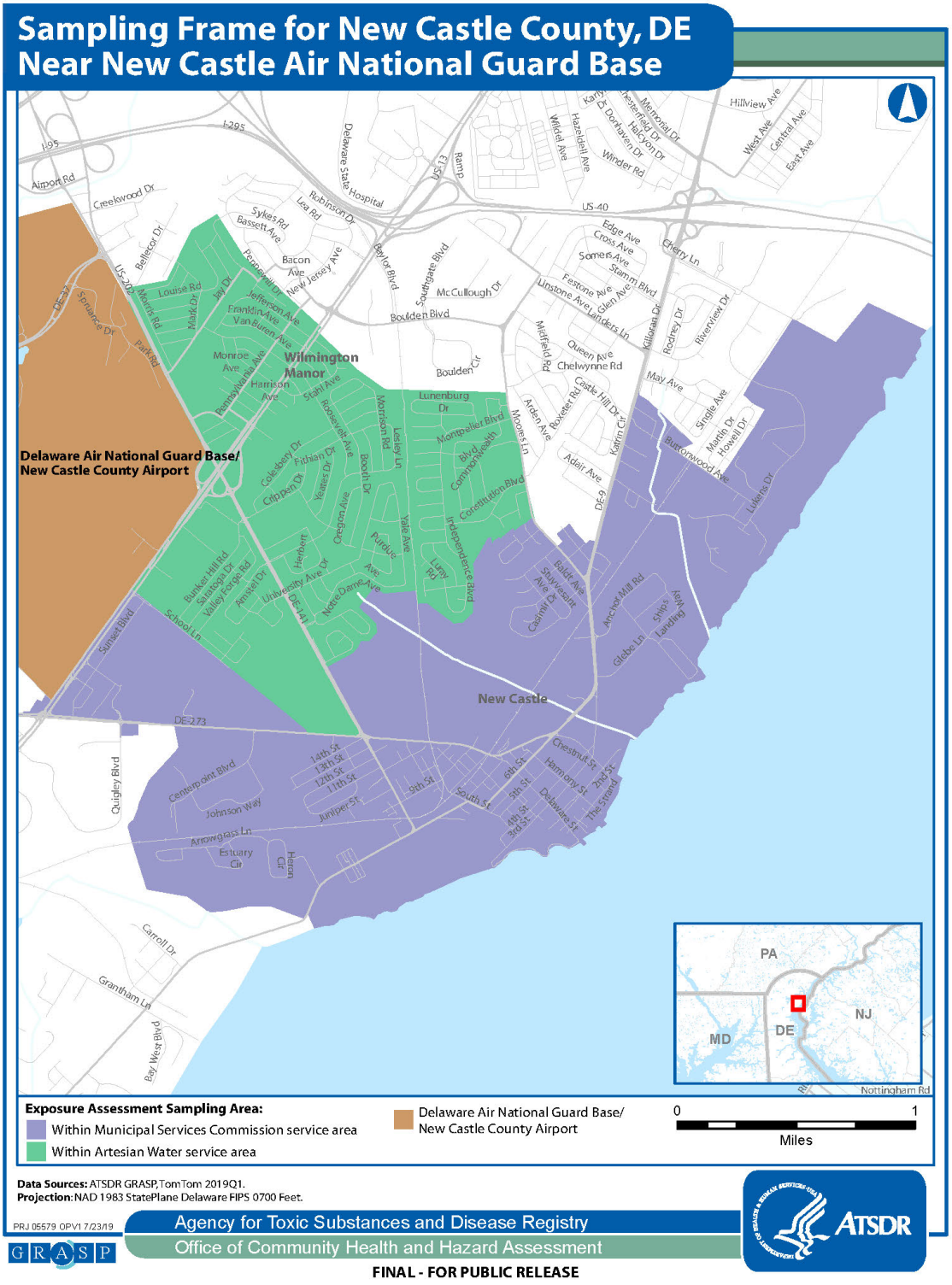
Methods

ATSDR's PFAS EA Protocol [ATSDR 2019a] details the approaches used to recruit participants, collect samples, administer exposure history questionnaires, and evaluate data. This section briefly describes how those methods were applied to the New Castle County EA.

Sampling Frame

This EA targeted a specific geographic area, called the sampling frame or sampling area. The sampling frame for this EA included two areas (see Figure 1). One was a portion of the Artesian Water service area in Wilmington Manor, Delaware. The other was the City of New Castle, Delaware, served by the municipal water system, MSC. Based on a review of New Castle County land parcel data, ATSDR determined that 6,998 households were located in the sampling frame. These households formed the sampling frame from which households were randomly selected for recruitment.

Figure 1. Sampling frame for the New Castle County Exposure Assessment



Participant Eligibility

New Castle County residents who were randomly selected to participate and met the following criteria were eligible to participate in the EA:

- Lived within the sampling frame for at least one year before August 5, 2014, for customers of the MSC water system or at least one year before July 18, 2016, for customers of the Artesian Water system. These dates correspond to when the water systems reduced PFAS drinking water concentrations below EPA's health advisory.
- Were at least 3 years old at the time of recruitment. This age criterion was used because national reference values are not available for children under the age of three.
- Did not have bleeding disorders and were not anemic, unless they confirmed with their doctor the ability to safely provide a blood sample.

People potentially exposed to PFAS occupationally, such as firefighters, active-duty military, and veterans, were able to participate if they met the three eligibility criteria. Participants did not receive incentives and paid no costs to participate.

Participant Recruitment

ATSDR randomly selected 3,000 households in the sampling frame for recruitment. This number was chosen to attempt to achieve the protocol recruitment target of 395 participants. Every household had an equal chance of being selected, and all members of randomly selected households who met eligibility criteria were invited to participate. This type of recruitment, called a one-stage cluster sampling design, means that a single household may have multiple participants.

Measuring PFAS in the blood of people from randomly selected households allowed ATSDR to estimate exposure to PFAS from public drinking water for the entire community (the sampling frame) in the affected area, even those who were not tested.

Recruitment was done through mailings, phone calls, and in-person visits to households that had not been reached by phone. Each household for which ATSDR had a phone number received a minimum of three recruitment call attempts. In each attempt, ATSDR called all working phone numbers (cell phone and landline) associated with a household. For calls that went to voicemail, ATSDR staff left messages encouraging residents to call back to schedule appointments. Door-to-door recruitment occurred after each household had received an initial outreach letter and at least one recruitment call attempt.

Results from the randomly selected participants can provide information about community-level exposure. Had ATSDR accepted volunteers, results could not be used to estimate exposure across the New Castle County EA sampling frame. After two waves of recruitment (initially reaching out to 885 households and later reaching out to an additional 2,115 households), 244 residents from 151 households scheduled appointments for biological sampling appointments and questionnaire completion.

ATSDR attempted to recruit approximately 10% of participating households for environmental sampling (i.e., 122 households from which at least one person had scheduled an appointment at the time environmental recruitment calls were made). ATSDR invited 42 households in two recruitment waves. In total, ATSDR scheduled 14 environmental sampling appointments.

Data Collection and Analysis

The New Castle County EA involved collection of three types of data: questionnaires, biological samples (blood and urine), and environmental samples (tap water and household dust). The ATSDR project team collected biological samples and administered questionnaires at the New Castle Visitor Center at 30 Market Street in New Castle between October 16 and October 27, 2019. During the same time frame, ATSDR also collected environmental samples in a subset of randomly chosen participant homes. All data met the stringent quality control requirements for sample collection and analysis.

Before any data collection, ATSDR obtained written consent from the participants. The purpose of the consent process was to ensure participants were fully aware of the purpose of the EA, sample collection procedures, benefits and risks of participating, and privacy protections. Copies of consent forms are included in the PFAS EA Protocol.

ATSDR project staff handled all data collected in accordance with the *Standard Operating Procedures of PFAS Exposure Assessment Data Management* [ATSDR 2019b]. These procedures have very strict requirements for handling any personally identifiable information. ATSDR project staff protected this information to the extent required by federal and Delaware law. All signed consent forms were mailed to and are securely archived at ATSDR headquarters. Questionnaire data were collected using dedicated encrypted laptops with no internet access, and these data were transferred at program completion to ATSDR's secure data network. All information provided by participants was kept confidential, and no personally identifiable information appears in any of ATSDR's public reports for this site.

Table 1, at the end of this section, provides more details on the number of participants enrolled and the final number of samples collected during this EA. Table 2 lists the PFAS measured in the EA's biological and environmental samples.

Biological Sampling and Questionnaire Administration

Of the 244 residents who scheduled data collection appointments, 216 (89%) participated in the EA. ATSDR administered exposure history questionnaires to these 216 participants: 204 adults 18 and older, and 12 children between the ages of 3 and 17. Both addressed topics relevant to PFAS exposure, such as residential and work histories, drinking water habits, and use of PFAS-containing consumer products.

Phlebotomists collected blood samples from 214 participants. The phlebotomists were not able to collect samples from 2 participants because they lacked viable veins or refused to provide a blood sample. ATSDR processed the blood samples in the field, aliquoting the serum portion of the blood.

After the sampling was complete and upon further review of each participant's residential history, ATSDR determined that all participants had lived in the sampling frame for at least one full year before the applicable eligibility date. This means that all 214 blood samples (203 adults and 11 children) were considered in the community statistics. These samples were collected from participants residing in 134 unique households. This represents a household participation rate of 4.5% (i.e., 4.5% of the 3,000 recruited households had at least one person participate in the EA).

Urine samples were collected from 216 participants (204 adults and 12 children). Per the EA protocol, 10% of the urine samples were randomly selected for initial analysis. These 22 samples were collected from participants (18 adults and 4 children) who resided in 20 unique households.

CDC's National Center for Environmental Health laboratory analyzed the serum portion of blood and urine samples for the suite of PFAS measured in the 2015–2016 National Health and Nutrition Examination Survey (NHANES) [CDC 2019]. As part of NHANES, CDC takes blood and urine samples and tests them for chemicals, including PFAS, from a representative sample of 5,000 people across the

country during each two-year cycle. All laboratory analyses followed established procedures for quality assurance and control according to the Center's methodology.

During the consent process, participants were given the option to allow ATSDR to store biological samples for potential future PFAS analysis. Blood and urine samples from participants who provided this consent are being stored frozen at CDC for potential future analysis.

Environmental Sampling

ATSDR collected tap water and dust samples from 13 of the 14 households that had initially scheduled appointments. One household was unavailable to keep their scheduled environmental sampling appointment. At each participating household, ATSDR collected a drinking water sample from the kitchen tap. If point-of-use filtration was in place, ATSDR project staff attempted to collect a sample before and after filtration. Tap water samples were collected and analyzed in accordance with EPA's *Method 537.1: Determination of Selected Per- and Polyfluorinated Alkyl Substances in Drinking Water by Solid Phase Extraction and Liquid Chromatography/Tandem Mass Spectrometry* [Shoemaker and Tettenhorst 2018].

Project staff also collected a composite dust sample from the floor at a minimum of three locations inside each selected home: the primary living space as identified by the homeowner (e.g., living room, family room, television room), the kitchen, and the bedroom in which participants reported spending the most time. Dust collection was intended to generate more information about the contribution of non-drinking-water exposures to overall PFAS exposure. Participants were instructed not to vacuum carpeting or sweep floors for five days prior to the scheduled visit. Adapting methods described in Scher et al. [2018], ATSDR collected dust samples using a high-volume air sampler connected to an open-faced 37 millimeter filter cassette with an 0.8 micron filter. A wooden 2 square foot (ft^2) sampling template was used to mark off each sampling area. ATSDR project staff attempted to collect at least 1 gram of dust from each home by vacuuming the same 2 ft^2 surface at least four times with the cassette (vertically, horizontally, and in circles). Samples were taken preferentially from mats, carpets, and area rugs. Household dust samples were analyzed in accordance with SGS AXYS Method MLA-110 (revision 01, version 06), *Analytical Procedure for the Analysis of Per- and Polyfluoroalkyl Substances (PFAS) in Aqueous Samples, Solids and Solvent Extracts by LC-MS/MS* [SGS AXYS 2019].

The environmental samples collected during the EA were consumed in the analytical process and are not available for potential future analysis.

Table 1. Summary of recruitment and data collection efforts

Recruitment	
Households invited to participate by mail	3,000
Wave 1 of recruitment	*885*
Wave 2 of recruitment	*2,115*
Households reached by mail	2,698
Households reached by phone	1,004
Household door-to-door visits	2,404
Biological sampling:	
Individuals enrolled	244
Households enrolled	151
Environmental sampling:	
Wave 1 Households invited	*26*
Wave 2 Households invited	*16*
Households enrolled	14
Data Collection	
Completed questionnaires	216
Adults	*204*
Children	*12*
Blood samples	
Included in community statistics (134 households)	214
Adults	*203*
Children	*11*
Urine samples	
Collected	216
Adults	*204*
Children	*12*
Included in community statistics (20 households)	22
Adults	*18*
Children	*4*
Dust samples collected and analyzed (one composite sample per household)	13
Tap water samples collected and analyzed (13 households)	20
Filtered	7
Unfiltered	13

Table 2. List of PFAS measured for in blood, urine, tap water, and dust

PFAS Abbreviation	PFAS Chemical Name	Measured in Blood?	Measured in Urine?	Measured in Water?	Measured in Dust?
PFBS	perfluorobutane sulfonic acid		✓	✓	✓
PFPeS	perfluoropentane sulfonic acid				✓
PFHxS	perfluorohexane sulfonic acid	✓	✓	✓	✓
PFHpS	perfluoroheptane sulfonic acid				✓
PFOS	perfluorooctane sulfonic acid	✓	✓	✓	✓
n-PFOS	sodium perfluoro-1-octanesulfonate	✓	✓		
Sm-PFOS	mixture of sodium perfluoro-5-methylheptane sulfonate isomers	✓	✓		
PFNS	perfluorononane sulfonic acid				✓
PFDS	perfluorodecane sulfonic acid				✓
PFDoS	perfluorododecanesulfonate				✓
PFBA	perfluorobutanoic acid		✓		✓
PFPeA	perfluoropentanoic acid		✓		✓
PFHxA	perfluorohexanoic acid		✓	✓	✓
PFHpA	perfluoroheptanoic acid		✓	✓	✓
PFOA	perfluorooctanoic acid	✓	✓	✓	✓
n-PFOA	ammonium perfluorooctanoate	✓	✓		
Sb-PFOA	mixture of perfluoro-5-methylheptanoic acid isomers	✓	✓		
PFNA	perfluorononanoic acid	✓	✓	✓	✓
PFDA	perfluorodecanoic acid	✓	✓	✓	✓
PFUnA	perfluoroundecanoic acid	✓	✓	✓	✓
PFDoA	perfluorododecanoic acid			✓	✓
PFTrA	perfluorotridecanoic acid			✓	✓
PFTA	perfluorotetradecanoic acid			✓	✓
PFOSA	perfluorooctanesulfonamide				✓
N-MeFOSA	N-methylperfluorooctanesulfonamide				✓
MeFOSAA	N-methyl perfluorooctanesulfonamidoacetic acid	✓		✓	✓
N-MeFOSE	N-methylperfluorooctanesulfonamidoethanol				✓
N-EtFOSA	N-ethylperfluorooctanesulfonamide				✓
N-EtFOSAA	N-ethyl perfluorooctanesulfonamidoacetic acid			✓	✓
N-EtFOSE	N-ethylperfluorooctanesulfonamidoethanol				✓
FtS 4:2	fluorotelomer sulfonic acid 4:2				✓
FtS 6:2	fluorotelomer sulfonic acid 6:2				✓
FtS 8:2	fluorotelomer sulfonic acid 8:2				✓
HFPO-DA (GenX)	hexafluoropropylene oxide dimer acid		✓	✓	✓
DONA	4,8-dioxa-3H-perfluorononanoic acid		✓	✓	✓
9Cl-PF3ONS	9-chlorohexadecafluoro-3-oxanone-1-sulfonic acid		✓	✓	✓
11Cl-PF3OUdS	11-chloroeicosafluoro-3-oxaundecane-1-sulfonic acid			✓	✓

Statistical Analysis

The EA Protocol describes the statistical methods used. Briefly, the data objectives of this EA were to (1) estimate geometric mean concentrations of PFAS in the sampling frame population (with a precision target of at least 15% and a 5% level of significance for PFOS), (2) compare community level data to national levels, and (3) explore relationships between questionnaire data and measured biological and environmental data.

ATSDR processed the PFAS sampling results in two ways before performing statistical analyses:

- First, ATSDR substituted all non-detect observations with a value equal to the limit of detection (LOD) divided by the square root of 2. (A non-detect result means the sample did not contain enough PFAS to be reliably measured by this project's highly sensitive laboratory methods.) This substitution method is consistent with that applied in CDC's NHANES. Note that Appendix B provides the results of a sensitivity analysis exploring alternate substitution approaches.
- Second, ATSDR calculated the total PFOA and total PFOS concentrations measured in each blood and urine sample. The laboratory reports two different measurements for PFOA and PFOS. For PFOA, the laboratory reports the amount of branched PFOA (Sb-PFOA) measured in the sample separate from the amount of linear PFOA (n-PFOA) in the same sample. ATSDR summed these values and performed statistical analyses using total PFOA results. Similarly, ATSDR calculated total PFOS by summing the linear PFOS (n-PFOS) and branched PFOS (Sm-PFOS) concentrations. These same summation methods are applied to NHANES data.

For blood and urine, ATSDR first calculated summary statistics for each PFAS (i.e., frequency of detection, maximum detected concentration, geometric mean, 95% confidence intervals around the geometric mean, and 25th, 50th [median], 75th, 90th, and 95th percentiles). The protocol specified that geometric means would be calculated if >=60% of samples had detections. Geometric means were calculated as the measures of central tendency because of the lognormal distribution

Statistical Terms

Geometric mean: The geometric mean is a type of average and provides an estimate of the central point of a set of numbers. It is often used for environmental data that exhibit a skewed distribution (e.g., a data set with several values that are much higher than the rest of the results). The geometric mean is less influenced by high values than an arithmetic mean.

Percentiles (25th, 50th, 75th, 90th, 95th): A percentile provides additional information about the distribution of a data set and represents the value below which a certain percentage of the data fall. For example, a 95th percentile of 25 micrograms per liter (µg/L) indicates that 95% of results fall below this concentration.

Confidence intervals: A confidence interval provides information about the reliability of a statistic. In this EA, ATSDR estimated geometric means for the PFAS blood levels measured among study participants. The 95% confidence interval around the geometric mean represents the range within which the true population mean is expected to lie. More specifically, if we hypothetically repeated the study 100 times, 95 times out of 100 the mean of the sampling frame population would fall within this range.

Precision: Precision provides information on the reproducibility of a study and is associated with sample size. The larger the sample size the higher the precision. In the context of this EA, precision was estimated based on the width of confidence intervals around the geometric mean. A wide confidence interval indicates low precision while a narrow confidence interval suggests high precision.

of blood and urine measurements. Note that many of the statistics could not be calculated for urine due to the low detection frequency.

One of the objectives of this EA was to estimate community-level exposures. While random recruitment at the household level helps allow for such an estimation, ATSDR evaluated demographic differences between the New Castle County EA participants and all residents in the sampling frame. This was done for age, race, and ethnicity using a two-sample test for equality of proportions. To correct for participation bias, ATSDR also calculated geometric means adjusted to the age distribution of the sampling frame population using 2010 Census block data.

ATSDR compared community-level statistics for PFAS in blood to national PFAS data reported by CDC in the 2015–2016 NHANES (i.e., for the EA sample population 12 years of age and older). To control for differences in the age distribution, the EA geometric means were adjusted to the age distribution of the U.S. population during NHANES 2015–2016. For urine, ATSDR compared community-level data to national-level data from the 2013–2014 NHANES compiled by Calafat et al. [2019], the only nationally representative data available for PFAS in urine. ATSDR relied on two sample t-tests for these comparisons, using a p-value of less than 0.05 to identify statistically significant differences.

A **p-value** helps determine the significance of the results of a statistical test, such as the difference between two means. The lower the p-value the more likely the observed difference is not due chance alone. In this report, a p-value of less than 0.05 ($p<0.05$) is described as *statistically significant*.

ATSDR then used information gathered in the exposure questionnaire to understand and quantify how demographic data and other exposure characteristics relate to PFAS measurements in blood. For this, ATSDR relied on self-reported information, such as age, race/ethnicity, sex, length of residency in the sampling frame, tap water and food consumption patterns, and work/school history. All numerical responses were treated as continuous variables. In some cases, categorical variables were collapsed when there were too few responses (<10) in a given category. In order to explore sex-specific associations (e.g., women having biological children [yes/no], having breastfed children [yes/no], duration of breastfeeding), ATSDR also evaluated multivariate models for males and females only.

ATSDR did not conduct detailed statistical analyses for urine data because of low frequencies of detection. ATSDR analyzed a subset of urine samples and found that, for all PFAS, the frequency of detection was < 60%. The protocol specified that all urine samples would be analyzed if the geometric mean calculated for any site exceeded the 95th percentile from NHANES. The protocol specified that geometric means would be calculated if >=60% of samples had detections, and the rest of the samples would be analyzed if the calculated geometric mean exceeded the NHANES 95th percentile. Since no PFAS were detected in 60% or more of the analyzed samples, no geometric means were calculated for any PFAS in urine and ATSDR did not analyze the remainder of the urine samples. ATSDR did calculate the 95th percentile concentration for PFBA, the only PFAS detected in urine samples.

For tap water data, ATSDR compared PFAS levels measured with and without filtration to EPA's health advisory value (70 ppt for PFOA and PFOS combined). For dust, ATSDR calculated summary statistics and compared results to those in selected peer-reviewed literature. ATSDR also evaluated correlations between PFAS levels measured in household dust and blood collected from participants residing in homes where dust samples were collected.

To account for the one-stage cluster design, ATSDR conducted all statistical analyses in SAS (release 9.4, SAS Institute, Cary, NC) using complex survey procedures (e.g., SURVEYMEANS, SURVEYREG). To do this, ATSDR assigned household IDs to all participants and calculated summary statistics while accounting for clustering at the household level. For blood results across all EA participants, intra-cluster correlation

coefficients ranged from 0.40 to 0.86, suggesting moderate to strong correlation of PFAS blood levels within a household. Appendix B provides more information on clustering, as well as further details on the statistical methods used for this EA and how results from this EA compared to the assumptions used to estimate the target sample size of 395 participants.

Results

This section summarizes EA findings. It first profiles the New Castle County EA participants and compares their demographics to those of people in the sampling frame population, then reviews the blood, urine, tap water, and household dust measurements that ATSDR collected. Those reviews use exposure history questionnaire data to provide further context on the measurements. (The next section, "Discussion," further evaluates the observed trends using insights from the broader scientific literature on PFAS drinking water exposures.)

Most analyses in this section reflect the entire New Castle County EA participant population, but some pertain to subsets of that population. This is because separate exposure history questionnaires were administered to adults and children and because some questions on the adult questionnaire only applied to females.

Profile of New Castle County EA Participants

EA participants responded to exposure history questions and reported information on many characteristics, such as their age, sex, race/ethnicity, residential and occupational history, and drinking water consumption. Table 3 summarizes this information.

Table 3. Characteristics of New Castle County EA participants

Characteristics	Count of EA Participants (n)*	Percent of EA Participants (%)
Adults and children combined		
Age (years)	(mean =59.1)	
<18	11	5
18 to <50	42	20
50+	161	75
Sex		
Male	99	46
Female	115	54
Race and ethnicity†		
White, not Hispanic	176	84
non-White or Hispanic	33	16
Adults only		
Years lived at current address	(mean =21.6)	
<10	47	23
10 to <20	52	26
20 to <30	43	21
30+	61	30
Current primary drinking water source		
Public water system	166	83
Bottled Water	35	17

Characteristics	Count of EA Participants (n)*	Percent of EA Participants (%)
Average tap water consumption while living at current home (8-ounce cups per day)	(mean = 5.7)	
0	8	4
>0 to <2	20	10
2 to <4	34	17
4 to <6	53	26
6 to <8	27	13
8+	61	30
Current use of treatment or filtration device		
One or more filter/treatment device(s)	129	64
None	74	36
Occupational exposures to PFAS in the past 20 Years		
One or more occupational exposure(s)	29	14
None	172	86

* The sums of participants for different fields in this table do not always add up to expected values, because not every participant answered corresponding questions during the questionnaire.

† ATSDR collapsed categories for race and ethnicity for all analyses because of the few responses across categories.

The average age of EA participants was 59.1 years, and 84% of the participants identified themselves as White non-Hispanic. Of EA participants, 54% identified as female, 46% identified as male, and 95% were adults, aged 18 years or older. The age cutoff is important because adults were administered a different exposure history questionnaire with more detailed questions. Among the adult participants, 77% reported living in their current homes for more than 10 years.

Adults were also asked about their current primary sources of drinking water: 83% said a public water system (Artesian Water or MSC), and 17% said bottled water. Adults reported drinking an average of 5.7 8-ounce cups of water a day at home, and 61% said they currently use some type of filtering or treatment device for their drinking water. Examples include filters on refrigerators, pitchers, and faucets; whole-house carbon filtration systems; and reverse osmosis treatment systems. The questionnaire asked adults for their occupational histories over the past 20 years; 14% reported holding one or more jobs with potential PFAS exposures (e.g., firefighting, military, aviation).

Comparison of New Castle County EA Participants' Demographics to Sampling Frame Demographics

This EA was designed to estimate PFAS levels in blood that were generalizable to the sampling frame as a whole (i.e., the area shown in Figure 1). The random sampling recruitment method used for this EA helps ensure the absence of selection bias—that is, everyone in the sampling frame had an equal chance of being chosen to participate. However, ATSDR also explored the potential for participation bias—that is, substantive differences between those who chose to participate and those who did not.

ATSDR used 2010 Census data (Table 4) [USCB 2010] to compare the EA participants' demographic profile with the profile of all residents in the sampling frame. ATSDR found two significant differences:

- **Age distribution.** The EA participants included a higher proportion of older adults (age 50+ years) and a lower proportion of younger adults (18–50 years) and children (<18 years) than the sampling frame population (Table 4). Specifically, 75% of the EA participants reported being 50

or older, but 37% of the sampling frame population falls in this age range. (ATSDR chose 50 years as a cutoff for older and younger adults based on the median age of menopause in the United States, which may affect exposure profiles.) Similarly, 5% of the EA participants reported being under 18, but 22% of the sampling frame population falls in that age range.

- **Race/ethnicity.** Among the race/ethnicity characteristics, only the percent of residents who identify as Black showed a significant difference between the EA participants and the sampling frame population (Table 4). Specifically, the EA population had statistically fewer Black participants (11%) and statistically more White participants (84%) than the sampling frame population (28% and 64%, respectively). For this comparison, combined race and ethnicity were not available at the block level from the Census. Therefore, only ethnicity and the race category of Black and White were compared because of the small number of respondents in other categories.

The effect of age on blood levels and its implications on community statistics is further explored throughout this report. Refer to the "Discussion" section for ATSDR's assessment of how these demographic differences influence data interpretations.

Table 4. Demographic comparison of EA participants and the sampling frame population

Demographics	Number of Participants (n)*	Percent of Participants (%)	Sampling Frame Distribution (%)†	p-Value‡
Age Group (years)				
<18	11	5.1	22.0	<0.001
18–50	42	19.6	41.3	<0.001
50+	161	75.2	36.7	<0.001
Race				
White	179	83.6	63.5	<0.001
Black or African American	23	10.7	27.6	<0.001
Am. Indian & AK Native	<10	—	0.5	—
Asian	<10	—	1.0	—
Nat. Hawaiian/Pacific Islander	<10	—	0.0	—
Ethnicity				
Hispanic or Latino (of any race)	<10	—	1.1	—

* Counts may not sum to total because participants may have refused to answer questions. Counts are not shown for categories with fewer than 10 participants.

† Sampling frame data are based on the 2010 U.S. Census. Demographic characteristics of the sampling frame may have changed between 2010 and 2019, the time of this EA.

‡ Two-sample test for equality of proportions with continuity correction comparing EA and 2010 Census data. A p-value of less than 0.05 indicates a statistically significant difference between EA participants and all residents in the sampling frame.

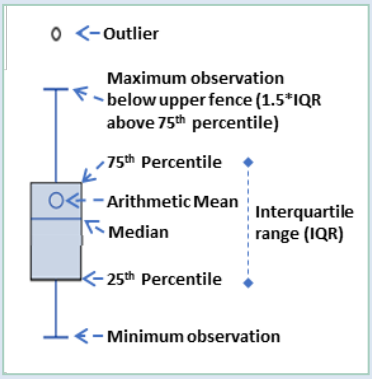
PFAS in Blood

This section summarizes PFAS levels that ATSDR measured from the 214 blood samples provided by eligible participants. Results are summarized in tables and 'box and whisker' plots (see text box).

Unadjusted Community Statistics for PFAS in Blood

ATSDR first calculated the mean levels of PFAS without accounting for the possible effect of age. Table 5 summarizes results for the seven PFAS measured in New Castle County EA participants' blood. All seven PFAS—PFHxS, PFOS, PFOA, PFNA, PFDA, PFUnA, and MeFOSAA—were detected in more than 60% of the blood samples. ATSDR's statistical analyses throughout this section focus on these seven chemicals, and Figure 2 shows the distributions of the individual measurements on a $\log_{10}$ scale. The $\log_{10}$ scale allows for more easily visualizing the wide range of serum concentrations as it uses equal spacing for each factor of 10 increase. The PFAS found at highest levels were PFOS (geometric mean = 21.5 micrograms per liter (µg/L)), PFHxS (20.1 µg/L), and PFOA (4.92 µg/L).

How to read a box and whisker plot:
A box and whisker plot illustrates a summary of the data using different statistical measures. See the image below for how to interpret the figures throughout this report.



The precision of geometric mean estimates for this EA ranged from approximately 6% to 302%, depending on the PFAS (Appendix B, Table B2). Except for PFNA, these values are all below the desired precision of 15% used to determine the target sample size for this EA, indicating that the collected data met the precision target specified in the EA protocol.

Table 5. Community statistics for PFAS in blood in micrograms per liter

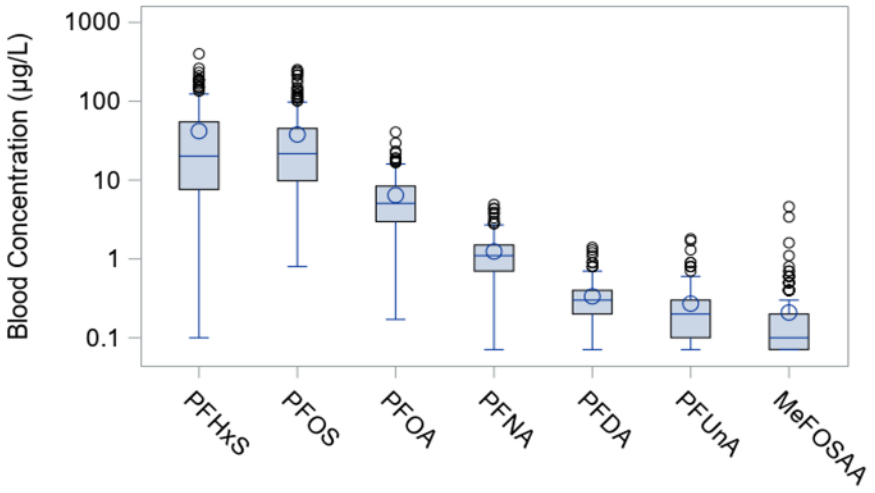
PFAS	FOD (%)	Max	Geometric Mean	95% CI for Geometric Mean	Percentiles				
					25th	50th (Median)	75th	90th	95th
PFHxS	100	400.2	20.1	16.2–25.1	7.55	20.0	54.7	108	152
PFOS	NA*	251.4	21.5	17.9–25.8	9.54	21.4	45.0	86.9	128
PFOA	NA*	40.6	4.92	4.37–5.53	2.93	4.97	8.39	13.0	15.7
PFNA	99.1	4.9	1.03	0.93–1.14	0.682	1.06	1.48	2.12	2.64
PFDA	91.1	1.4	0.271	0.243–0.302	0.136	0.242	0.370	0.572	0.708
PFUnA	87.9	1.8	0.210	0.189–0.234	NA†	0.169	0.296	0.440	0.558
MeFOSAA	60.7	4.6	0.133	0.118–0.151	NA†	NA†	0.169	0.320	0.508

FOD = frequency of detection, CI = confidence interval, NA = not applicable

* PFOA and PFOS are calculated sums of branched and linear subsets and are not measured directly. Linear PFOA was detected in 100.0% of samples with a geometric mean of 4.80 micrograms per liter (µg/L); branched PFOA was detected in 9.3% of samples. Linear PFOS was detected in 100.0% of samples with a geometric mean of 15.4 µg/L; branched PFOS was also detected in 100.0% of samples, with a geometric mean of 5.90 µg/L.

† Percentile is below the LOD.

Figure 2. Distribution of PFAS blood levels (log scale)



See 'How to read a box and whisker plot' earlier in the PFAS in Blood section.
A log10 scale is used to allow easier visualization of the wide range of measured blood levels, as it uses equal spacing for each factor of 10 increase.

Community Statistics for PFAS in Blood Age-Adjusted to Sampling Frame

Since the demographic profile comparison reported above showed that EA participants were significantly older than the sampling frame as a whole, ATSDR also calculated geometric means that were age-adjusted to the sampling frame population based on 2010 Census data for comparison. Age-adjusted geometric means correct for the participation bias discussed earlier and are more generalizable to the sampling frame community. Table 6 shows that in general, age-adjusted blood PFAS geometric means are lower than unadjusted values. Of the three PFAS with the highest concentration (PFHxS, PFOS, and PFOA), age-adjusted geometric means are between 27% and 43% lower than unadjusted values. The lower values for age-adjusted geometric means reported here are consistent with older adults having higher blood PFAS levels than younger adults. The effect of age and the implications of these age-adjusted statistics are further discussed throughout this report.

Table 6. Geometric means for PFAS in blood in micrograms per liter, unadjusted and age-adjusted to the sampling frame

	Unadjusted		Age-Adjusted to Sampling Frame	
PFAS	Geometric Mean	95% CI for Geometric Mean	Geometric Mean	95% CI for Geometric Mean
PFHxS	20.1	16.2–25.1	11.5	9.12–14.5
PFOS	21.5	17.9–25.8	12.8	10.8–15.1
PFOA	4.92	4.37–5.53	3.59	3.20–4.02
PFNA	1.03	0.93–1.14	0.841	0.774–0.915
PFDA	0.271	0.243–0.302	0.271	0.247–0.297
PFUnA	0.210	0.189–0.234	0.194	0.171–0.220
MeFOSAA	0.133	0.118–0.151	0.119	0.104–0.135

CI = confidence interval

Comparison of EA Participants' PFAS Blood Levels to the National Population

This section compares PFAS levels among New Castle County EA participants to levels found in the U.S. general population. To explore effects related to differences in the age distribution of EA participants vs. the NHANES populations, ATSDR calculated both unadjusted geometric means of all EA participants and geometric means adjusted to the age distribution of the U.S. population in NHANES 2015–2016.

Table 7 shows the unadjusted comparison for the entire pool of EA participants to the most recent data available from NHANES, which are the geometric means for the 2015–2016 survey [CDC 2019]. For five PFAS (PFHxS, PFOS, PFOA, PFNA, and PFDA), unadjusted geometric mean blood levels among New Castle County EA participants were statistically ($p<0.05$) higher than the national geometric mean. Geometric means were not calculated during NHANES for PFAS detected in less than 60% of samples, which included PFUnA and MeFOSAA. In this EA, PFUnA and MeFOSAA were detected in over 60% of samples and geometric means were calculated.

Of the PFAS analyzed in blood, PFHxS levels had the largest elevations when compared to national levels. The unadjusted geometric mean blood PFHxS level among New Castle County EA participants was 17 times higher than the national level. Blood PFHxS levels were above the national geometric mean for 99% of the New Castle County EA participants and above the NHANES 95th percentile for 86%. The unadjusted geometric mean blood PFOS and PFOA levels among New Castle County EA participants were 4.6 and 3.2 times higher, respectively, than the national level. Blood PFOS levels were above the national geometric mean for 91% of the EA participants and above the NHANES 95th percentile for 57%. Blood PFOA levels were above the national geometric mean for 95% of New Castle County EA participants and above the NHANES 95th percentile for 57%.

On average, total PFOS measurements were composed of 72% linear PFOS (n-PFOS) and 28% branched PFOS (Sm-PFOS). The proportion of n-PFOS found in EA participants' blood is lower than that found in standard PFOS products (76%–79%) [Kärrman et al. 2007] but comparable to levels found in the blood of the general U.S. population [CDC 2019]. Measurements of total PFOA were composed of 98% of linear PFOA (n-PFOA) and 2% branched PFOA (Sb-PFOA), which is also comparable to measurements from the U.S. population [CDC 2019]. All remaining statistical analyses in this report focus on total PFOA and PFOS rather than treating the linear and branched isomers separately.

For this EA, ATSDR also calculated geometric means age-adjusted to the NHANES population. Because the 2015–2016 NHANES survey does not report data for individuals under 12 years of age, these geometric mean calculations are based on 209 EA participants. Table 7 and Figure 3 show that blood PFAS geometric means adjusted to the NHANES population profile are lower than unadjusted values. The adjusted geometric mean blood PFHxS level among New Castle County EA participants was 9.8 times the national level. The age-adjusted geometric mean blood PFOS and PFOA levels among New Castle County EA participants were 2.8 and 2.4 times the national average, respectively. Even when controlling for the age-distribution in the population, EA participants had statistically higher blood levels of PFHxS, PFOS, PFOA, PFNA, and PFDA than the U.S. population.

Table 7. Comparison of PFAS blood geometric means (GMs) and 95th percentiles in New Castle County, Delaware, with the U.S. population (NHANES 2015–2016) in micrograms per liter

PFAS	NHANES GM (CI)*	New Castle County GM (CI)†: Unadjusted	New Castle County GM (CI)†: Age-Adjusted to NHANES 2015-2016	Percent of New Castle County Results over NHANES GM (%)	NHANES 95th Percentile*	New Castle County 95th Percentile	Percent of New Castle County Results over NHANES 95th Percentile (%)
PFHxS	1.18 (1.08–1.30)	20.1 (16.2–25.1) *p<0.001*	11.5 (9.05–14.7) *p<0.001*	98.6	4.90	152	86.0
PFOS	4.72 (4.40–5.07)	21.5 (17.9–25.8) *p<0.001*	13.5 (11.2–16.3) *p<0.001*	91.1	18.3	128	56.5
PFOA	1.56 (1.47–1.66)	4.92 (4.37–5.53) *p<0.001*	3.74 (3.31–4.24) *p<0.001*	95.3	4.17	15.7	57.5
PFNA	0.577 (0.535–0.623)	1.03 (0.935–1.14) *p<0.001*	0.903 (0.831–0.980) *p<0.001*	86.0	1.90	2.64	12.1
PFDA	0.154 (0.140–0.169)	0.271 *(*0.243–0.302*)* *p<0.001*	0.279 (0.252–0.309) *p<0.001*	83.6	0.700	0.708	5.14
PFUnA	NA‡	0.210 (0.189–0.234)§	0.208 (0.184–0.235) §	100	0.400	0.558	12.6
MeFOSAA	NA‡	0.133 (0.118–0.151)§	0.130 (0.108–0.146) §	100	0.600	0.508	3.27

µg/L = micrograms per liter, NA = not applicable

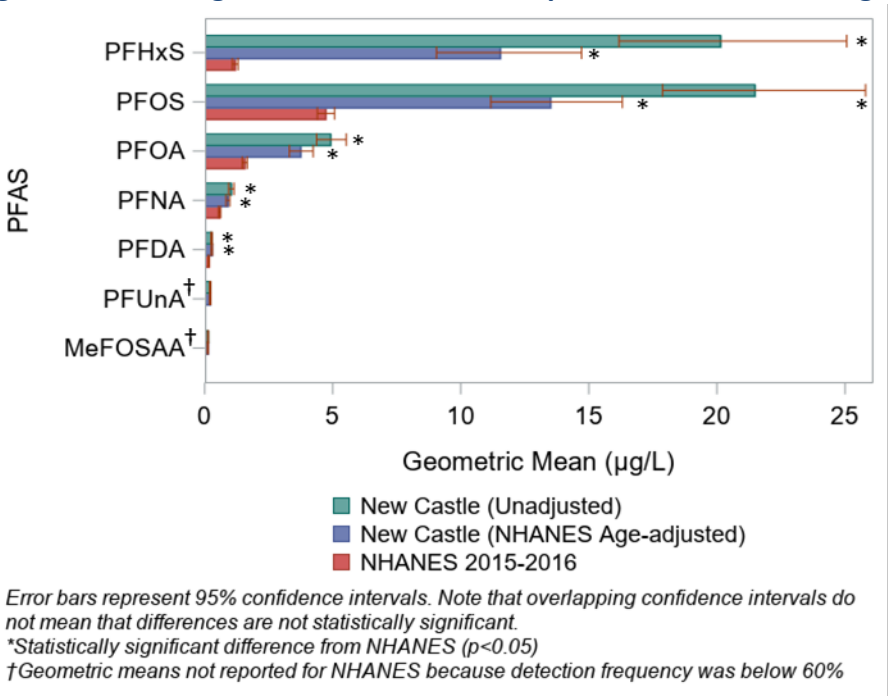
* Source: CDC 2019

† P-values represent a t-test comparisons between the New Castle County GM and NHANES GM

‡ Per the protocol, geometric means were not calculated for PFAS detected in less than 60% of samples.

§ No statistical comparison could be made with NHANES because NHANES did not calculate a geometric mean for this PFAS because this PFAS was detected in less than 60% of NHANES samples.

Figure 3. EA average PFAS blood levels compared to national averages



Error bars represent 95% confidence intervals. Note that overlapping confidence intervals do not mean that differences are not statistically significant.
**Statistically significant difference from NHANES ($p<0.05$)*
†Geometric means not reported for NHANES because detection frequency was below 60%

Correlations Among PFAS in Blood

ATSDR also evaluated correlations between PFAS in blood (log_{10}). This analysis determined whether any PFAS tended to have similar patterns in the blood of New Castle County EA participants. ATSDR used Pearson correlation coefficients (r) for this analysis. An r of 0 means two data sets are uncorrelated, and an r of 1 means two data sets are exactly correlated (i.e., they rise and fall in proportional amounts). Table 8 shows the Pearson correlation coefficients for the seven PFAS.

PFHxS, PFOS, and PFOA blood levels showed the strongest correlations (Table 8). All pairings of these chemicals had Pearson correlation coefficients close to 1 (r = 0.83–0.94). On the other hand, PFNA, PFDA, and PFUnA were moderately correlated with each other (r = 0.48–0.69). MeFOSAA had the weakest correlations with other PFAS (r = 0.06–0.14).

Table 8. Pearson correlation coefficients between PFAS in blood (log_{10})

	PFHxS	PFOS	PFOA	PFNA	PFDA	PFUnA	MeFOSAA
PFHxS	1.00	0.94	0.83	0.51	0.19	0.09*	0.07*
PFOS	0.94	1.00	0.83	0.60	0.24	0.12*	0.06*
PFOA	0.83	0.83	1.00	0.73	0.37	0.18*	0.08*
PFNA	0.51	0.60	0.73	1.00	0.69	0.48	0.14*
PFDA	0.19	0.24	0.37	0.69	1.00	0.64	0.12*
PFUnA	0.09*	0.12*	0.18*	0.48	0.64	1.00	0.06*
MeFOSAA	0.07*	0.06*	0.08*	0.14*	0.12*	0.06*	1.00*

* Correlations not significant, i.e., $p>0.05$.

PFAS Blood Levels by Demographics and Other Exposure Characteristics

This section examines how the demographic and exposure history information collected during the questionnaire relates to blood PFAS levels. Since different questionnaires were administered to adult and child participants, responses were analyzed separately. Additionally, some questions were

applicable only to female adult participants and are therefore also presented separately. Appendix C (Tables C1 and C2) summarizes all adult and child questionnaire responses.

ATSDR used univariate and multivariate models to evaluate the relationships between questionnaire data and blood PFAS levels. This section summarizes relationships that were found to be statistically significant. For this EA, the following demographic and exposure characteristics were found to be associated with at least one PFAS in either univariate or multivariate models:

- age,
- sex,
- race/ethnicity,
- length of residence in the sampling frame,
- current main source of drinking water,
- drinking water source,
- use of a water filtration or treatment device,
- kidney disease history,
- use of stain-resistant products, and
- cleaning frequency.

ATSDR created mathematical models to identify demographic and lifestyle characteristics associated with PFAS blood levels.

Univariate models evaluated the effects of one variable, or exposure characteristic, at a time while multivariable models evaluated the joint effect of multiple characteristics on blood PFAS levels at the same time. **Multivariable regression models** describe the average increases in PFAS blood levels for each unit increase in the exposure characteristics.

Table 9 summarizes the demographic and exposure characteristics that were statistically significant in each adult multivariate model.

Table 9. Summary of statistically significant variables (p<0.05) in multivariate regression models*

Parameter	PFHxS			PFOS			PFOA		
	All Adult	Adult Female	Adult Male	All Adult	Adult Female	Adult Male	All Adult	Adult Female	Adult Male
Sex (categorical)	—	NA	NA	✓	NA	NA	—	NA	NA
Public water supply [MSC or Artesian] (categorical)	✓	✓	✓	✓	✓	✓	✓	—	✓
Years in sampling frame in the past 20 years [Residency duration] (continuous)	✓	✓	✓	✓	✓	✓	✓	✓	✓
Tap water filtration at home (categorical)	✓	✓	—	✓	—	✓	✓	✓	✓
Kidney disease history (categorical)	✓	—	—	—	—	—	—	—	—
Home cleaning frequency (categorical)	✓	—	—	✓	—	—	—	—	—

✓ = statistically significant, '—' = not statistically significant, NA = not applicable

* ATSDR tried to develop models for PFNA, PFDA, and MeFOSAA but after following the model building steps final models for all three PFAS resulted in only a single variable.

The following subsections briefly summarize results for these topics. All other results are presented in Appendix C, as described below.

- Tables C1 and C2 present response frequencies for all questions included in the adult and child questionnaire, respectively. These tables also present geometric means and 95% confidence intervals around geometric means stratified by the response options (e.g., statistics are presented separately for males and females) for PFHxS, PFOS, PFOA, PFNA, PFDA, PFUnA, and MeFOSAA. While adjusted geometric mean blood levels of MeFOSAA were not found to be statistically higher than the national geometric mean, levels were detected at a high enough frequency to present meaningful results. Summary statistics for this PFAS are therefore provided in Appendix C for completeness, but not discussed below.
- Tables C3 and C4 present univariate modeling results for all questions in the adult and child questionnaire for the same seven PFAS, as data allow. Data are presented only when a category had at least 10 responses. Some categories were collapsed to meet this threshold.
- Tables C5–C13 present multivariate modeling results for PFHxS, PFOS, and PFOA. ATSDR tried to develop multivariate models for PFNA, PFDA, and MeFOSAA but after following the model building steps final models for all three PFAS resulted in only a single variable. Multivariate models, including the goodness-of-fit measure, R-squared or R^2, are presented separately for all adults, male adults only, and female adults only. The closer the R^2 value is to 1, the more the variables in the model explain the variability in blood PFAS levels. Across all models, R^2 values ranged from 0.14 to 0.57. ATSDR modeled males and female adults separately to explore sex-specific differences including the potential effect of childbirth and breastfeeding on female blood PFAS levels. The variables considered in male-only and female-only models were limited to those that were significant in final all-adult models. ATSDR did not develop multivariate models for children because of the small sample size for this population (n=11).
- Figures C1–C25 present box and whisker plots for unadjusted blood levels by each demographic and exposure characteristic included in the statistical analyses.

Goodness of Fit Measure

R-squared or R^2 is a statistical measure used to evaluate how well a mathematical model explains the measured data by looking at the differences between the observed PFAS concentrations and values predicted by the model.

- An R^2 of 1 means the model completely predicts the observed PFAS concentrations, so that there are no differences between the model and the PFAS concentrations and 100% of the PFAS concentrations are explained by the model.
- An R^2 of less than 1 means that there are measurements scattered higher and/or lower than the model predictions and there are differences between the two.

Variability describes the spread or dispersion of data values. If the values are similar to each other there is little variability, if the values are spread out there is more variability.

Multivariable regression can help us understand how much of the variability in PFAS blood levels can be explained by the combination of factors in the model such as age, sex, and length of residency among others. If the model does not explain a large portion of the variability, that means there are other unknown factors influencing PFAS levels in blood.

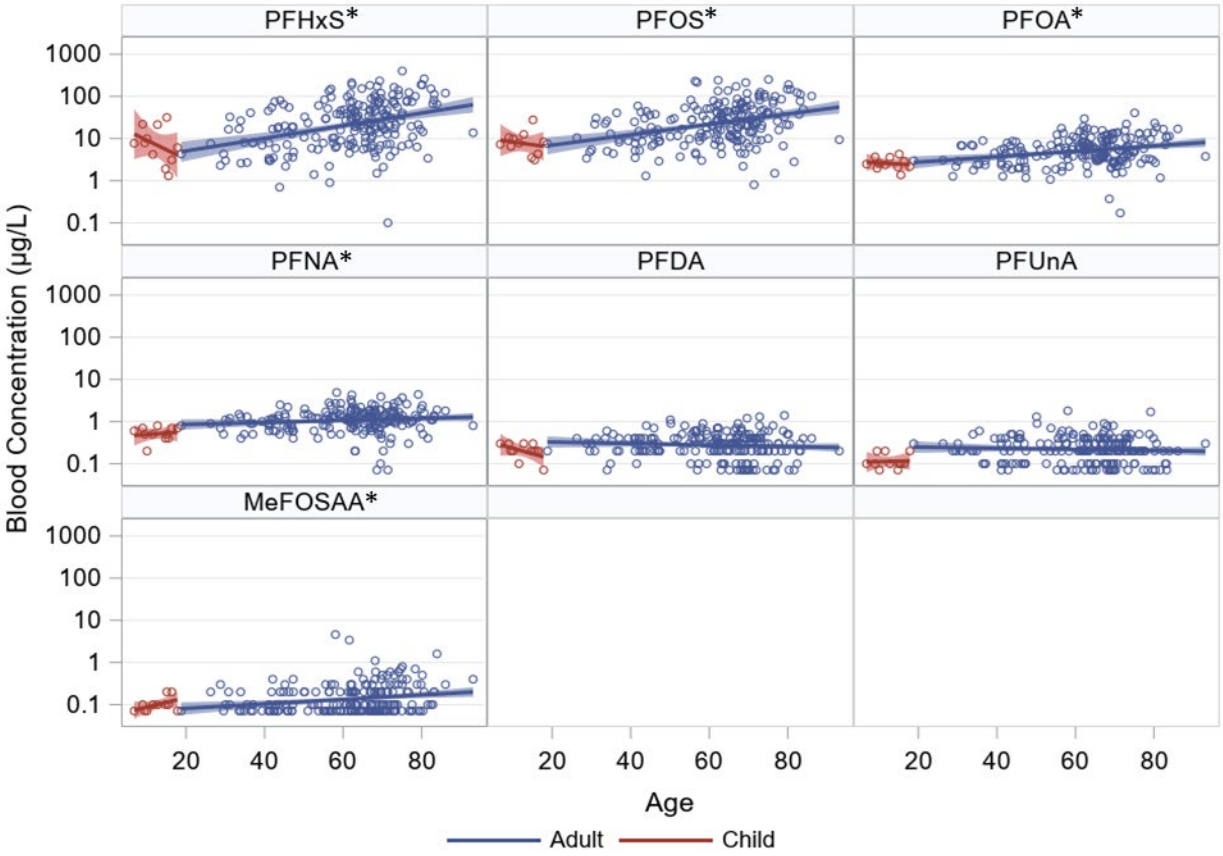
Blood PFAS Levels and Age

Because many studies have found that older people have higher blood PFAS levels, ATSDR investigated how New Castle County EA participants' ages related to their blood levels. As Figure 4 illustrates, the blood levels for PFHxS, PFOS, PFOA, PFNA, and MeFOSAA increased with participant age for adults, but trends for children were not statistically significant. Results for children should be interpreted with caution due to the small sample size.

For adults, ATSDR's univariate analysis showed that blood PFHxS, PFOS, PFOA, PFNA, and MeFOSAA were higher in older individuals than in younger individuals, and this finding was statistically significant. As Figure 4 shows, PFHxS had the strongest age dependence. The univariate analysis indicates that on average, blood PFHxS levels in New Castle County EA participants increased 3.5% for every year of age in adults. This suggests a 41% increase in blood PFHxS levels for every 10 years of age in adult participants. The calculated increases for PFOS (2.9% per year of participant age), PFOA (1.5% per year of participant age), PFNA (0.55% per year of participant age), and MeFOSAA (1.2% per year of participant age) were lower. However, age did not remain a significant predictor of blood levels in all-adult multivariate models. This was due to a strong correlation between age and residence duration (discussed below).

The model results depicted in Figure 4 showed blood PFHxS, PFOS, PFOA, PFDA, and PFUnA levels were higher in younger children for participants under 18, but the trends were not statistically significant. Figure 4 shows that blood PFNA levels were lower in younger children for participants under 18, but this trend was not statistically significant in univariate analyses. These results should be interpreted with caution due to the small sample size. Multivariate models were not explored for children because of the small sample size.

Figure 4. PFAS blood levels in adults and children (log scale)



A log10 scale is used to allow easier visualization of the wide range of measured blood levels, as it uses equal spacing for each factor of 10 increase.
**Statistically significant trend (p<0.05)*

Blood PFAS Levels by Sex

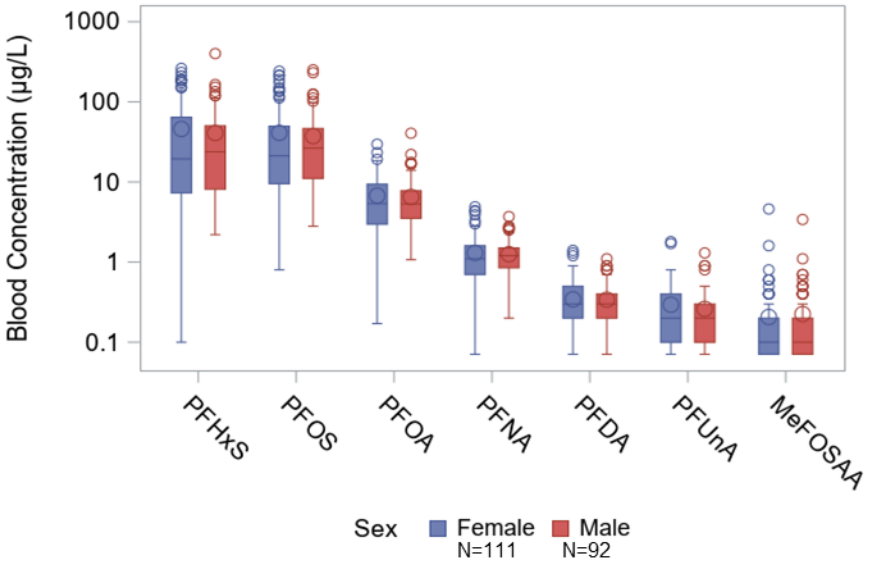
ATSDR investigated how blood PFAS levels vary between males and females because previous research has shown that, all other factors considered equal, adult males tend to have higher blood PFAS levels than adult females. ATSDR's univariate analyses did not show significant differences in PFAS levels by sex (Figure 5). However, ATSDR's multivariate analyses, which controlled for other potential confounders, showed that PFOS levels were statistically higher in adult males than in adult females. Modeled blood levels in adult males were 28% higher for PFOS in the all-adult multivariate model.

What are confounders?

Confounding is a distortion in the estimated relationship between a potential predictor and measure of exposure due to the presence of a third variable—called a confounder. In order for confounding to occur, that third variable must be associated with both the predictor (or independent variable) and the measure of exposure (or dependent variable). For example, age can act as a confounder on the estimated strength of association between length of residence in the sampling frame and blood PFAS levels.

By adjusting for these types of confounding variables in multivariate statistical models, ATSDR can calculate less biased estimates of the relationships between dependent and independent variables of interest.

Figure 5. PFAS blood level in adults by sex (log scale)



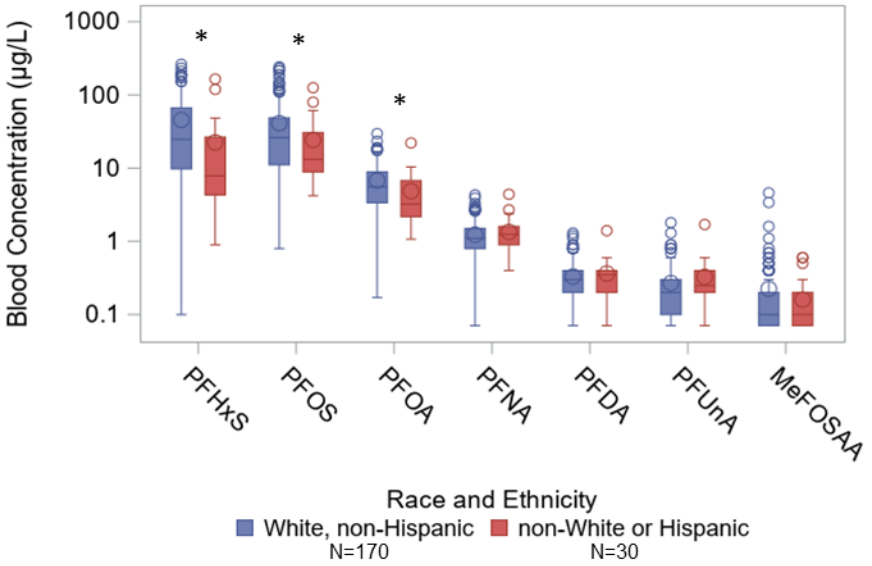
See 'How to read a box and whisker plot' earlier in the PFAS in Blood section.
A log10 scale is used to allow easier visualization of the wide range of measured blood levels, as it uses equal spacing for each factor of 10 increase.
**Statistically significant difference (p<0.05)*

Blood PFAS Levels by Race/Ethnicity

The exposure history questionnaire asked participants to provide information about their race and ethnicity. Because there were not enough participants in different race and ethnicity categories to support robust statistical analyses, ATSDR focused on differences between New Castle County EA participants who self-identified as White, non-Hispanic and those who identified as non-White, or Hispanic.

Figure 6 shows that on average, when compared to those who identified as White, non-Hispanic, blood levels in non-White, or Hispanic participants had 56% lower for PFHxS, 33% lower for PFOS, and 30% lower for PFOA in univariate models. Race and ethnicity did not remain as significant predictors of these PFAS in multivariate analyses. This may result from age being correlated with race and ethnicity in the U.S. population (White, non-Hispanic populations tend to be older than non-White, or Hispanic populations). Also, in the wider U.S. population, levels of PFAS in Hispanics tended to be lower than in other race and ethnicity groups.

Figure 6. PFAS blood level in adults by race and ethnicity (log scale)



See 'How to read a box and whisker plot' earlier in the PFAS in Blood section.
A log10 scale is used to allow easier visualization of the wide range of measured blood levels, as it uses equal spacing for each factor of 10 increase.
**Statistically significant difference (p<0.05)*

Blood PFAS Levels and Tap Water Consumption

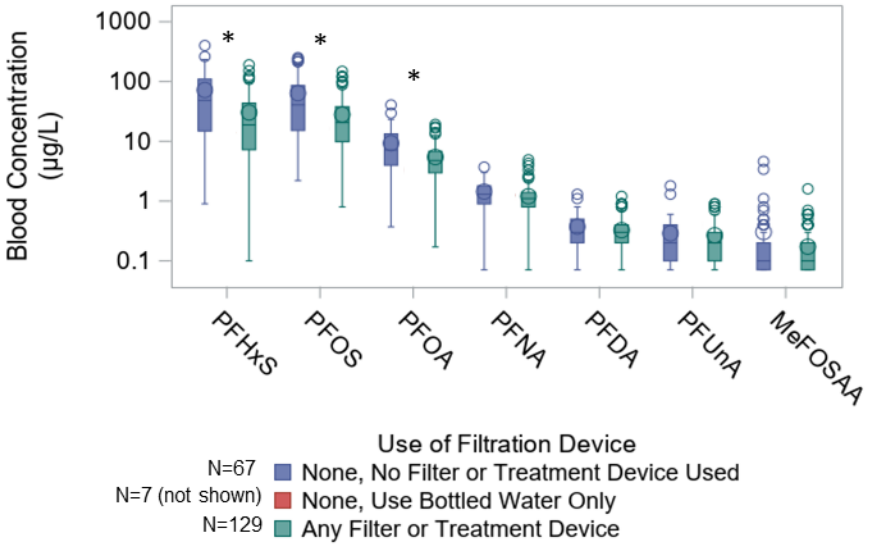
ATSDR investigated several questions from the adult and child questionnaires to characterize relationships between blood PFAS levels and consumption of PFAS-contaminated drinking water. These questions are about the drinking water source, amount of tap water consumed at home or school, and residential history. In some cases, data trends may have been affected by subtleties in the wording of exposure history questions, as described below.

For adults, ATSDR first considered participants' primary drinking water source. Adult participants were asked, "What is your current main source of drinking water in your home?" Nearly all of the responses were tap water (83%) or bottled water (17%). Among PFAS analyzed in blood, only MeFOSAA was statistically associated with current main drinking source, with participants that reported drinking mainly bottled water having 24% lower blood MeFOSAA levels than participants that reported drinking mainly from the public water system. There were no statistically significant differences in blood levels of other analyzed PFAS between these two groups in univariate or multivariate analyses. The lack of

significant differences for PFHxS, PFOS, and PFOA was an unexpected result, which ATSDR believes may be a result of how the question was worded—particularly the word "current." ATSDR also asked participants about any changes to their drinking water habits in the past year; 2.0% reported switching from public water to bottled water in the past year. However, since drinking water exposure was mitigated in 2014 for MSC customers and 2016 for Artesian customers, changes in drinking water behavior within the past year would not affect drinking water exposure. It is possible that participants who reported currently drinking bottled water or switching water sources in the past year drank tap water during the period of contamination, but the extent to which that occurred is not known. Due to these considerations, ATSDR's data analysis did not rely on answers to these questions when interpreting associations between PFAS levels and exposure characteristics.

ATSDR also considered relationships between blood PFAS levels and current use of drinking water filtering devices and water treatment devices. As Figure 7 shows, 64% of participants reported using a filter or treatment device on the tap water that they drink at home, and 33% of participants reported no filter or treatment device on the tap water that they drink at home. In ATSDR's univariate analyses, participants that reported using a filter or treatment device on the tap water that they drink at home on average had statistically lower blood levels of PFHxS, PFOS, and PFOA. These results remained statistically significant in multivariate models. In all-adult multivariate models, participants that reported using a filter or treatment device on average had blood PFAS levels that were 39% lower for PFHxS, 37% lower for PFOS, and 32% lower for PFOA.

Figure 7. PFAS blood level in adults by use of filtration device (log scale)

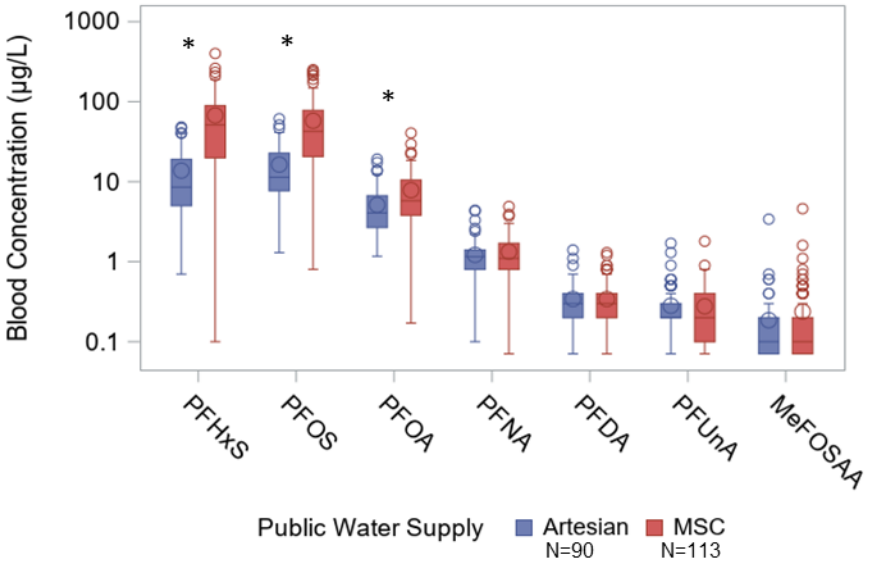


See 'How to read a box and whisker plot' earlier in the PFAS in Blood section.
A log10 scale is used to allow easier visualization of the wide range of measured blood levels, as it uses equal spacing for each factor of 10 increase.
**Statistically significant difference (p<0.05)*

ATSDR also considered participants' public water systems. In the sampling frame, adult participants either lived in homes that received drinking water from Artesian Water (n=90) or from MSC (n=113). Figure 8 shows blood PFAS levels in participants who lived in the MSC service area compared to levels in participants who lived in the Artesian Water service area. MSC participants had significantly higher blood levels of PFHxS (339%), PFOS (195%), and PFOA (37%) than participants who lived in the Artesian service area. These relationships remained significant in all-adult multivariate analyses. After controlling for other variables, participants who lived in the MSC service area had 247% higher PFHxS blood levels,

148% higher PFOS blood levels, and 25% higher PFOA blood levels than those who lived in the Artesian service area. This association remained significant in sex-stratified models with the exception of the female-only PFOA model.

Figure 8. PFAS blood level in adults by public water system (log scale)



See 'How to read a box and whisker plot' earlier in the PFAS in Blood section.
A log10 scale is used to allow easier visualization of the wide range of measured blood levels, as it uses equal spacing for each factor of 10 increase.
**Statistically significant difference (p<0.05)*

ATSDR also considered participants' self-reported tap water consumption rates. Adult participants were asked, "During the time you lived in a home served by the water source identified above [i.e., for the question quoted in the previous paragraph], on average how many 8-ounce cups of water or beverages prepared with tap water did you drink while at home per day?" ATSDR's univariate and multivariate analyses did not reveal a significant linear relationship between blood PFAS levels and the amount of tap water consumed.

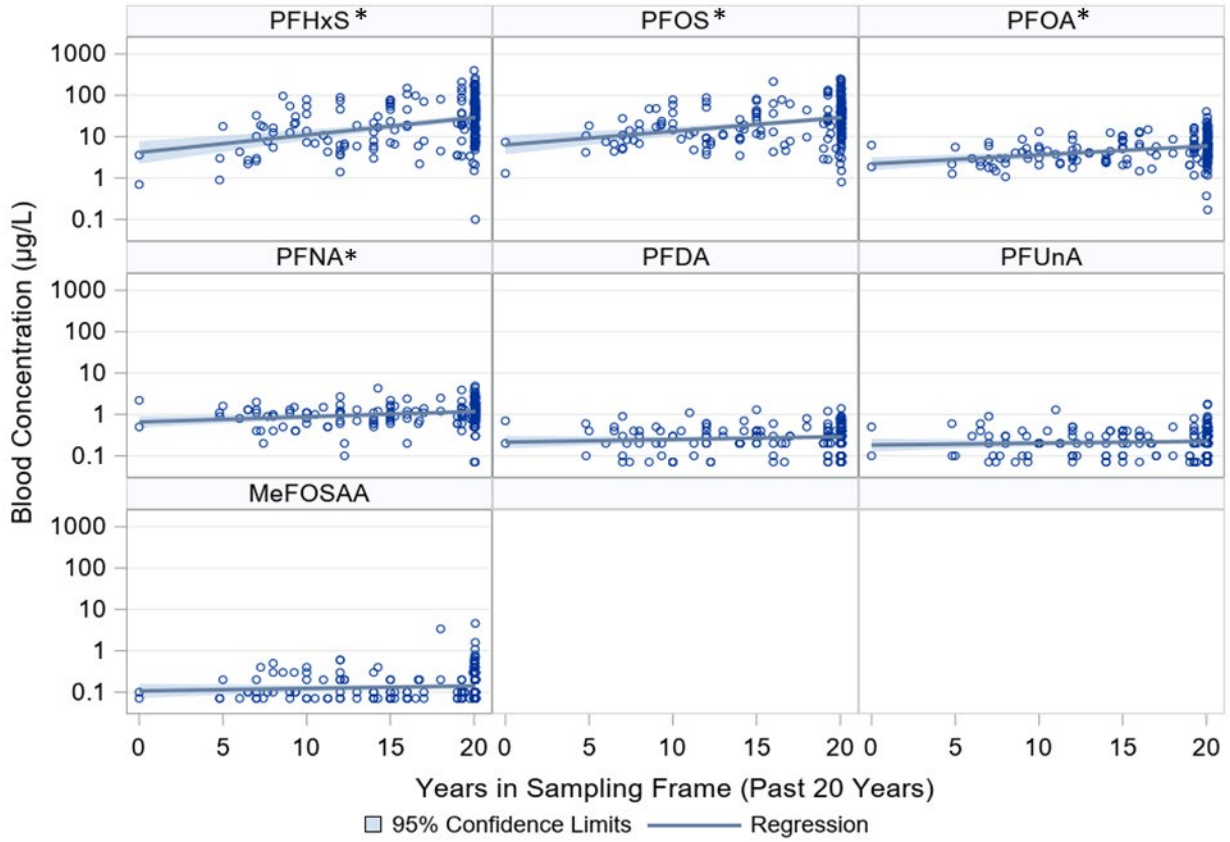
For adults, ATSDR also considered the length of residency. The exposure history questionnaire asked adults where they had lived for the past 20 years. ATSDR calculated the total amount of time participants reported living in the sampling frame over this period. These responses can serve as a proxy for potential exposure to PFAS-contaminated drinking water in the community. That is, the longer the residency within the sampling frame, the greater the likelihood of past PFAS exposure from the MSC or Artesian drinking water supply. Any resident reporting prior residences with addresses in "New Castle, Delaware" or "Wilmington Manor, Delaware" were assumed to fall within the sampling frame.

Figure 9 shows the relationship between reported residence duration in New Castle or Wilmington Manor for the past 20 years and blood PFAS levels. A consistent relationship was observed for PFHxS, PFOS, PFOA, and PFNA: blood levels increased with the number of years participants lived in the sampling frame, and this effect was most pronounced for PFHxS. The multivariate analysis showed that this relationship remained statistically significant for PFHxS, PFOS, and PFOA. In the all-adult model, for every additional year that an adult participant lived in New Castle County, blood PFHxS increased by 8.4%, blood PFOS increased by 7.1%., and blood PFOA increased by 4.6%. In both male-only and female-only models, the association remained statistically significant and was generally stronger in males than females.

Finally, an exposure history question pertained to whether adult participants drank tap water while at work. However, because identifying whether a participant's place of employment was in the sampling frame was difficult, ATSDR did not evaluate the data for drinking water consumption patterns at work.

PFHxS, PFOS, and PFOA were detected in both MSC and Artesian Water drinking water systems (highest sampling results in Artesian Water was 680 ppt for PFHxS, 1,800 ppt for PFOS, and 140 ppt for PFOA; highest in the MSC system was 1,400 parts per trillion ppt for PFHxS, 2,300 ppt for PFOS, and 440 ppt for PFOA). Therefore, one explanation for the correlation among these compounds is that the New Castle County EA participants had a common exposure profile for PFHxS, PFOS, and PFOA, such as drinking water. However, the correlations alone cannot be used to identify the underlying source or combination of sources that contributed most to exposure.

Figure 9. PFAS blood levels in adults by length of residence in sampling frame (log scale)



A log10 scale is used to allow easier visualization of the wide range of measured blood levels, as it uses equal spacing for each factor of 10 increase.
**Statistically significant trend (p<0.05)*

Blood PFAS Levels and Kidney Disease

Adult participants were asked about whether they had a history of kidney disease, because it can affect blood PFAS levels [Barry 2013; Watkins 2013]. The questionnaire results indicated that only 6% of adults (n=13) reported a diagnosis of kidney disease, but these adults did not have statistically different blood PFAS levels than those without a diagnosis of kidney disease in univariate analyses. However, in multivariate analyses, after controlling for other variables, participants who reported a history of kidney disease had PFHxS blood levels that were 56% greater than those who did not. Too few participants reported a history of kidney disease to include this variable in sex-stratified models. The results for

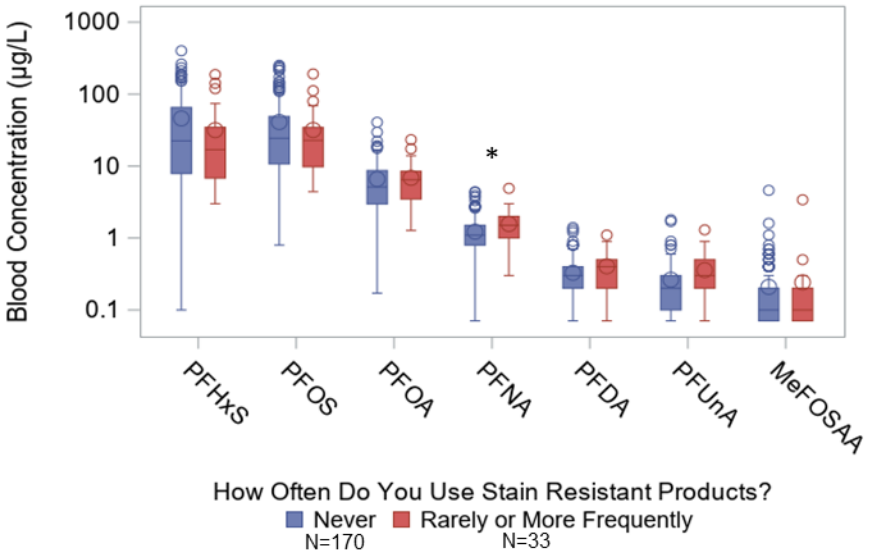
kidney disease for this EA are based on limited data and should be interpreted with caution. Note that kidney disease was self-reported and there may be misclassification with this variable.

Blood PFAS Levels and Use of Stain-Resistant Products

Many stain-resistant products used to treat fabrics and carpet have been formulated with PFAS. The exposure history questionnaire asked adult EA participants how frequently they used these products, because such uses may be associated with PFAS exposures. The questionnaire had several response options, including "never," "rarely," "a few times per year," "a few times per month," and "3 times per week or more." Because of the small sample size for some response options, ATSDR collapsed responses into just two categories: never used stain-resistant products (170 adult EA participants) and any reported use (33 adult EA participants). Figure 10 shows how blood PFAS levels varied between these two categories of EA participants.

As Figure 10 shows, New Castle County EA adult participants with any self-reported stain-resistant product use had statistically elevated (29%) blood levels of PFNA when compared to participants who reported never using these products. However, this relationship did not remain statistically significant in multivariate models.

Figure 10. PFAS blood level in adults by stain-resistant product use (log scale)

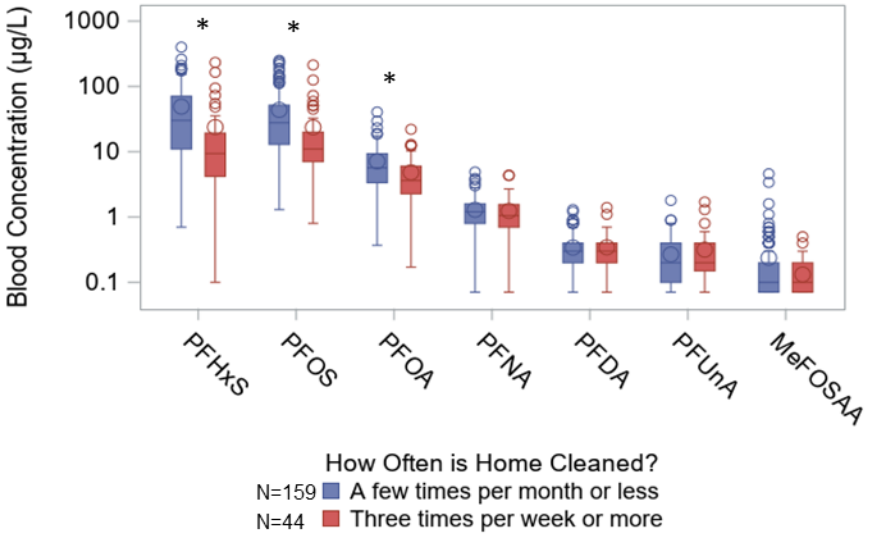


See 'How to read a box and whisker plot' earlier in the PFAS in Blood section.
A log10 scale is used to allow easier visualization of the wide range of measured blood levels, as it uses equal spacing for each factor of 10 increase.
**Statistically significant difference (p<0.05)*

Blood PFAS Levels and Cleaning Frequency

Adult participants were asked about the frequency at which they clean their homes. In univariate models, adult participants who reported cleaning their homes three times per week or more on average had statistically lower PFHxS, PFOS, PFOA, and MeFOSAA blood levels than adult participants who reported cleaning their homes a few times per month or less (Figure 11). Similarly, in all adult multivariate models, adult participants that reported cleaning their homes three times per week or more on average had PFHxS serum levels 42% lower and PFOS serum levels 34% lower than adult participants that reported cleaning their homes a few times per month or less.

Figure 11. PFAS blood level in adults by cleaning frequency (log scale)



See 'How to read a box and whisker plot' earlier in the PFAS in Blood section.
A log10 scale is used to allow easier visualization of the wide range of measured blood levels, as it uses equal spacing for each factor of 10 increase.
**Statistically significant difference (p<0.05)*

Blood PFAS Levels and Other Variables

Through the exposure history questionnaires, ATSDR gathered information on several other behaviors and possible contributing factors to PFAS exposures. The variables listed below were not statistically associated with blood levels of PFHxS, PFOA, PFOS, PFNA, PFDA, PFUnA, or MeFOSAA among EA study participants in univariate or multivariate analyses.

- **Blood donation frequency.** Adult participants were asked how often they donate blood or plasma, because frequent blood and plasma donations might result in decreasing blood PFAS levels. Relatively few participants (n=23) reported donating blood once or more a year, and no statistically significant relationship was observed with blood PFAS levels in adults.
- **Soil exposure.** Adult and child participants were asked how often they play in or touch soil or dirt in the sampling frame. No statistically significant relationship was observed for self-reported soil contact frequency and blood PFAS levels in adults. There were too few children with responses across the categories to evaluate this variable in children.
- **Flooring.** Adult participants were asked about the type of flooring in their living rooms, kitchens, and bedrooms. While carpet has been linked to increased PFAS exposure because PFAS containing stain- and grease-repelling coatings are often applied to carpet [Beesoon et al. 2012], the presence of carpet in EA participants' rooms was not statistically associated with blood PFAS levels among adults.
- **Consumption of Selected Local Food Items.** Some PFAS accumulate in plants, fish, and animals. The questionnaire asked adult and child participants how often they consume locally grown fruits and vegetables, locally caught fish, and milk from animals in the sampling frame. Too few adult EA participants reported consuming locally caught fish (n=1) or locally produced milk (n=0) to allow for meaningful statistical analyses, and a statistically significant relationship was not

observed between consumption of locally grown fruits and vegetables and blood PFAS levels. There were too few children with responses across the categories to evaluate these variables in children.

- **Fast food consumption.** PFAS may be present in fast food take-away containers and food packaging. Consumption of fast food may serve as an additional source of PFAS exposure. However, among New Castle County EA adult participants, the reported frequency of fast food consumption was not statistically associated with blood PFAS levels. In recent years, fast food packaging has likely been reformulated to contain shorter chain PFAS compounds. This shift may make it more challenging to link PFAS exposure to fast food consumption.
- **Occupation.** Adult participants were asked about their occupational history over the past 20 years. Participants were specifically asked about experience working at manufacturers of PFAS or PFAS-containing products (e.g., nonstick cookware, water-resistant clothing) and past work in firefighting, the military, or aviation. The 14% of adults (n=29) who identified working in at least one job with potential exposures to PFAS in the past 20 years did not have statistically different PFAS levels than those without occupational exposures.
- **Childbirth (adult females) and birth order (children only).** Adult female participants were asked whether they had any biological children, and if so, how many. Children were asked their birth order. Birth may lead to lower blood PFAS levels for mothers, and birth order may be related to PFAS levels in children (with first-born children having higher PFAS levels than last-born children). Less than half of adult female EA participants (32%) reported having biological children. Neither having children nor the number of children was statistically associated with blood PFAS levels. Half of all children reported being the first born; birth order was not statistically associated with blood PFAS levels.
- **Breastfeeding.** During breastfeeding, some PFAS in the breast milk might be transferred from mother to child. Therefore, breastfeeding might reduce PFAS levels in mothers and increase PFAS levels in their breastfed children [Kim 2020; Kingsley 2018]. Accordingly, the adult and child exposure history questionnaires included questions about breastfeeding. A question was also included for children about their consumption of formula (as opposed to breast milk), and if the formula was made using tap water. Breastfeeding (yes/no), breastfeeding duration, and formula consumption were not associated with blood PFAS levels in either univariate models or female-only multivariate regression models.

PFAS in Urine

The study protocol calls for ATSDR to initially analyze 10% of urine samples collected. The protocol indicates that ATSDR will analyze all participants' urine samples if the initial analysis shows geometric mean urine concentrations of any PFAS greater than the NHANES 95th percentile values; however, this threshold was not met. Note that only PFBA and PFHxA were detected in more than 5% of the NHANES samples.

For the New Castle County EA, ATSDR randomly selected 22 participants' urine samples for analysis. These samples were provided by 18 adults and 4 children, and these individuals lived in 20 different households. PFBA was the only PFAS chemical detected in any of the 22 urine samples. Of note, there are challenges in measurement of trace levels of PFBA in urine, including selectivity of the analytical instrumentation and potential for external contamination [Abraham et al. 2021]. Therefore, we advise caution when interpreting the PFBA results in urine. Table 10 presents PFBA summary statistics for the randomly selected urine samples and national statistics for comparison. 4 of the 22 samples had PFBA urine concentrations greater than the NHANES 95th percentile. The protocol specified that all urine

samples would be analyzed if the geometric mean exceeded the 95th percentile from NHANES. Since no PFAS were detected in more than 60% of the analyzed samples, no geometric means were calculated for any PFAS in urine and ATSDR did not analyze the remainder of the urine samples.

Table 10. Community statistics for PFAS in urine reported in micrograms per liter

PFAS	Frequency of Detection (%)	Range of Concentrations	New Castle County Geometric Mean	New Castle County 95th Percentile	NHANES Geometric Mean *	NHANES 95th Percentile
PFBA	59.1	ND–0.7	NA*	0.59	NA*	0.300

µg/L = micrograms per liter, ND = not detected, NA – Not applicable

* Geometric mean was not calculated because chemical was not detected in at least 60% of the samples (detected in 13.3% of samples in Calafat et al. [2019]).

PFAS in Tap Water

As noted previously, ATSDR collected tap water samples from 13 randomly selected participant households (3 serviced by Artesian Water and 10 serviced by MSC) and analyzed these samples for PFAS. Six households only provided an unfiltered water sample, and seven provided both filtered and unfiltered samples. Detection limits were 2 ppt for all PFAS, except for HFPO-DA (5 ppt). PFBS, PFHxA, PFHpA, and PFOA were detected in 3 of the 13 unfiltered tap water samples, all from households serviced by Artesian Water. In one of these unfiltered samples, HFPO-DA (GenX) was also detected. The maximum concentrations in these unfiltered samples were 3.8 ppt PFBS, 37 ppt PFHxA, 9.2 ppt PFHpA, 9.6 ppt PFOA, and 7.8 ppt HFPO-DA (GenX). In two of the seven filtered tap water samples collected, PFHxA was detected at a maximum concentration of 6.2 ppt. Both samples were from households serviced by Artesian Water. Geometric means were not calculated for any PFAS in filtered or unfiltered tap water because no PFAS was detected in at least 60% of the filtered or unfiltered samples. All measured concentrations were below EPA's health advisory of 70 ppt for PFOA and PFOS combined. There are no EPA health advisory levels for PFBS, PFHxA, PFHpA, or HFPO-DA (GenX).

Because of the limited PFAS detections in the tap water samples, ATSDR did not investigate correlations between these sampling results and the blood data.

PFAS in Household Dust

ATSDR collected dust samples from the same 13 randomly selected participant households where tap water samples were collected and analyzed these samples for PFAS. These samples were taken from multiple locations in each household, including the primary living space as identified by the homeowner (e.g., living room, family room, television room), the kitchen, and the bedroom in which participants reported spending the most time. When necessary, additional sampling was performed in other rooms to allow ATSDR to collect the proper amount of dust for testing. Table 11 lists the specific PFAS compounds that were measured in dust along with detailed summary statistics (i.e., frequency of detection, geometric means, 95% confidence intervals around the geometric means, and percentiles). Note that several PFAS were not detected in any sample and are therefore not included in Table 11 (i.e., PFPeS, PFHpS, PFNS, PFDoS, N-MeFOSA, N-EtFOSA, FtS 4:2, HFPO-DA, ADONA, 9CL-PF3ONS, and 11CL-PF3OUdS).

Table 11. Summary statistics for dust samples (n=13) collected in New Castle County

PFAS	FOD (%)	Maximum Detected Result (ng/g)	Geometric Mean (ng/g)	95% Confidence Interval for Geometric Mean (ng/g)	Percentiles (ng/g)		
					50th (Median)	90th	95th
PFBS	54	50.9	NA*	NA*	1.62	25.2	39.1
PFHxS	54	28.3	NA*	NA*	2.99	6.63	14.4
PFOS	85	67.5	10.9	5.63–21.2	9.31	50.3	59.6
PFDS	38	3.39	NA*	NA*	1.47	2.53	2.96
PFBA	77	56.0	14.1	8.73–22.9	11.4	42.7	49.2
PFPeA	77	14.1	6.09	4.44–8.35	5.41	12.2	13.7
PFHxA	100	41.1	10.1	6.45–15.7	6.91	28.7	34.9
PFHpA	85	85.3	7.41	4.17–13.2	5.82	18.2	42.3
PFOA	85	115	13.3	7.09–25.1	12.9	37.1	67.6
PFNA	85	44.3	7.87	4.23–14.6	4.77	36.5	39.5
PFDA	92	20.1	9.19	6.48–13.0	8.97	16.4	18.0
PFUnA	92	24.1	7.63	4.96–11.8	5.07	17.7	20.7
PFDoA	85	13.5	5.88	4.07–8.48	5.22	12.5	13.1
PFTrA	77	14.6	5.18	3.47–7.72	4.02	12.4	14.0
PFTA	85	13.2	3.85	2.61–5.69	4.14	7.72	10.1
PFOSA	15	3.39	NA*	NA*	1.15	2.45	2.96
MeFOSAA	46	15.9	NA*	NA*	1.72	7.47	10.8
N-MeFOSE	46	297	NA*	NA*	18.0	54.5	145
EtFOSAA	77	21.6	7.94	5.47—11.5	6.88	18.8	20.7
N-EtFOSE	38	1110	NA*	NA*	10.7	38.2	417
FtS 6:2	31	24.4	NA*	NA*	9.00	18.2	21.4
FtS 8:2	31	13.6	NA*	NA*	NA†	NA†	NA†

FOD = frequency of detection, ng/g = nanograms per gram, NA = not applicable
A total of 13 dust samples are summarized in this table
* Per the EA protocol, geometric means were not calculated for PFAS detected in less than 60% of samples.
† Percentile is below the LOD.

PFOS, PFBA, PFPeA, PFHxA, PFHpA, PFOA, PFNA, PFDA, PFUnA, PFDoA, PFTrA, PFTA, and EtFOSAA were detected in more than 77% of the households evaluated. Of these, PFBA, PFOA, and PFOS were measured at the highest levels on average, with geometric mean values of 14.1 nanograms/gram (ng/g)[3] (95% confidence interval = 8.7–22.9 ng/g), 13.3 ng/g (95% confidence interval = 7.1–25.1 ng/g), and 10.9 ng/g (95% confidence interval = 5.63–21.2ng/g), respectively. Every other PFAS had geometric mean concentrations less than 10.9 ng/g.

To provide some context to the results summarized above, average levels of PFAS measured in the 13 samples collected as part of this EA were compared to average dust levels reported in other U.S.-based studies. This includes evaluations of indoor dust collected at 30 homes in the greater Boston area [Fraser et al. 2013], 124 homes in California [Wu 2015], 15 U.S. homes [Karásková et al. 2016], and 19 homes in

[3] This unit (in this case, representing nanograms of PFAS measured per gram of dust collected) is equivalent to parts per billion and micrograms per kilogram.

Minnesota cities with PFAS-contaminated soil and drinking water [Scher et al. 2018]. Across these studies, PFOA and PFOS were consistently reported at the highest concentrations. Geometric mean concentrations ranged from 24 to 45 ng/g for PFOA and 27 to 35 ng/g for PFOS (Fraser et al. 2013; Wu et al. 2015]. Two of the studies did not report geometric means; for these studies, median concentrations were reported at 9 ng/g and 51 ng/g for PFOA and 14 ng/g and 67 ng/g for PFOS [Karásková et al. 2016 and Scher et al. 2018, respectively]. Geometric mean and median concentrations for PFOA and PFOS measured in the 13 samples collected as part of this EA were lower than what was reported from these four studies. Details on these studies and comparisons with all other measured PFAS can be found in Appendix A, Table A1.

While these results suggest that PFAS measured in the dust samples collected in New Castle County are lower than those reported elsewhere in the United States, note that the studies referenced here do not necessarily provide representative comparison values and are provided only for additional context. The sample collection methods and analytical methods were also not consistent among these studies.

ATSDR also evaluated the correlation between PFAS measured in dust and blood. This analysis included analytical data from 13 dust samples summarized above and from the 18 blood samples collected from participants residing in the same homes. Using log-transformed data, ATSDR calculated Pearson correlation coefficients for all of the PFAS measured in at least 60% of the dust and the same PFAS measured blood samples for this assessment. Data were log-transformed because dust and blood concentrations were log-normally distributed.

None of the PFAS measured in dust were statistically correlated ($p<0.05$) with the same PFAS measured in blood. Pearson correlation coefficients for these comparisons ranged from -0.22 to 0.36, indicating weak correlations between concentrations measured in dust and blood. Note that the sample size for dust measurements in New Castle County is relatively small. ATSDR will further explore these findings, as well as correlations between different PFAS measured in dust and blood (e.g., the correlation between PFOA in dust and PFOS in blood) in the PFAS EA aggregate report.

The dust results presented here are exploratory and should be interpreted with caution. They are based on a limited set of samples, and in some cases those samples are based on a small sample mass. The target sample mass for this study was 1 gram, but this target was not always met. Results based on less than 1 gram of dust have higher detection limits, a possible source of bias.

Discussion

At least one PFAS was detected in the blood of all New Castle County EA participants (100%). Because of the widespread use of PFAS, such high detection frequencies are common in the general U.S. population [CDC 2019]. All seven PFAS (PFHxS, PFOS, PFOA, PFNA, PFDA, PFUnA, MeFOSAA) were frequently detected in the blood of New Castle County participants (detection frequencies above 60%).

Results from this EA were compared to NHANES data from 2015–2016.[4] Age-adjusted geometric mean blood levels of PFHxS, PFOS, PFOA, PFNA, and PFDA were statistically greater than these national geometric means (1.6 to 9.7 times higher).

All PFAS measured in blood for this EA have been phased out of production in the United States. Following this phase-out, national blood PFAS levels have been steadily declining since 2000 [CDC 2019].

[4] Newer NHANES data are now available, but this report (and all individual EA reports) compares EA results to 2015-2016 NHANES data to be consistent with individual results letters provided to participants. ATSDR will consider including the newer data in the aggregate report.

Differences between geometric mean New Castle County EA blood levels, collected in 2019, and the NHANES 2019-2020 geometric mean (not yet available) could be greater than the differences between geometric mean New Castle County EA blood levels and the NHANES 2015-2016 geometric mean presented here.

ATSDR compiled blood PFAS levels for the three most prevalent PFAS (PFHxS, PFOS, and PFOA) from other studies to provide further context on the current (2019) New Castle County EA blood levels (Appendix A, Table A2):

- New Castle County EA participants' blood PFHxS levels are higher than the range of those observed in other communities with contaminated drinking water: Little Hocking, Ohio, and Portsmouth, New Hampshire [Frisbee et al. 2009; NH DPHS 2016]. Water in Little Hocking, Ohio was contaminated due to fluoropolymer manufacturing and had a larger fraction of PFOA (and smaller fractions of PFOS and PFHxS) in the water compared to New Castle. Water in Portsmouth, New Hampshire was contaminated due to AFFF and had a similar mixture of PFAS as observed in New Castle and Wilmington Manor.
- New Castle County EA participants' blood PFHxS levels are higher than national geometric means from NHANES 1999–2000, the time NHANES first measured PFAS and the time the highest PFAS levels were observed [CDC 2019]. PFHxS has been detected in legacy AFFF formulations and may be present in groundwater because of degradation of other PFAS. The half-life of PFHxS is between 4.7 and 35 years and is longer than the half-lives for PFOS and PFOA, which may explain why blood PFHxS levels were more elevated than levels of other PFAS. [ATSDR 2021]
- PFOA and PFOS, on the other hand, did not exhibit these trends. For PFOS and PFOA, blood levels among New Castle County EA participants are lower than those observed in some other communities with contaminated drinking water: Little Hocking, Ohio; and Decatur Alabama [Frisbee et al. 2009; ATSDR 2013]. However, PFOS and PFOA blood levels in New Castle County EA participants are higher than more recent studies in Westhampton Beach/Quogue Area, New York; Portsmouth, New Hampshire; and Montgomery and Bucks Counties, Pennsylvania [NYDOH 2019; NH DHHS 2016; PA DOH 2019].

Generalizability of New Castle County EA Community Statistics

The random sampling recruitment method used for this EA was designed to produce summary statistics of blood PFAS levels that were generalizable to the sampling frame as a whole (i.e., the area shown in Figure 1 consisting of the communities of City of New Castle and Wilmington Manor). Although the population invited to participate was likely representative of the sampling frame, the population that ultimately enrolled was older and contained fewer Black individuals. Specifically, adults aged 50 or older represented 75% of the EA population compared with 37% of the sampling frame, and participants who identified as Black represented 11% of the EA population and 28% of the sampling frame population. Given the 4.5% response rate, it is also possible that other factors were present at different rates than the community as a whole.

Since age and race/ethnicity were associated with blood PFAS levels in univariate analyses, the summary statistics for blood PFAS (Table 5) may be biased, or deviate from the true value, when generalizing to the entire sampling frame. ATSDR was concerned about the potential bias caused by the older age of EA participants since levels of PFAS are known to vary depending on people's age. Therefore, ATSDR quantified the magnitude of this bias by calculating geometric means that were adjusted to the age distribution of sampling frame (Table 6). This analysis showed that differences in age distribution between the sampling frame and the EA participants resulted in unadjusted geometric means for blood

PFHxS, PFOS, PFOA, and PFNA were biased high 23% to 75%. This same analysis showed that differences in age distribution between the sampling frame and the EA participants resulted in unadjusted geometric means for PFDA, PFUnA, and MeFOSAA were biased 0% to 12%. Since univariate analyses showed that non-White, or Hispanic participants had lower blood levels of PFHxS, PFOS, and PFOA, ATSDR believes that the lower number of Black participants in this EA when compared to the sampling frame demographics might lead to higher geometric mean estimates reported here. ATSDR did not calculate community level statistics adjusted for race and ethnicity to account for this bias because PFAS blood levels are not as strongly associated with race and ethnicity. Therefore, the sampling frame age-adjusted geometric means may be more representative of the average levels in the community.

Relationships Between Demographics and PFAS Blood Levels

When evaluating differences in demographic factors by PFAS levels, adult males had statistically higher geometric mean blood levels for PFOS, based on results from the all-adult multivariate models. This trend has been observed in other studies in communities with contaminated drinking water and for the general U.S. population [e.g., ATSDR 2013; NH DPHS 2016; CDC 2019]. Sex-based differences are likely due to additional excretion routes in females including through menstrual fluid, breastfeeding, pregnancy, and renal clearance rate differences [ATSDR 2021]. PFAS have been demonstrated to pass through the placental barrier and into the developing fetus during gestation and have been measured in maternal serum, cord blood, breast milk [Cariou et al. 2015], placenta [Chen et al. 2017], fetal tissue [Mamsen et al. 2019], and neonates [Wang et al. 2014]. These studies suggest gestation, birth, and breastfeeding as excretion pathways for mothers and gestation and breastfeeding as potential exposure pathways for infants. However, in this EA, breastfeeding and having children were not found to be statistically associated with blood levels of PFAS among adult women.

Blood PFAS levels were statistically higher in older adults than younger adults. Blood PFAS levels were found to be higher in younger children or remain unchanged with age among children (3–18 years). Differences in the associations between blood PFAS levels and age in adults and children have been observed in other studies [ATSDR 2013; NH DPHS 2016; CDC 2019]. Generally, increasing blood levels in adults are due to the long biological half-lives of PFAS and diminishing excretion rates with increasing age. The half-life of a chemical is the amount of time it takes for 50% of the substance to be eliminated from the body. Some studies estimate that the half-life of PFHxS is between 4.7 and 35 years. Half-life estimates range from 3.3 to 27 years for PFOS and from 2.1 to 10.1 years for PFOA. In the presence of continued exposures that exceed clearance rates, PFAS will accumulate in the human body over time. On the other hand, PFAS blood levels in children may be associated with age due to multiple factors including early life exposures and growth dilution. Early-life exposures may have occurred since PFAS can cross the placenta and are found in breast milk [ATSDR 2021]. In addition, hand-to-mouth touching and spending more time closer to the floor with settled dust in toddlers is much greater than in older children. As a child grows, these early-life exposure factors diminish. Additionally, large increases in body size lower blood levels despite increasing or constant PFAS body burdens. This process is known as growth dilution [Koponen et al. 2018].

Blood PFAS levels were statistically lower in adult participants who self-identified as non-White or Hispanic compared to those who identified as White, non-Hispanic. These differences are also observed in the wider U.S. population and may reflect differences in exposure patterns such as lifestyle, diet, and use of PFAS containing products [Calafat et al. 2007b].

Significance of Drinking Water Exposures

ATSDR conducted EAs to learn more about how exposure to PFAS-contaminated drinking water affects blood PFAS levels. This relationship is complicated because EA participants were likely exposed to PFAS not only in contaminated drinking water but also in various consumer products and food items unrelated to the water. ATSDR considered the following lines of evidence to understand the potential significance of the drinking water exposure pathway:

- PFHxS, PFOS, PFOA, PFNA, and PFDA blood levels in EA participants were statistically higher than 2015-2016 NHANES national geometric means. PFAS were first detected in the MSC system in 2009 and the Artesian Water system in 2014, though contamination likely began before then. Among the site documents ATSDR reviewed, the highest sampling result from an active well in the MSC system was 1,400 ppt for PFHxS, 2,300 ppt for PFOS, and 440 ppt for PFOA. In the Artesian Water system, the highest sampling results from an active well were 680 ppt for PFHxS, 1,800 ppt for PFOS, and 140 ppt for PFOA. In 2014, MSC reduced its PFAS levels below EPA health advisory for PFOS and PFOA, and in 2016 Artesian Water reduced their water PFAS levels below the health advisory. However, these PFAS have very long biological half-lives (2.1 to 35 years). Therefore, even though drinking water PFAS concentrations in both systems were significantly reduced by July 2016, past drinking water exposures were likely a contributing factor to the EA participants' elevated blood PFAS levels observed 3 years and 3 months later for Artesian Water customers and 5 years and 2 months later for MSC customers. Furthermore, in this EA, PFHxS had the largest deviation from the national average and showed the greatest association with reported drinking water consumption, which is what would be expected given that PFHxS has the longest half-life of the three PFAS.
- PFHxS, PFOS, and PFOA were highly correlated in blood (*r* between 0.83 and 0.94), suggesting similar or common background sources or exposure pathways. PFHxS and PFOS, and to a lesser extent PFOA, have many common exposure sources, as these compounds are often found together in consumer products. While correlations between PFAS have been observed in other studies [NH DPHS 2016; ATSDR 2013; CDC 2019], the correlations observed between these three PFAS in the blood results for this EA are much higher than those observed in the general U.S. population (*r* between 0.46 and 0.66) [Calafat et al. 2007b]. Instead, the high correlation between PFHxS, PFOS, and PFOA is consistent with those found in the blood of people living in communities with contaminated drinking water [ATSDR 2013], providing further evidence that drinking water was likely a contributing source of exposure among New Castle County EA participants. In addition, the correlations between PFHxS, PFOS, and PFOA in this study are much higher than the correlations observed for PFNA and PFDA, two compounds that were not found in Artesian Water or MSC systems at elevated levels, providing further evidence of a distinct exposure pathway for these three compounds.
- Univariate statistical analyses of the EA data found that one of the most consistent predictors of adult blood PFAS levels was length of residency in the City of New Castle or Wilmington Manor. ATSDR considered residency duration to be a suitable surrogate for drinking water exposures because only residents who lived in the sampling frame before each system's eligibility date (August 2014, for customers of the MSC system or July 2016, for customers of the Artesian Water system) would have had any exposure to the PFAS-contaminated drinking water, and because of the likelihood that exposure would increase with the number of years that EA participants lived in the area. However, since older adults tended to live in the sampling frame longer, this variable was correlated with age in adults ($r=0.36$, $p<0.0001$). Because of this, it was unclear from univariate models alone whether the association between the time someone lived

in the sampling frame and PFAS blood levels was primarily due to age. After controlling for other variables, the multivariate statistical analysis found that residency duration remained statistically associated with blood PFHxS, PFOS, and PFOA blood levels and age did not. Age is generally a strong predictor of PFAS levels and could have replaced residency duration in these models, but residency duration was a stronger predictor.

- In ATSDR's univariate and multivariate analyses, participants who reported using a filter or treatment device on tap water at home had on average lower PFHxS, PFOS, and PFOA blood levels. Even though drinking water consumption rates were not statistically associated with blood PFAS levels as expected, the associations with filter type provided further evidence for a drinking water exposure route.
- ATSDR also considered which public water system served EA participants. In both univariate and multivariate analyses, participants who lived in the MSC service area had significantly higher PFHxS, PFOS, and PFOA blood levels than participants who lived in the Artesian Water service area. The last documented exceedance of the EPA health advisory in the MSC system occurred two years earlier than in the Artesian Water system. This might suggest that participants in the MSC system should have had lower blood PFAS levels based on a longer period of being unexposed. However, another consideration is the historic PFAS levels in each system's water. The maximum concentrations detected in MSC's system were generally higher than those in the Artesian Water system: 720 ppt higher for PFHxS, 500 ppt for PFOS, and 300 ppt for PFOA. In addition, all MSC water sources were contaminated whereas only a small portion of Artesian Water's sources were affected. All MSC customers would have therefore likely received levels approaching the maximum observed concentrations in the water. In contrast, Artesian Water customers received a blend of contaminated and uncontaminated water and the sampling frame was determined based on an engineering judgement of the area of influence around the contaminated water sources.
- One line of evidence that ATSDR considered and dismissed was the lack of associations between EA participants' self-reported drinking water source (public water or bottled water) and blood PFHxS, PFOS, and PFOA levels. Among the PFAS, only MeFOSAA was statistically associated with EA participants' self-reported drinking water source. As noted previously, the questionnaire asked only about current drinking water sources, which may not reflect the participants' drinking water sources before PFAS contamination in Artesian Water or MSC systems was mitigated. Similarly, any reported changes to drinking water behavior in the past year were not relevant for determining behavior during the period of exposure. Anecdotally, many participants informed EA field staff that they switched to bottled water upon learning of PFAS contamination in their water system, but this information was not systematically collected in the questionnaires. As a result, the lack of associations between current drinking water source or recent changes in drinking water behavior and participants' blood PFHxS, PFOS, and PFOA levels was considered a weak finding based on the data available for the analyses.

Taken together, the data suggest that past drinking water exposure contributed to the elevated blood levels of PFHxS, PFOS, and PFOA observed in the New Castle County EA participants.

Other Exposure Characteristics

Other exposure characteristics that showed statistically significant associations with blood levels of one or more PFAS in either univariate or multivariate analyses included the following:

- **Kidney disease.** Previous research shows that kidney disease can affect blood PFAS levels [Barry 2013; Watkins 2013]. Six percent of adult participants (n=13) reported a diagnosis of kidney

disease, but these adults did not have statistically different blood PFAS levels than those without a diagnosis of kidney disease in univariate analyses. However, in multivariate analyses participants who reported a history of kidney disease had PFHxS blood levels that were 56% greater than those who did not. These results are based on limited data and should be interpreted with caution.

- **Stain-resistant product use.** Stain-resistant products are sometimes applied to carpeting or upholstered furniture and have been linked to PFAS exposures [Beesoon et al. 2012]. Few participants reported frequent use of stain-resistant products at home; however, the 16% (n=33) of participants who reported "ever" using stain resistant products had elevated blood levels of PFNA in a univariate model compared to those who did not. Both PFOS and PFHxS are primary ingredients in historical formulations of stain-repellent consumer products used to treat carpet, furniture, and clothing. PFNA may be present in these products but it is not a generally a primary ingredient. These results are based on limited data and should be interpreted with caution.
- **Cleaning frequency.** In univariate analyses, adult participants who reported cleaning their homes three times per week or more on average had statistically lower PFHxS, PFOS, and PFOA blood levels than adult participants who reported cleaning their homes a few times per month or less. These results remained significant in multivariate models for PFHxS and PFOS. PFAS may be present in dust and therefore participants who live in homes that are cleaned less frequently may have increased PFAS exposures.

New Castle County Community-Wide Findings

Finding 1. Average blood levels of PFHxS, PFOS, PFOA, PFNA, and PFDA in the New Castle County EA site participants are higher than national levels.

Geometric means (i.e., averages) for PFHxS, PFOS, PFOA, PFNA, and PFDA blood levels were statistically higher ($p<0.05$) in New Castle County EA participants when compared to CDC's NHANES (2015–2016) testing, which was limited to people over 12 years old. The statistically higher blood PFAS levels were observed for both unadjusted geometric means for all EA participants and geometric means adjusted to the age distribution of the U.S. population from NHANES 2015–2016.

Of the PFAS analyzed in blood, PFHxS had the largest elevations when compared to national levels. The age-adjusted geometric mean blood PFHxS level among all New Castle County EA participants was 9.8 times higher than the national geometric mean. Blood PFHxS levels were above the national geometric mean for 99% of the New Castle County EA participants and above the NHANES 95th percentile for 86%. The age-adjusted geometric mean blood PFOS, PFOA, PFNA, and PFDA levels among New Castle County EA participants were 2.9, 2.4, 1.6, and 1.8 times higher, respectively.

PFUnA and MeFOSAA were detected in greater than 60% of samples, but ATSDR was unable to compare the geometric means calculated for these PFAS with NHANES because these PFAS were detected in fewer than 60% of NHANES samples.

Finding 2. Elevated blood levels of PFHxS, PFOS, and PFOA may be associated with past drinking water contamination.

Three PFAS (PFHxS, PFOS, and PFOA) with statistically elevated blood levels compared to national geometric means were detected in the MSC system as early as 2009 and in the Artesian Water system as early as 2014. We do not know if PFAS contamination began earlier, because data are not available before 2009 for the MSC system and 2014 for the Artesian Water system. The maximum concentrations observed in active drinking water wells in the MSC system were 1,400 parts per trillion (ppt) for PFHxS,

2,300 ppt for PFOS, and 440 ppt for PFOA. In the Artesian Water system, the maximum concentrations observed in active drinking water wells were 680 ppt for PFHxS, 1,800 ppt for PFOS, and 140 ppt for PFOA. In 2014, the MSC water supply system mitigated the contamination. The Artesian water supply system took similar action in 2014. In 2016, an additional well was found to be contaminated above the 2016 EPA HA so final mitigation in the Artesian system was not completed until 2016. However, these PFAS have very long biological half-lives (2.1 to 35 years). Therefore, even though drinking water PFAS exposures in New Castle County were reduced in 2014 and 2016, past drinking water exposures were a likely contributing factor to the EA participants' elevated blood PFAS levels, observed 3 to 5 years later. PFHxS has the longest estimated half-life (up to 35 years) of the three compounds, which may be why it exceeded the NHANES 2015-2016 geometric mean by the largest margin.

PFHxS, PFOS, and PFOA were highly correlated in New Castle County EA participants' blood (Pearson correlation coefficient, *r* between 0.83 and 0.94). This means that, typically, residents who had elevated blood PFHxS levels also had elevated blood PFOS and blood PFOA levels. This correlation suggests a common exposure source, such as the public water supplies, though other sources of exposure may also have contributed to the observed blood levels.

Additional observations support the finding that past exposure to contaminated drinking water may have contributed to the elevated blood levels.

- First, in univariate and multivariate models, a consistent predictor of participant blood PFHxS, PFOS, and PFOA levels was how long the resident had lived in New Castle County during the past 20 years. Those who lived in the area longest had the highest PFHxS, PFOS, and PFOA blood levels—and also likely drank the contaminated water for the longest period.
- Second, in univariate and multivariate analyses, adults who used at least one filter or treatment device had statistically lower PFHxS, PFOS, and PFOA blood levels when compared to those who did not have a filter.

ATSDR also considered differences in participants' public water systems. In multivariate analyses, participants who lived in the MSC service area had significantly higher blood PFHxS (247%), PFOS (148%), and PFOA (25%) levels than participants who lived in the Artesian Water service area. The differences between the water systems were consistent with the degree of historical contamination (i.e., higher historical PFAS levels in MSC public water and higher blood PFAS levels in residents served by MSC).

In contrast, while blood levels of PFNA and PFDA in New Castle County EA participants were statistically elevated compared to the U.S. population, few drinking water related variables were associated with these PFAS in the blood of participants.

Finding 3. Sex, kidney disease, and cleaning frequency were associated with some PFAS blood levels.

PFAS blood levels varied with different demographic and exposure characteristics of the participant population. The following statistically significant relationships in the New Castle County EA data set were observed in adult participants (and are consistent with those reported in other non-ATSDR PFAS studies):

- Males had statistically higher blood levels of PFOS than females. Specifically, multivariate models found blood levels in adult males to be 28% higher than adult females for PFOS.
- Adult participants who reported a history of kidney disease had PFHxS blood levels that were 56% higher in multivariate models than those who did not report kidney disease. Only 6% (n=13)

of adult participants reported a history of kidney disease, so these results should be interpreted with caution.

- Adult participants who reported cleaning their homes three times per week or more had PFHxS and PFOS blood levels that were 42% and 34% lower than adult participants who reported cleaning their homes a few times per month or less.

Most associations in children (<18 years) could not be evaluated because of the small number of child participants (n=11). However, blood levels of PFHxS and PFOS increased with self-reported water consumption levels at school, this finding should be interpreted with caution due to the small number of children who participated in the EA. The final report on all EA sites will include a more robust analysis of children.

Finding 4. Only one PFAS was detected in urine and at low concentrations.

ATSDR analyzed 22 (10%) of the urine samples collected. Only perfluorobutanoic acid (PFBA) was detected; it was detected in 59% of the 22 samples that were analyzed. ATSDR did not analyze all participants' urine samples because none of the species were detected in more than 60% of the samples analyzed.

Finding 5. All New Castle County tap water samples collected during the EA in 2019 met the EPA's HA for PFAS in drinking water.

This is based on 13 unfiltered and 7 filtered tap water samples collected in 13 households (3 serviced by Artesian Water and 10 serviced by MSC) during the EA.

Finding 6. Patterns and levels of dust contamination measured in participating EA households are comparable to those reported in selected U.S. studies.

Among the PFAS detected most frequently in household dust samples, PFBA, PFOA, and PFOS were measured at the highest concentrations. No nationally representative comparison values are available, but geometric mean and median concentrations for PFAS measured in dust collected in a small subset of participating households (n=13) were within the range of levels reported in a few published studies looking at other U.S. communities (with or without PFAS contamination). None of the PFAS measured in this EA's household dust samples were statistically correlated with the same PFAS measured in participants' blood. The final aggregate report on all EA sites will include a more robust comparison of PFAS measured in dust and blood.

Limitations

There are several limitations associated with this assessment.

- The random sampling recruitment method used for this EA was designed to measure blood PFAS concentrations that were generalizable to all New Castle County residents who were customers of the MSC water system and a small portion of customers from the Artesian Water system. However, the EA participant sample may not be fully representative of the community. Only 5% of the households from the random sample participated in the EA sample collection event, and participant characteristics were different than those of the area's overall population. Participants were older and less likely to be Black. ATSDR addressed some of these differences by calculating geometric mean estimates that were adjusted to the age distribution of the community.
- Measurement of blood, urine, and environmental PFAS concentrations in EA participants may improve the understanding of exposure in this community but will not provide discrete information about all sources of exposure. Additionally, identifying every potential confounding exposure is not possible.

- There are challenges in measurement of trace levels of PFBA in urine, including selectivity of the analytical instrumentation and potential for external contamination. Therefore, we advise caution when interpreting the PFBA results in urine.
- Multivariate regression models did explain a moderate portion of the variability in participants' blood PFHxS and PFOS levels (R-squared or R^2, a measure of model goodness-of-fit, ranged between 0.41 and 0.49, in the "all adult" models), but explained a smaller portion of blood PFOA levels ($R^2 = 0.22$). This means that other factors not identified could influence the relationships reported in this assessment (see "Statistical Analysis" section for details).
- This study did not directly assess tap water consumption prior to the reduction of PFAS from the two public water supplies.
- This EA was not designed to investigate health outcomes. Without additional information about exposure-response relationships, the results of this EA cannot be used to assess current or past health problems or predict the future occurrence of disease. PFAS found in a person's blood or urine means that exposure has occurred. The presence of PFAS in blood or urine does not tell us how, where, when, or for how long a person was exposed to PFAS. Exposure to PFAS does not mean adverse health effects will result, either now or in the future.
- The dust results are exploratory and should be interpreted with caution. They are based on a limited set of samples, and in some cases those samples are based on a small sample amount.

Recommendations

This PFAS EA provides evidence that past exposures to PFAS in drinking water have impacted the levels of PFAS in people's bodies. These PFAS are eliminated from the body over a long period of time. This allowed ATSDR to measure PFAS even though exposures through drinking water were mitigated, or lowered, years ago.

Although the exposure contribution from PFAS in drinking water in Artesian Water and MSC systems has been mitigated, there are actions community members and local officials can take to further reduce exposures to PFAS and protect public health.

Based on the PFAS drinking water test results from the Artesian and MSC water systems, ATSDR does not recommend an alternate source of drinking water at this time.

1. What Artesian Water and MSC can/should do:
    a. Operators of the two public water systems should continue to monitor concentrations of PFAS in drinking water delivered to the New Castle County community to ensure that concentrations of PFAS remain below the EPA's HA for specific PFAS in drinking water. Results of PFAS monitoring should be shared with community members through appropriate communication channels (Consumer Confidence Reports for Artesian Water, https://www.artesianwater.com/my-bills-services/water-quality-reports/; Consumer Confidence Reports for MSC, https://newcastlemsc.delaware.gov/consumer-confidence-reports/).
    b. All treatment systems to remove PFAS from the drinking water in the Artesian Water and MSC systems should be maintained appropriately to ensure that PFAS concentrations remain below the EPA's HA for specific PFAS in drinking water.

2. What community members can/should do:
    a. Become familiar with Consumer Confidence Reports (Artesian Water, https://www.artesianwater.com/my-bills-services/water-quality-reports/; MSC, https://newcastlemsc.delaware.gov/consumer-confidence-reports/) for information on each system's water quality.
    b. Nursing mothers should continue breastfeeding. Based on current science, the known benefits of breastfeeding outweigh the risks for infants exposed to PFAS in breast milk.
    c. When possible, eliminate or decrease potential exposure to PFAS in consumer products such as stain-resistant products and food packaging materials. To learn more visit: https://www.fda.gov/food/chemical-contaminants-food/questions-and-answers-pfas-food
    d. Pay attention to advisories about food consumption, such as local fish advisories.
    e. Discuss any health concerns or symptoms with your health care provider. Share results of PFAS blood testing with your health care provider and make them aware of ATSDR resources for clinicians (https://www.atsdr.cdc.gov/pfas/resources/info-for-health-professionals.html). Follow the advice of your health care provider and the recommendations for checkups, vaccinations, and health screening tests.
    f. At this time, ATSDR does not have plans to conduct additional blood testing for PFAS nor recommend PFAS EA participants get retested for PFAS in blood.
        - The biological half-lives of many of the PFAS measured in people's blood are long. PFHxS, in particular, has one of the longest half-lives–some estimates range in the decades. This means that PFAS blood levels are not expected to change significantly in the near-term, even if exposure stops. Additionally, it is unclear what an individual's PFAS test results mean in terms of possible health effects.

        For the general population, blood tests for PFAS are most useful when they are part of a scientific investigation like the EA. Test results tell you how much of each PFAS is in your blood, but it is unclear what the results mean in terms of possible health effects. In addition, blood testing for PFAS is not a routine test offered by most doctors or health departments. Talk to your health care provider and make them aware of ATSDR resources for clinicians (https://www.atsdr.cdc.gov/pfas/resources/info-for-health-professionals.html).
    g. Follow the advice of your child's health care provider and the recommendations for well child checkups, vaccinations, and recommended health screening tests. Consult https://health.gov/myhealthfinder to help identify those vaccinations and tests.
    h. For additional information about environmental exposures and children's health, contact the Pediatric Environmental Health Specialty Units, a nationwide network of experts in reproductive and children's environmental health (https://www.pehsu.net/).

For More Information

If you have questions or comments or want more information on the New Castle County EA site, call 800-CDC-INFO or email pfas@cdc.gov. For more information on the work CDC/ATSDR is doing to address PFAS exposure, visit ATSDR's PFAS website: https://www.atsdr.cdc.gov/pfas/. For other EA or PFAS-related questions, email pfas@cdc.gov.

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This list includes references for Appendices A, B, and C, as well as the sections above.

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