ATSDR

Health Consultation

Evaluation of Per- and Polyfluoroalkyl Substances (PFAS) in public drinking water

NASA Wallops Flight Facility

Wallops Island, Accomack County

Virginia

EPA/CERCLA ID: VA8800010763

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U.S. Department of Health and Human Services
Agency for Toxic Substances and Disease Registry

Health Consultation: A Note of Explanation

A health consultation is written documentation of analysis and health conclusions from ATSDR about health risks related to a National Priorities List (NPL) or other specific site, a chemical release, or the presence of hazardous material. To prevent or mitigate exposures, a consultation may lead to specific actions, such as restricting use of or replacing water supplies; intensifying environmental sampling; restricting site access; or removing the contaminated material. In addition, consultations may recommend additional public health actions, such as conducting health surveillance activities to evaluate exposure or trends in adverse health outcomes; collection and analysis of additional environmental samples to better characterize exposures; conducting biological indicators of exposure studies to assess exposure; and providing health education for health care providers and community members. This health consultation is released for a 45-day public comment period. ATSDR will address all public comments and revise or append the document as appropriate. The health consultation will then be reissued as a final document. The final document will conclude the public health assessment process for this site, unless additional information is obtained by ATSDR which, in the Agency's opinion, indicates a need to revise or append the conclusions previously issued.

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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 tribal, state, and local governments to study possible health risks in communities where people could come in contact with dangerous chemicals. For more information about ATSDR, visit the ATSDR website.

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Evaluation of Per- and Polyfluoroalkyl Substances (PFAS) in Public Drinking water

NASA Wallops Flight Facility

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EPA/CERCLA ID: VA8800010763

Cost Recovery:

Prepared by:

U.S. Department of Health and Human Services
Agency for Toxic Substances and Disease Registry
Office of Community Health Hazard Assessment

Atlanta, GA 30333

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Abbreviations and Acronyms used in this report

µg/L	micrograms per liter
4:2 FTS	4:2 fluorotelomer sulfonate
6:2 FTS	6:2 fluorotelomer sulfonate
8:2 FTS	8:2 fluorotelomer sulfonate
9-Cl-PF3ONS	perfluoro(2-((6-chlorohexyl)oxy)-ethanesulfonic acid)
11Cl-PF3OUDS	11-chloroeicosafluoro-3-oxaundecane-1-sulfonic acid
ADONA	4,8-dioxa-3H-perfluorononanoic acid
AFFF	aqueous film-forming foam
ATSDR	Agency for Toxic Substances and Disease Registry
CDC	Centers for Disease Control and Prevention
CTE	central tendency exposure
EPA	United States Environmental Protection Agency
CVs	health-based comparison values
HED	human equivalent dose
HFPO-DA	hexafluoropropylene oxide dimer acid
HI	hazard index
kg	kilogram
L	liter
LOAEL	lowest observed adverse effect level
MOE	margin of exposure
mg	milligram
MRL	minimal risk level
NASA	National Aeronautics and Space Administration
ND	not detected
NFDHA	perfluoro-3,6-dioxaheptanoic acid
ng	nanogram
NEtFOSAA	N-ethyl-perfluorooctanesulfonamido-acetic acid
NMeFOSAA	N-methyl perfluorooctane-sulfonamidoacetic acid
NOAEL	no observed adverse effect level
PFAS	per- and polyfluoroalkyl substances
PFBA	perfluorobutanoic acid
PFBS	perfluorobutanesulfonic acid
PFDA	perfluorodecanoic acid
PFDoA	perfluorododecanoic acid
PFEESA	perfluoro(2-ethoxyethane)sulfonic acid
PFHpA	perfluoroheptanoic acid
PFHpS	perfluoroheptane sulfonic acid
PFHxA	perfluorohexanoic acid
PFHxS	perfluorohexane sulfonic acid
PFMBA	perfluoro-4-methoxybutanoic acid
PFMPA	perfluoro-3-methoxypropanoic acid
PFNA	perfluorononanoic acid
PFOA	perfluorooctanoic acid
PFOS	perfluorooctanesulfonic acid
PFPeA	perfluoropentanoic acid
PFTeDA	perfluorotetradecanoic acid
PFTrDA	perfluorotridecanoic acid
PFUnA	perfluoroundecanoic acid
ppb	parts per billion
ppt	parts per trillion
PWS	public water system
RfD	Reference Dose
RME	reasonable maximum exposure
RMEG	Reference Dose Media Evaluation Guide
ToC	Town of Chincoteague
VADEQ	Virginia Department of Environmental Quality
VDH	Virginia Department of Health
WFF	Wallops Flight Facility

1. Summary

In July 2019, Local 1923 of the American Federation of Government Employees (hereafter "Union") petitioned the Agency for Toxic Substances and Disease Registry (ATSDR) to assess exposures to per- and polyfluoroalkyl substances (PFAS) from releases at the National Aeronautics and Space Administration (NASA) Wallops Flight Facility Main Base (WFF). This request included assessing exposures from the contamination of the drinking water production wells for the Town of Chincoteague (ToC). The ToC obtains its drinking water from four deep and three shallow drinking water production wells near the eastern boundary of WFF in Accomack County, Virginia. WFF also has its own deep drinking water production wells located in the central portion of the Main Base NASA property. NASA began sampling for PFAS from the ToC drinking water production wells and ToC finished drinking water in April 2017.

WFF conducted fire training from the 1970s to 1988 at three known locations. Firefighters trained with aqueous film-forming foam (AFFF) that contained PFAS. AFFF was also used to extinguish fires from an aircraft crash that occurred on the eastern side of WFF in 1998.

ToC drinking water production wells and finished drinking water were first tested for PFAS in April 2017. Several PFAS were detected in ToC finished water and drinking water production wells, including at levels above EPA's 2016 health advisory (in place at the time) for perfluorooctane sulfonic acid (PFOS) and perfluorooctanoic acid (PFOA) in three of the wells. The NASA WFF Main Base drinking water production wells and finished drinking water samples, which were tested in November 2016 and routinely since April 2017, have had either no PFAS detections or detections only slightly above the laboratory detection limits.

Shortly after the discovery of PFAS in ToC's drinking water production wells, NASA implemented multiple response actions, including shutting down the contaminated ToC shallow drinking water production wells, addressing the backflow issue that likely contaminated one deep well, and began supplementing ToC drinking water with water from NASA WFF's drinking water production wells. NASA then developed and installed a drinking water treatment system for ToC, which began providing finished drinking water to ToC on April 27, 2021. Following the installation of the treatment system, ToC resumed use of its shallow drinking water production wells. Between May 2017 and July 21, 2022, the most recent sampling data indicatedno PFAS detections at levels of potential health concern in ToC finished drinking water.

ATSDR evaluated the public health implications of exposure to measured PFAS in ToC finished drinking water from April 2017 to present and reached four central conclusions associated with ToC finished drinking water and exposure to biota and surface water. ATSDR did not consider inhalation or dermal exposure routes, which may have a negligible effect on PFAS absorption from drinking water compared to direct ingestion [ATSDR 2021].

Conclusion 1

ATSDR is unable to conclude whether there are ongoing risks of noncancer or cancer health effects from ingestion of PFOA, PFOS, and PFHpA in WFF finished drinking water or ToC finished drinking water for a year or more after April 2017. Any ongoing increased risk is expected to be minimal compared to other sources of environmental exposure to PFAS. The levels of PFBS and PFHxA detected in ToC finished drinking water since April 2017 are not expected to harm people's health.

Basis for Conclusion

PFOA and/or PFOS were occasionally detected in WFF drinking water production wells and in ToC drinking water production wells and finished drinking water while the contaminated wells were not in use, between April 2017 and April 2021, at levels above the ATSDR health-based comparison values (CVs). However, each compound was only detected in less than 10% of samples. As a result, it is not possible to calculate an exposure point concentration for water from the WFF system or from ToC after April 2017. There were no detections of PFAS in ToC finished drinking water after the installation of granular activated carbon treatment in April 2021 through the last set of data reviewed, from July 2022.

Because chronic exposure to PFOA and PFOS has the potential for health effects at concentrations below the laboratory limits of detection, we cannot rule out health effects from these compounds. However, any increased risk of health effects from drinking ToC finished drinking water after April 2017 or WFF finished drinking water is expected to be well below background risks from other sources of PFAS exposure.

Other PFAS, particularly PFHxA and PFHpA, were also detected in WFF water and in ToC samples collected after April 2017. PFBS and PFHxA concentrations were orders of magnitude lower than corresponding CVs and thus these compounds are not expected to contribute to health risks from drinking water. Very limited research is available on PFHpA health effects, which prevents ATSDR from making conclusions about risks from exposure to this compound, although the PFHpA levels detected were very low.

Conclusion 2

Although no data are available for PFAS in ToC prior to April 2017, conclusions were developed based on the assumption that exposure occurred at the levels measured during the initial round of testing. These conclusions may overestimate actual risk. ATSDR concludes that past daily exposure to PFOS alone or to the PFAS mixture in ToCs drinking water at the levels detected in April 2017 for 15–365 days (i.e., an intermediate exposure duration) could have harmed people's health. Exposures of over two weeks could cause immune suppression for children under 6 and may be a health risk for other particularly susceptible individuals, such as infants, those with suppressed immune systems or those at highest risk of heart attacks. Visiting infants under 1 year old who averaged three days a week or more drinking ToC water would likely also have been at risk of immune suppression. These risks would have been expected to be present for the 2016–2017 winter and early spring. ATSDR cannot conclude whether there were risks from earlier exposures to PFAS in drinking water given the limited available data.

ATSDR concludes that past PFAS exposure through drinking ToC finished drinking water for a year or more before mitigation efforts began in April 2017 could have harmed people's health. Chronic exposures to low levels of PFAS are associated with noncancer health effects that include immune system, developmental, liver, and cardiovascular toxicity.

ATSDR is unable to evaluate whether exposure to PFAS in ToC finished drinking water before April 2017 could have led to a higher risk of cancer in residents.

Basis for Conclusion

To estimate past exposure, ATSDR used the maximum concentrations for individual PFAS from two finished drinking water samples collected on consecutive days in April 2017 before mitigation was implemented. PFAS levels were likely increasing in the ToC drinking water wells when they were first detected, and thus earlier well concentrations are predicted to have been lower than those measured in April 2017. A higher percentage of ToC water was coming from the affected wells over the 2016-2017 winter, so PFAS concentrations in finished water may have been as high or possibly higher than measured in April 2017 for four to six months, even if well concentrations were lower. However, during peak summer months, ToC used less water from the affected wells. Therefore, resident exposures before October 2016 were likely to lower concentrations of PFAS.

ATSDR assessed whether past exposures to PFAS in drinking water at the levels found in ToC drinking water during the initial testing in April 2017 would result in harmful health effects for intermediate duration exposures (more than two weeks up to a year). Maximum PFOS exposure doses for children under 6 years old and average exposure doses for children under 1 year old were above ATSDR's minimal risk level (MRL), which is based on developmental and immune effects. Maximum PFOS doses for formula-fed infants under 1 year old were close to human equivalent doses that resulted in immune suppression during intermediate duration studies in mice. Children, particularly infants, are at a sensitive stage of development for immune suppression and the immunological studies were not done at a sensitive stage in mouse development, suggesting more potential harm than was observed in those studies. The presence of PFOA and PFHxS in the drinking water further contributed to the overall PFAS risk from intermediate duration exposures, although neither was present alone at levels that are known to cause toxicity following exposures of less than a year. The dose of PFOS reached a level of concern when infants consumed high-end volumes of ToC drinking water at least three out of seven days per week. Because we do not know when exposure to PFAS first started, and because the available data suggest that PFAS levels were increasing when they were first detected, we cannot evaluate intermediate-term exposures to PFAS more than 6 months before April 2017.

Based on average drinking water ingestion rates in humans, the concentration of PFAS detected in ToC finished drinking water in April 2017 resulted in estimated doses for all age groups that exceeded adverse health effect levels associated with noncancer adverse health effects in human studies. These human health studies are assumed to involve PFAS exposures of over a year. With data only available for two samples collected on consecutive days in April 2017, it is very difficult to predict the concentrations of PFAS going back more than a year from that time. However, the measured levels of PFOS, PFOA, and PFHxS were each orders of magnitude higher than the corresponding concentrations of health concerns for exposures of over a year. Even with potentially much lower concentrations in the months and years before sampling data are available, it is likely that PFAS were present at levels of potential health concern in ToC finished drinking water for more than a year before the contaminated shallow ToC drinking water production wells were removed from service following the detection of PFAS in April 2017. Adverse health effects that can result from chronic PFAS exposures include decreased vaccine efficacy, decreased birth weight, increased cholesterol, and increased risk of liver damage (EPA 2024a, EPA 2024b)

To evaluate the risk of cancer from an exposure, ATSDR needs to estimate when the exposure first started. ATSDR does not know when PFAS first reached the contaminated shallow ToC drinking water production wells that were removed from service in April 2017. Levels of PFAS found in monitoring of the shallow wells from November 2020 through July 2022 were approximately double or more compared to concentrations that were initially measured in April 2017. The substantial increase in PFAS levels in the shallow wells between 2017 and 2020 suggests that PFAS had not fully reached the wells in April 2017 when those wells were shut down. Therefore, the duration of exposure was likely much shorter than the durations assumed in ATSDR's standard exposure scenarios for cancer. There is no way to address the lack of data available for past exposures to PFAS in ToC finished drinking water. Given that EPA has estimated that PFOA increases the risk of cancer even at very low doses, it is possible that PFOA present in finished drinking water could meaningfully increase cancer risks at concentrations below those detected in April 2017. However, with the uncertainty in the duration and dose of the exposure, ATSDR cannot evaluate whether the PFOA levels in finished ToC drinking water were high enough for long enough to increase residents' cancer risk. EPA's estimate of the increase in cancer risk from an increase in PFOS dose is much lower than PFOA; therefore, PFOS is not expected to significantly impact the estimated increased cancer risk from the PFOA dose.

Conclusion 3 ATSDR is unable to determine whether a health concern exists for consumption of fish or shellfish from the waters surrounding or downstream from WFF.

Basis for Conclusion ATSDR is not aware of any PFAS biota data (i.e., shellfish or finfish) collected near WFF. PFAS readily bioaccumulate, so even with very low or non-detect concentrations in water or sediment, it is not possible to evaluate health risks associated with fish or shellfish without PFAS measurements in those organisms.

Conclusion 4 Based on available information, ATSDR concludes that inhalation, ingestion, and/or skin contact with PFAS in off-site groundwater, surface water, or soil are not expected to harm people's health.

Basis for Conclusion NASA investigated off-site migration of PFAS by installing monitoring wells and sampling both the monitoring wells and private wells to the west and north of NASA WFF. Based on review of environmental data collected to date, private wells outside the boundaries of WFF have not been contaminated with PFAS. ATSDR reviewed the limited surface water and sediment data from three offsite surface water bodies (Little Mosquito Creek, Jenneys Gut, and the Boat Basin). PFAS have been detected in surface water and sediment a short distance from WFF. Surface water levels were higher than drinking water comparison values but were below levels that would be expected to be a concern from wading or swimming. Sediment levels were below soil comparison values for intermediate-duration exposures.

Next Steps ATSDR supports reducing PFAS exposures, especially exposures for persons who may be more susceptible to the effects of PFAS.

Current scientific information suggests that the health and nutritional benefits of breastfeeding outweigh the potential risks associated with PFAS in breastmilk [ATSDR 2024b]. Studies have shown that infants can be exposed to PFAS during pregnancy by transfer through the mother to the fetus and through breastfeeding. However, breastfeeding provides clear health and nutritional benefits, including a reduced risk for ear and respiratory infections, asthma, obesity, and sudden infant death syndrome. Breastfeeding can also help lower a mother's risk for high blood pressure, type 2 diabetes, and ovarian and breast cancer [AAP 2012]. In general, the Center for Disease Control and Prevention (CDC) and the American Academy of Pediatrics [AAP 2012] recommend breastfeeding despite the potential presence of chemical contaminants in breast milk.

(see https://www.atsdr.cdc.gov/pfas/prevent-exposure/breastfeeding.html).

ATSDR recommends the following actions:

- While the contaminated wells are in use, ToC/NASA monitor drinking water quality and maintain the drinking water filtration system to remove harmful contaminants.

- While the contaminated wells are in use, ToC/NASA monitor PFAS concentrations in raw and finished water on a routine basis to ensure contaminant removal effectiveness.

- NASA support efforts by the State of Virginia Departments of Environmental Quality and Health to conduct PFAS testing in shellfish and finfish from Jenneys Gut, Little Mosquito Creek, Mosquito Creek, and/or Simoneaston Bay to determine if consumption may pose a health risk. The decision to test should be inclusive of health and welfare concerns from the affected community, including those who harvest fish and shellfish.

- Residents concerned about their past exposure to PFAS discuss their concerns with their health care provider. ATSDR has information for health care providers and the public at https://atsdr.cdc.gov/pfas/resources/index.html. ATSDR also provides guidance and tools for reducing stress and building resilience in communities during public health responses to environmental contamination at its Community Stress Resource Center at https://atsdr.cdc.gov/community-stress-resource-center/index.html

- Nursing mothers can continue to breastfeed and contact their healthcare providers with specific concerns. ATSDR is available to provide information to healthcare providers as needed.

- ATSDR's [2024a] current information on evaluation of patients exposed or potentially exposed to PFAS for clinicians https://atsdr.cdc.gov/pfas/hcp/resources/ is available as a resource for informing patients and guiding treatment.

For More Information

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2. Background

2.1 Statement of Issue and Purpose

In July 2019, ATSDR received a petition from the Union, Local 1923 of the American Federation of Government Employees. The Union requested that ATSDR conduct a public health assessment investigating the PFAS contamination at the NASA WFF Main Base near the ToC, Accomack County, Virginia, and specifically, risks to residents of ToC, NASA WFF employees and tenants, and people who might be exposed to NASA WFF-related PFAS in off-base private wells north and west of WFF and through other exposure pathways (i.e., seafood, locally grown vegetables and fruits).

This Health Consultation evaluates the potential for community PFAS exposure as a result of contamination at the WFF, primarily from drinking water from the ToC and WFF public wells. Available data suggest that contamination did not affect private wells and that there was very little, if any, risk of exposure through direct contact with surface water or sediment. The potential for human exposure through aquatic biota could not be evaluated due to a lack of available data.

2.2 Site Description and Timeline

The NASA WFF Main Base (Figure B-1) is composed of approximately 2,000 acres and is located near the intersection of Virginia Routes 798 and 175. WFF Main Base was constructed in 1942 during World War 2 as the Naval Auxiliary Air Station Chincoteague and transferred to NASA in 1959. The ToC is located about 5 miles east of the NASA WFF. A timeline for the site is shown in Figure 1.

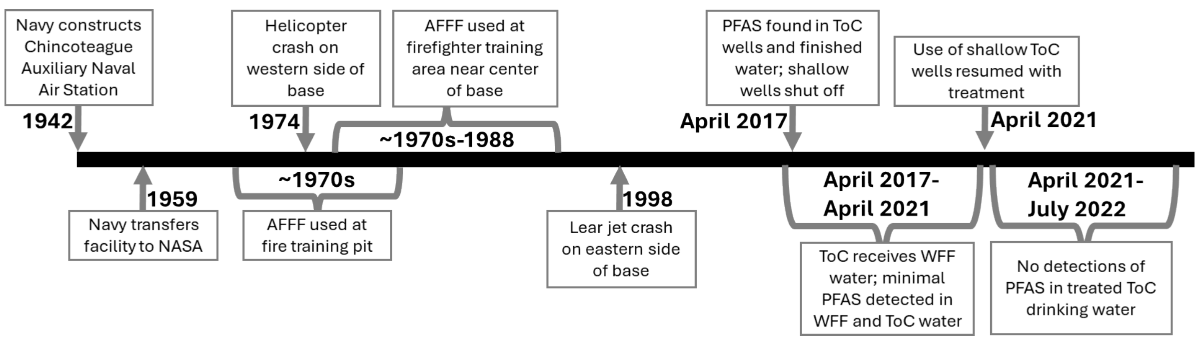

Figure 1. Timeline of contamination and mitigation events for the Site.

NASA WFF and ToC drinking water wells are at different physical locations, but both wells are located on NASA property. The NASA WFF currently obtains drinking water from wells that are over 200 ft deep in the central portion of the Main Base. NASA alternates the use of the five wells to provide drinking water to the facility employees, visitors, and on-facility housing residents. Historically, the ToC obtained drinking water from four deep wells (over 150 feet deep) and three shallow wells (approximately 60 feet deep) located on the NASA WFF. All of ToC's drinking water wells are located at the eastern boundary of the NASA WFF. Monthly pumping rates are available for each of the ToC's drinking water production wells (2011 to present). Because its deeper wells were contaminated with natural arsenic at levels slightly above the 10 ppb EPA maximum contaminant level (MCL) and the shallower water was undesirably acidic, ToC mixed water from the shallower wells with water from the higher production deep wells. The balance of shallow water to deep water varied throughout the year. Drinking water is distributed to the ToC's residents and businesses after being blended at the central drinking water plant.

Fire training activities, starting in the 1970s in one training pit and moving west and continuing from the 1970s to 1988, were conducted on the north-central portion of Wallops' Main Base. Firefighters conducted training with aqueous film-forming foam (AFFF) that contained PFAS. AFFF was also used to extinguish fires from an aircraft crash that occurred at Wallops in 1998 and may have been used after a helicopter crash in 1974.

During the 2014 Five Year Review for the Former Fire Training Area (FFTA) contamination site at the NASA WFF, PFAS were identified as a possible issue because past firefighting training activities used

AFFF that contained PFAS. In 2016, when the US Environmental Protection Agency (EPA) issued a drinking water health advisory for PFOA and PFOS of 70 ng/L (individually or combined, EPA 2016a, EPA 2016b), NASA sampled the 14 existing FFTA shallow monitoring wells and the NASA WFF finished drinking water. PFOA and PFOS were detected in groundwater under the FFTA at maximum concentrations of 3,600 ng/L and 24,000 ng/L, respectively. PFAS were not detected in the NASA WFF Main Base finished drinking water sample at that time.

Because elevated PFAS concentrations were found in FFTA groundwater, NASA began researching the use of AFFF at the WFF and identified an additional five sites suspected of AFFF usage: the Main Base Fire House, the 1970s Fire Training Pit, the 1974 Helicopter Crash site, the 1998 Lear Jet Crash site, and the West Training area. In April 2017, NASA expanded the PFAS investigation to include these five potential sites and various drinking water sources. The investigation activities included the following:

- Sampling the NASA WFF drinking water system, including each of the five production wells and the finished drinking water,
- Sampling six additional shallow monitoring wells adjacent to some of the potential new sites,
- Sampling four temporary monitoring wells on the western and southern property boundaries, and
- Sampling the ToC's drinking water system, including the three shallow wells, the four deep production wells, and the finished drinking water.

In May 2017, the PFAS investigation was further expanded to include additional testing:

- Sampling several off-facility, adjacent residential private wells north and west of WFF, and
- Sampling the Trails End Utility Company public drinking water system northeast of the contaminated groundwater on the other side of Little Mosquito Creek, including the one shallow well and two deep production wells and finished drinking water.

PFAS contamination was not detected in the adjacent residential private wells or the Trails End Utility Company public drinking water system.

The first full round of PFAS sampling of the NASA WFF and the ToC's drinking water systems were completed between April 12–26, 2017. A spatial representation of PFAS analytical results from the April 2017 PFAS Investigation is presented in Appendix B, Figure B-2.

The ToC's finished drinking water was sampled in April 2017. PFOA, PFOS, and other PFAS were detected in the ToC's finished drinking water (see Table 1). The combined PFOA/PFOS detected in the ToC's finished drinking water were found at levels below the 2016 EPA PFOA/PFOS drinking water health advisory level of 70 ng/L in place at that time. Water sample results from the ToC's production wells (see Table 1) indicated that PFOA and PFOS were above 70 ng/L in three of the ToC's production wells (shallow wells DW-003B and DW-003C, and deep well DW-005). Water samples from the same three production wells were also found to contain PFHpA, PFHxS, and PFNA. Although shallow production well

DW-003A was not found to be contaminated with PFOA/PFOS above the 2016 EPA PFOA/PFOS drinking water health advisory at that time, it also contained the same five PFAS.

From April 2017 to November 2021, all ToC and the NASA WFF drinking water production wells (including the PFAS contaminated wells), as well as the finished drinking water from both systems, were sampled for PFAS at least monthly. After November 2021, this sampling cadence was switched to quarterly sampling for the NASA WFF finished water and all the production wells. ToC finished water is still sampled monthly.

After it was determined that they were contaminated with PFAS, ToC production wells DW-003A, DW-003B, and DW-003C were taken offline in April 2017. A deep well (DW-005) with elevated PFAS was connected to the shallower wells through a common pipe; backflow prevention was added to prevent further contamination. These actions reduced PFAS exposure in drinking water after April 2017. While these contaminated ToC production wells were offline, NASA supplemented the ToC's drinking water with water from NASA WFF production wells, while at the same time exploring groundwater treatment. NASA then developed and installed a groundwater treatment system for the ToC. The treatment system began operational testing in August 2020, with finished water being sent to ToC starting on April 27, 2021. This enabled the ToC to resume use of its production wells without PFAS contamination reaching the finished water.

The NASA WFF production wells and finished drinking water samples, as well as the finished ToC drinking water since April 2017, have either indicated no detections of PFAS or detections only slightly above the laboratory detection limits. PFAS concentrations measured in the shallow ToC wells' water increased substantially during the time when the wells were not in use, between April 2017 and November 2020. Subsequent testing of the shallow wells has shown variability in PFAS concentrations but no clear increase or decrease. The northern ToC shallow well and monitoring wells to the south of the ToC wells have lower levels of PFAS, while the southern two ToC shallow wells have much higher concentrations of PFAS.

Given their location and the direction of groundwater flow, the Main Base Fire House and Lear Jet Crash Site are potential sources of contamination of the ToC shallow wells, while groundwater flow from the other identified sources would be expected to carry contaminants away from the ToC wells.

NASA conducted environmental investigations to determine whether and how the NASA WFF PFAS contamination has migrated into the local surface water and sediment, to understand if PFAS could have harmed the local surface water biota. NASA identified and mitigated multiple pathways through which PFAS contamination was reaching surface water.

3. Community Description and Concerns

3.1 Community Demographics

During the 2020 Census, the ToC had a year-round population of 3,304. This population is much higher during the summer, up to 10-fold higher according to the petition, due to an influx of tourists and seasonal residents. ToC is predominately white (92%) and has a high density of residents over 65 (37%).

Residents of neighboring areas that would not be exposed through public drinking water at home but who could be exposed at work or through other pathways, are of lower socioeconomic status with lower percentage of non-Hispanic whites than residents of ToC and are more likely to have other sources of environmental exposures. Accomack County, including ToC, is 58% non-Hispanic white, 12% non-Hispanic black, and 19% Hispanic.

3.2 Community Concerns

Community concerns about the ToC public water system (PWS) PFAS exposures and PFAS exposures at the NASA WFF site have been raised to ATSDR via the petition process and through interactions with community members at NASA public meetings. Community members have expressed concern over the health implications of PFAS exposures to people using the drinking water provided by ToC, using private wells, consuming local biota and fruits/vegetables, and NASA WFF workers and tenants (individuals residing in on-base housing) drinking water from NASA WFF public drinking water.

The community also has concerns/questions regarding exposure to historical PFAS levels in ToC drinking water during visits (overnight, weekends, vacations, and/or working/visiting during the entire summer). Furthermore, the community has raised questions about whether they should get their blood tested for PFAS to understand their exposure, and whether ATSDR would conduct that testing.

4. Sampling Data

ATSDR reviewed drinking water sampling results and other environmental data provided by NASA.

The first data set available that included testing for PFAS was for NASA's initial round of testing in November 2016, which included monitoring wells around WFF and the drinking water wells and finished drinking water for WFF. After finding concerning levels of PFAS in the monitoring wells, but not the WFF wells, NASA expanded their investigation. In April 2017, they retested the samples from the first round, added additional monitoring wells, and tested the ToC production wells and finished drinking water. After the April 2017 round of testing, NASA conducted biweekly testing of ToC drinking water until October 2017, when they switched to monthly testing that continued through the most recent data analyzed in July 2022. NASA conducted monthly testing of WFF wells and finished water from April 2017 until November 2021, when they switched to bimonthly testing, which continued through the most recent data analyzed in July 2022.

All monitoring well and drinking water samples collected were analyzed for six PFAS: PFOA, PFOS, perfluorobutanesulfonic acid (PFBS), perfluorononanoic acid (PFNA), perfluorohexanesulfonic acid (PFHxS), and perfluoroheptanoic acid (PFHpA). In February 2019, NASA added testing for perfluorodecanoic acid (PFDA), perfluorododecanoic acid (PFDoA), perfluorohexanoic acid (PFHxA), perfluorotetradecanoic acid (PFTeA), perfluorotridecanoic acid (PFTrA), perfluoroundecanoic acid (PFUnA), N-ethyl perfluorooctanesulfonamidoacetic acid (NEtFOSAA), and N-methyl perfluorooctanesulfonamidoacetic acid (NMeFOSAA). In September 2019, NASA added testing for hexafluoropropylene oxide dimer acid (HFPO-DA, also known as GenX), 4,8-dioxa-3H-perfluorononanoic acid (ADONA), perfluoro(2-((6-chlorohexyl)oxy)ethanesulfonic acid) (9Cl-PF3ONS), and 11-

chloroeicosafluoro-3-oxaundecane-1-sulfonic acid (11Cl-PF3OUDS). In February 2022, they added perfluorobutanoic acid (PFBA), perfluoropentanesulfonic acid (PFPeS), perfluoroheptanesulfonic acid (PFHpS), perfluoropentanoic acid (PFPeA), 4:2 fluorotelomersulfonic acid (4:2 FTS), 6:2 fluorotelomersulfonic acid (6:2 FTS), 8:2 fluorotelomersulfonic acid (8:2 FTS), perfluoro-3,6-dioxaheptanoic acid (NFDHA), perfluoro(2-ethoxyethane)sulfonic acid (PFEESA), perfluoro-3-methoxypropanoic acid (PFMPA), and perfluoro-4-methoxybutanoic acid (PFMBA).

For context regarding the contribution of individual ToC production wells to the finished drinking water, ATSDR reviewed well production volume data from ToC for January 2012 through July 2018.

PFAS have been detected in surface water and sediment on-base and near WFF. ATSDR reviewed surface water and sediment data from the 2019 PFAS Sampling Annual Summary Report [NASA 2021].

ATSDR is not aware of any PFAS biota data (i.e., shellfish or finfish) collected near WFF.

5. Scientific Evaluations

ATSDR follows the public health assessment (PHA) process as outlined in the Public Health Assessment Guidance Manual [ATSDR 2023a]. A summary of the general PHA process is given in Appendix A.

5.1 Exposure Pathway Analysis

A chemical only poses a risk to people near a chemical release if they come into contact with the chemical. Exposure might occur by eating food, accidentally swallowing a substance, breathing air, skin contact with a substance, or drinking a substance containing the contaminant. A release does not always result in exposure.

ATSDR evaluates site conditions to determine if people could have been (a past scenario), are (a current scenario), or could eventually be (a future scenario) exposed to site-related contaminants. ATSDR also considers the route a substance takes from its source (where it began) to its end point (where it ends), and how people can come into contact with it (or get exposed). This is an exposure pathway. An exposure pathway has five elements:

1) a source of contamination (i.e., a spill or release)
2) an environmental media and transport mechanism (e.g., groundwater)
3) a point of exposure (e.g., tap water)
4) a route of exposure (e.g., drinking)
5) a receptor population (e.g., people exposed or potentially exposed)

When evaluating exposure pathways, ATSDR determines whether there is evidence that all of the elements are present, whether one or more elements are unknown, or if there is evidence that one or more elements are not occurring. Exposure pathways are complete if all five elements of a human exposure pathway are present. A potential pathway occurs when one or more pathway elements cannot be proved or disproved. A pathway is eliminated if at least one element is missing (see Table B-1).

For PFAS releases from the WFF source, potential media for exposure include the following:

- Groundwater affecting the ToC public drinking water wells, WFF public drinking water wells, and off-base private wells north and west of WFF
- Surface water
- Sediment
- Biota grown in or with surface water or groundwater, particularly fish and shellfish
- On-site soils

For drinking water contaminated with PFAS, the main concern is intentional ingestion. PFAS are not volatile and are poorly absorbed from the skin when dissolved in water. The contribution of inhalation and skin absorption of PFAS in drinking water is expected to be negligible compared to the absorption through drinking the water. Therefore, ATSDR only considered direct ingestion of PFAS for drinking water.

There were PFAS detections in the finished drinking water distributed to ToC in April 2017 (Table 1), so ingestion of ToC drinking water at around that time was a complete exposure pathway that warranted further analysis. There are no data available for ToC drinking water before that time, so drinking ToC water before Spring 2017 is a potential route of exposure. During the period when ToC was receiving water from WFF, from April 2017 to April 2021, there were occasional detections of PFAS in finished ToC drinking water, so this exposure pathway was also complete. This exposure pathway was incomplete once granular activated carbon was used to remove PFAS from ToC finished drinking water, starting in April 2021. No detections of PFAS were observed in ToC finished drinking water from May 2021 through the most recent data reviewed, from July 2022.

There have been occasional detections of PFAS in finished WFF drinking water since November 2016, so this is a complete exposure pathway that is carried forward for further analysis. Exposure to PFAS in WFF water before that time is a potential exposure pathway, given the lack of data from before 2016. However, given the high percentage of non-detects in the later samples, this pathway was eliminated from further evaluation.

There were no detections of PFAS in off-site private wells north and west of WFF, indicating that this was an incomplete exposure pathway eliminated from further consideration.

Surface water, sediment, and biota were considered potential exposure routes. There were detections of PFAS in surface water and sediment collected from water bodies around the WFF. However, it is unknown whether there are any scenarios in which workers or neighboring residents would be meaningfully exposed to water or sediment, so this is a potential exposure pathway. Direct exposure to surface water and sediment were carried forward for further qualitative analysis.

Biota, particularly fish and shellfish, may absorb PFAS from the water or sediment. There are no data available for biota collected from around WFF or bioconcentration factors that could allow this pathway to be estimated. Fish and shellfish are known to be consumed from areas within a half mile to the south and east of WFF. The stretch of Little Mosquito Creek to the northwest of WFF is closed for shellfishing, due to bacterial contamination, and most of the rest of that stream is only open for oysters that are relayed to a clean water body to reside for at least 15 days. The Boat Basin is located entirely on WFF property and off limits to shellfishing. Jenneys Gut and Mosquito Creek, which run southwest and west of WFF, are open to shellfishing. Therefore, consumption of aquatic biota that are contaminated through water and/or sediment is considered a potential exposure route that will be considered qualitatively.

5.2 Evaluation of Drinking Water

5.2.1 Screening Analysis

The next step in ATSDR's evaluation process is to screen the environmental data against chemical-specific screening values. This step allows ATSDR to focus attention on areas and contaminants of most potential concern by eliminating contaminants that are unlikely to result in harmful exposures from further consideration. ATSDR uses health-based comparison values (CVs), concentrations of chemicals in drinking water below which no harmful health effects are expected to occur, to screen chemicals. CVs are not regulatory clean up values, and concentrations higher than the corresponding CV do not necessarily result in harm. ATSDR further evaluates contaminants at concentrations above a CV [ATSDR 2023a]. ATSDR has derived intermediate CVs called environmental media evaluation guides, or EMEGs, for four PFAS: PFOA, PFOS, PFHxS, and PFNA. ATSDR has also adopted chronic CVs called reference dose media evaluation guides, or RMEGs, based on EPA reference doses for seven PFAS: HFPO-DA, PFBS, PFBA, PFOA, PFOS, PFHxS, and PFHxA.

For PFAS in drinking water, ATSDR uses an additional triage step. This triage step focuses our efforts on situations where PFAS is present at levels where there are no technological limitations that would limit efforts to control the risk. EPA has determined that several PFAS exhibit toxic effects at concentrations that are well below what can be readily detected with available technology. Reduction of PFAS in drinking water to levels that are expected to be safe may also not be achievable with available technology. EPA has established maximum contaminant levels (MCLs), allowable concentrations of PFAS in public drinking water, that are at concentrations where some health effects may be observed for six PFAS (PFOA, PFOS, PFHxS, PFNA, HFPO DA, and PFBS) either alone or as mixtures. Given the technological limitations and their frequent occurrence in drinking water, ATSDR has elected to screen those six compounds for chronic toxicity against their MCL rather than the corresponding RMEG, to focus our assessment efforts on situations where it is practical to mitigate the corresponding risks.

Table 1 presents the April 2017 detected PFAS levels in the ToC PWS wells, ToC finished water PFAS levels, and CVs used in this screening evaluation for PFOS, PFOA, PFHxS, PFNA, and PFBS. PFOA, PFOS, and PFHxS were detected in the ToC PWS well water at up to 0.12, 0.61, and 0.25 μg/L, respectively, and in ToC finished water at 0.012 (J qualified), 0.047, and .045 μg/L, respectively. A "J" qualified data result is an estimated value for a result that is above the method detection limit (MDL) but below the reporting limit (RL). PFHpA, a PFAS with positive detections but lacking a CV or MCL, was retained for further qualitative evaluation.

PFOA, PFOS, and PFHxS each exceeded their MCL and were carried forward for analysis of the risks from long term exposure. PFOS was the only compound to exceed an intermediate CV and was carried forward for analysis of its risk of toxicity from shorter duration exposures. PFOA and PFHxS were present at concentrations that could contribute to toxic effects from intermediate exposures as part of a mixture. An in-depth toxicological discussion of the April 2017 PFAS levels in ToC finished drinking water and its implications for intermediate and chronic exposures is provided in the following section. PFHpA does not have a chronic or intermediate CV or an MCL and will be considered qualitatively.

Table 1. The maximum April 2017 ToC PWS well and ToC finished drinking water concentrations, screened by available chronic and intermediate screening values for six compounds: PFOS, PFOA, PFHxS, PFHpA, PFNA, and PFBS.

Chemical	Chronic Screening Value (μg/L)	Intermediate Screening Value (μg/L)	Maximum PFAS Concentrations (μg/L) in Water from all ToC PWS Wells April 2017	ToC Finished Drinking Water Maximum PFAS Concentrations (μg/L) April 2017
PFHpA	None*	None*	0.160	0.011
PFBS	2.0‡	2.1§	0.065	ND
PFHxS	0.01‡	0.140§	**0.25†**	**0.045†**
PFNA	0.01‡	0.021§	**0.073†**	ND
PFOA	0.004‡	0.021§	**0.12†**	**0.012 J†¶**
PFOS	0.004‡	0.014§	0.61	**0.047†**

Source: [NASA 2019]. 2018 PFAS Sampling Annual Summary Report, Goddard Space Flight Center Wallops Flight Facility Wallops Island, Virginia. October 2019.
https://www.nasa.gov/sites/default/files/atoms/files/final2018pfassamplingannualsummaryreport.pdf

Note: †= Concentrations are above a health-based comparison value.

* Although lacking health-based comparison values, PFHpA was selected for qualitative analysis because it was detected above PFOA and PFOS MCLs. ATSDR cannot include PFAS with no CV in its evaluation of mixtures.

§ ATSDR-derived value for children's exposures. This value is called a reference dose media evaluation guide (RMEG). RMEGs are based on EPA RfDs and conservative assumptions about exposure, such as intake rate, exposure frequency and duration, and body weight. Child drinking water RMEGs are based on an infant (age birth to one year old) weighing 7.8 kg and an intake rate of 1.113 liters per day.

‡ EPA-derived MCL. These values are set at a level that is either expected to be without toxic effects or at a level that can reasonably be achieved using currently available technology and where the benefits of the regulation exceed the costs. ATSDR uses MCL values to triage results for PFAS in drinking water to focus our efforts on situations where meaningful improvements in human health risks can be achieved.

¶ Laboratory estimate

Table 2 shows the number of detections and the maximum and minimum ToC finished drinking water concentrations in samples collected in the time between when the ToC shallow wells were shut off in April 2017 until the granular activated carbon system began treating the water in April 2021. Although there were a few detections for PFOA, PFHpA, and PFHxA, the detections were all at very low levels. The small amount of PFOA and possibly PFHpA present in the ToC finished drinking water during this time might theoretically increase a person's risk, but the effects would be minimal compared to the typical PFAS body burden through other routes of exposure. The concentrations of PFHxA were well below any level of concern. Given the very low levels of PFAS present and the infrequency of detections in ToC finished drinking water from April 2017 through April 2021, this pathway was not carried forward for further evaluation.

Table 2. ToC Finished Drinking Water PFAS Results (µg/L) from May 2017 to April 2021.

Chemical	Chronic Screening Value (µg/L)	Detections/# samples	Minimum (µg/L)	Maximum (µg/L)
PFOA	0.004[‡]	7/128	0.00044 J[¶]	0.00061 J[¶]
PFHpA	none*	3/128	0.00046	0.0011
PFHxA	3.5[§]	11/74	0.00037	0.0016

PFAS not detected: PFOS, PFBS, PFHxS, PFNA, NEtFOSAA, NMeFOSAA, PFDA, PFDoA – perfluorododecanoic acid, PFTeA, PFTrDA, PFUnA, HFPO-DA, ADONA, 9CL-PF3ONS, 11CL-PF3OUDS, PFBA.

* Although lacking health-based comparison values, these were selected for qualitative analysis because they were detected above PFOA and PFOS MCLs. ATSDR cannot include PFAS with no CV in its evaluation of mixtures.

§ ATSDR derived value for children's exposures. This value is called a reference dose media evaluation guide (RMEG). RMEGs are based on EPA RfDs and conservative assumptions about exposure, such as intake rate, exposure frequency and duration, and body weight. Child drinking water RMEGs are based on an infant (age birth to one year old) weighing 7.8 kg and an intake rate of 1.113 liters per day.

‡ EPA-derived MCL. These values are set at a level that is either expected to be without toxic effects or at a level that can reasonably be achieved using currently available technology and where the benefits of the regulation exceed the costs. ATSDR uses MCL values to triage results for PFAS in drinking water to focus our efforts on situations where meaningful improvements in human health risks can be achieved.

¶ Laboratory estimate

Table 3 shows the results from sampling NASA WFF On-base finished drinking water from November 30, 2016, to July 2022. Although the maximum PFOS concentration was above the chronic health-based comparison value, over 95% of samples did not have measurable PFOS levels. Overall, although some PFAS may contribute to health effects at very low concentrations, these data do not suggest a meaningful increased risk of health effects from PFAS beyond the background level of risk from other sources of PFAS exposure. Exposure to NASA WFF finished drinking water was not carried forward for further analysis.

Table 3. NASA WFF On-base Finished Drinking Water Detected PFAS Results (µg/L) from November 2016 to July 2022.

Chemical	Chronic Screening Value (µg/L)	Detections/# samples	Minimum (µg/L)	Maximum (µg/L)	95% Upper Confidence Limit (µg/L)
PFOA	0.004‡	20/153	0.00047 J¶	0.0012	--
PFOS	0.004‡	6/153	0.00098 J¶	**0.0061 J**	--
PFBS	2.0‡	1/153	--	0.0074 J¶	--
PFHpA	none*	74/153	0.00054 J¶	0.0033	0.0013
PFHxS	0.010‡	10/153	0.00084 J¶	0.0084	--
PFHxA	3.5§	88/94	0.00071 J¶	0.0039	0.0018

PFAS not detected: PFNA, NEtFOSAA, NMeFOSAA, PFDA, PFDoA, PFTEA, PFTrDA, PFUnA, HFPO-DA, ADONA, 9CL-PF3ONS, 11CL-PF3OUDS, PFBA.

* Although lacking health-based comparison values, these were selected for qualitative analysis because they were detected above PFOA and PFOS MCLs. ATSDR cannot include PFAS with no CV in its evaluation of mixtures.

§ ATSDR derived value for children's exposures. This value is called a reference dose media evaluation guide (RMEG). RMEGs are based on EPA RfDs and conservative assumptions about exposure, such as intake rate, exposure frequency and duration, and body weight. Child drinking water RMEGs are based on an infant (age birth to one year old) weighing 7.8 kg and an intake rate of 1.113 liters per day.

‡ EPA-derived MCL. These values are set at a level that is either expected to be without toxic effects or at a level that can reasonably be achieved using currently available technology and where the benefits of the regulation exceed the costs. ATSDR uses MCL values to triage results for PFAS in drinking water to focus our efforts on situations where meaningful improvements in human health risks can be achieved.

¶ Laboratory estimate

5.2.2 Health Evaluation for ToC Finished Drinking Water

5.2.2.1 Exposure Assessment

Based on the ToC finished drinking water results in Table 1, the levels of PFOA, PFOS, and PFHxS (0.012 µg/L, 0.047 µg/L, and 0.045 µg/L, respectively) present in ToC finished drinking water in April 2017 were high enough to warrant further analysis. To further investigate the risks of harmful health effects, ATSDR examined the amount of PFAS in drinking water that ToC residents were exposed to. To this end, we estimate how much of the chemical these residents would ingest each day, known as a daily exposure dose, and how long the exposure continued, known as an exposure duration.

The estimated dose is expressed on a body weight basis (amount of contaminant per kilogram of body weight) per day to allow comparison with relevant health-based guidance values presented in the same units. Appendix A details how ATSDR estimated exposure doses in this report. We adhered to ATSDR's Public Health Assessment Guidance Manual (PHAGM) to estimate exposure doses for age groups ranging from birth through adulthood and who consumed water at rates ranging from typical (i.e., average) to high-end (i.e., 95th percentile) for each age group [ATSDR 2016c]. Except where the seasonal exposure scenario is noted, we assumed daily consumption of water containing the highest contaminant concentration measured in finished drinking water.

Health-based guidance values used in this report are ATSDR minimal risk levels (MRLs) and EPA reference doses (RfDs). These represent a dose of a single contaminant that is unlikely to result in harmful health effects, to even the most sensitive groups, over the timeframe of exposure. Doses less than the MRL/RfD are unlikely to result in harmful noncancer effects, while higher doses are evaluated more thoroughly to determine whether harmful health effects are possible. ATSDR has derived intermediate oral MRLs for PFOA, PFOS, PFHxS, and PFNA [ATSDR 2021]. The EPA has derived chronic RfDs for HFPO-DA (GenX), PFOS, PFOA, PFHxS, PFBA, and PFHxA.

For the drinking water exposures evaluated in this report, the highest estimated doses are for formula-fed infants from birth to one year old who drink high-end amounts of water (that is, more water than 95% of their age group). For PFAS, this likely underestimates the risk for breastfeeding infants, as PFAS are concentrated from the mother's blood into breastmilk and breastfed infants typically have much higher serum concentrations of PFAS than formula fed infants. At this time, ATSDR does not have an approach to estimating PFAS exposures from breastfed infants.

Tables B-6, B-7, and B-8 present the exposure doses and corresponding hazard quotients estimated for those PFAS with health-based guidance values g available for the intermediate exposures lasting less than 1 year.

5.2.2.2 Noncancer health effects from exposure to PFAS

Many human epidemiology studies have examined associations between various harmful health effects and serum levels of PFAS in exposed workers, residents exposed to high levels of PFAS released by facilities, and people exposed to background levels of PFAS. The weight of evidence suggests links between PFAS exposure and several harmful noncancer health effects in humans, including increased cholesterol levels, increased risk of liver damage, decreased vaccine response in children, increased risk of high blood pressure (i.e., preeclampsia) in pregnant women, and small decreases in infant birth weight [ATSDR 2021; ATSDR 2020]. More recently, EPA also evaluated the weight of evidence supporting the role of PFAS in these harmful health effects [EPA 2024a; EPA 2024b; EPA 2025]. EPA found evidence to suggest that PFAS cause the same set of noncancer health effects identified by ATSDR. However, EPA determined that the strength of the human epidemiological evidence suggests that those health effects can occur after much lower doses of PFOA and PFOS than the MRLs identified by ATSDR. Given that PFAS take time to accumulate in the body, ATSDR uses the EPA values for risks from chronic exposures of longer than one year and the ATSDR MRLs for risks from shorter-duration exposures.

ATSDR relied on experimental toxicology studies on laboratory animals, which have greater ability to control and measure exposures and examine specific biological mechanisms, as the primary basis for developing its intermediate MRLs for PFAS. This approach introduces uncertainty because humans are much slower at removing PFAS from the body. Rather than using simple dose extrapolation, the nominal doses to which animals are exposed should be converted, whenever possible, to human equivalent doses to relate animal toxicity data to possible effects in humans. In addition to its intermediate MRLs, ATSDR also used chronic RfDs that EPA developed [EPA 2024a; EPA 2024b; EPA 2021] based on human epidemiology studies. However, there are also limitations to these studies. Epidemiological studies often do not fully assess how much of a chemical people were exposed to or for how long. They also often do not fully characterize the routes of exposure. Most studies involved potential exposures to multiple PFAS at once, and also involve other, often uncharacterized, exposures that could contribute to or offset the observed health outcomes [ATSDR 2021].

The primary noncancer effects observed in toxicological studies on animals exposed to PFAS include developmental toxicity, immune toxicity, and liver toxicity [ATSDR 2021; NTP 2016]. Other effects, typically observed at higher doses, include weight loss and changes in the microscopic structure of reproductive tissues or the thyroid gland. Not all these effects have been observed across all PFAS tested, and effect levels varied. However, in general, the sensitive targets of toxicity identified in laboratory animals are similar to those observed in human epidemiology studies [ATSDR 2021].

In general, the epidemiological studies [ATSDR 2021] identify the immune system as a sensitive target of perfluoroalkyl toxicity. The strongest evidence of the immunotoxicity of PFAS in humans comes from epidemiological studies finding associations regarding the antibody response to vaccines. The immunotoxicity associations regarding antibody response have been reported for PFOA, PFOS, PFHxS, and PFDA. There is also some limited evidence for decreased antibody response for PFNA, PFUnDA, and PFDoDA. The National Toxicology Program [NTP 2016] concluded that exposure to PFOA or PFOS is presumed to be an immune hazard to humans based on a high level of evidence that PFOA and PFOS suppressed the antibody response from lab animals and a moderate level of evidence from studies in humans. It was noted that the strongest evidence is for suppression of the antibody response and, for PFOA only, increased hypersensitivity.

Epidemiological studies have evaluated several aspects of immunotoxicity including immunosuppression, hypersensitivity, and autoimmunity [ATSDR 2021]. Several general population studies have found significant inverse associations between serum PFAS levels and antibody responses to vaccines. However, no consistent associations were found between serum PFAS and disease resistance, as measured by episodes of common cold, cough, fever, or hospitalization for infectious disease. In tests of hypersensitivity, there is some evidence of an association between serum PFOA and asthma diagnosis in children and adults, although this finding was not consistent across studies; increased risk of allergy or allergic sensitization does not appear to be associated with serum PFOA. Based on the findings of an occupational exposure and community exposure study, there is some suggestive association between serum PFOA and an increased risk of ulcerative colitis but not for other autoimmune diseases. Animal studies also suggest that the immune system is a sensitive target of PFAS toxicity. Several studies in mice have demonstrated evidence of immunosuppression and increased hypersensitivity. Laboratory animal studies have also found secondary immune outcomes in the spleen and thymus, which included decreases in organ weight and decreases in the number of lymphocytes.

5.2.2.3 Intermediate Exposures to Individual PFAS

The only PFAS species detected in finished drinking water above an intermediate screening value was PFOS (see Table B-2). The measured concentration of PFOS in April 2017 finished drinking water was 0.047 µg/L (47 ppt). Drinking water with this concentration of PFOS would result in doses ranging from 1.5×10^{-6} to 6.7×10^{-6} mg/kg/day for various age groups with high-end water consumption rates (more than 95% of their age group). Doses for age groups up to 6 years old exceed the corresponding MRL for PFOS of 2×10^{-6} mg/kg/day, while pregnant women are expected to be exposed to very close to the MRL. Age groups with typical water consumption (that is, about average for their age group) would have lower doses than those with high consumption, but typical formula-fed infants under 1 year old would still exceed the MRL.

The toxicology literature has identified several potential health effects from PFOS exposures. A brief summary of the developmental, immune, and liver effects considered primary effects observed in animals exposed to PFOS for intermediate durations of exposure is presented below. Associations between PFOS and similar health effects have been observed in humans, although the duration of exposure for those studies may be longer than a year.

- **Developmental effects.** Offspring of rats exposed to PFOS by gavage before mating, during gestation, and after giving birth showed delays in eye opening and a transient decrease in body weight [Luebker et al. 2005; ATSDR 2021].
- **Immune effects.** Mice exposed to PFOS by gavage at a human equivalent dose of 0.000031 mg/kg/day showed decreased resistance to influenza A virus infection [Guruge et al. 2009]. In two reports from another study, mice exposed to a human equivalent dose of 0.00041 mg/kg/day of PFOS by gavage had a decreased immune response to sheep red blood cells [Dong et al. 2011; Dong et al. 2009].
- **Liver effects.** Monkeys exposed to PFOS were found to have increased liver weights and other hepatic changes at a human equivalent dose of 0.010 mg/kg/day [Seacat et al. 2002].

Other sensitive effects, such as changes in glucose metabolism in mice fed a high-fat diet [Wan et al. 2014] or changes in levels of estradiol, a female reproductive hormone, in male monkeys [Seacat et al. 2002], have been observed upon exposure of animals to low levels of PFOS. The biological significance of these changes is uncertain, and ATSDR has not evaluated the quantitative potential for such effects [ATSDR 2021].

ATSDR began its analysis by looking at the highest exposed group. For ToC, the highest estimated exposure doses were for the youngest age group. The PFOS exposure dose with the CTE assumptions for an infant less than 1 year is 3.6 x 10^{-6} mg/kg/day and the RME exposure dose is 6.7 × 10^{-6} mg/kg/day. These calculated doses are based on water consumption rates for formula fed infants and may underestimate the exposures to infants who breastfeed. Breastfed infants are exposed to higher levels of PFAS than formula fed infants, because PFOS concentrates from the mother's blood into breast milk [EPA 2024b; Goeden et al. 2019; van Beijsterveldt et al 2022].

The margin of exposures (MOEs) that show the difference between the maximum exposure dose for formula-fed infants and the lowest observed adverse effect level human equivalent dose ($LOAEL_{HED}$) (2.1 × 10^{-3} mg/kg/day, from Luebker et al [2005] for developmental effects) were approximately 700 and 310 (both over 2 orders of magnitude below LOAEL) for the CTE and RME scenarios, respectively. Given the orders of magnitude difference between levels where developmental toxicity was observed in animal studies and human doses and the well-designed animal study, developmental effects are not anticipated based on PFOS exposure for less than a year.

MOEs were also calculated based on immune effect levels observed in the Dong et al. [2011] and the Guruge et al. [2009] studies for RME and CTE scenarios. For the RME scenario, dividing the $LOAEL_{HD}$ values derived from Dong et al. [2011] and Guruge et. al [2009] by the dose for formula-fed infants resulted in MOEs of 61 and 5, respectively; for the CTE scenario, the MOEs were 110 and 9, respectively. For infants, both RME and CTE exposures are close enough to the dose of PFOS that caused immune suppression in adult mice that there is a substantial concern for immunologic effects. Furthermore, the RME scenario for infants resulted in a PFOS dose that was approximately equal to the no observed adverse effect level (NOAEL) in adult mice in the Guruge et al. [2009] study and just below the NOAEL from Dong et al. [2011], so the exposure levels are approximately the same as the highest levels of PFOS that did not affect mice. RME doses for children ages 1 to 6 were also close to levels that resulted in toxicity in animal studies.

Given that the first year of life is a particularly sensitive time for immune disruption in humans, that humans are likely more sensitive to immune suppression from PFAS than rodents, and that these calculations may underestimate the dose of PFAS for breastfed infants, ATSDR concludes that immune suppression from intermediate exposure was likely for infants up to 1 year old and possible for children ages 1 to 6 from PFOS in ToC finished drinking water in April 2017. The levels of PFOS in ToC finished drinking water were likely high enough to cause immune suppression from intermediate-duration exposures during the 2016–2017 off-peak season.

We do not know whether earlier exposures would involve PFOS levels high enough to cause immune suppression. Given higher percentage contributions from the expected wells to the finished ToC drinking water during the late fall and winter of 2016-2017, it is estimated that there were likely still level of concern through this time. Because the ToC shallow wells were contributing a smaller percentage of the water consumed during the peak summer season, PFAS concentrations in summer 2016 were likely lower than those observed in April 2017. It is also likely that the PFAS-containing groundwater plume was affecting the shallow wells less in 2016 or earlier. Overall, the weight of evidence suggests that intermediate-duration PFAS exposures from summer 2016 or earlier were likely lower than what was observed in April 2017. However, given the major data limitations, we are not able to make conclusions about the risks from past intermediate-duration exposures more than six months before sampling began.

5.2.2.4 Intermediate Exposures to PFAS Mixtures

Because ToC finished drinking water contained multiple PFAS and PFAS are known to act through common mechanisms, ATSDR proceeded with a mixture evaluation. For mixtures, ATSDR recommends a tiered approach to determine whether further evaluation of mixture effects is necessary [ATSDR 2018]:

- In Tier 1, a hazard quotient is calculated for each of the identified contaminants in each age group and/or sensitive population. The hazard quotient is the ratio of the estimated dose of a contaminant and its corresponding noncancer or cancer-based health guidance value. Mixtures of contaminants with hazard quotients greater than 0.1 are carried forward for Tier 2 analysis.

- In Tier 2, for multi-component mixtures, all hazard quotients (regardless of the target organ) are summed to obtain a hazard index. Mixtures with a hazard index greater than 1 are carried forward to Tier 3 analysis. Tier 2 analysis assumes that doses are additive.

- Tier 3 analysis is a detailed analysis of potential mixture effects, considering, for example, shared target toxicities of each mixture component, sensitive subpopulations, or more refined estimates of potential exposure to the mixture.

Tier 1 analysis identified three PFAS to be included in the Tier 2 analysis for intermediate duration exposure (see Tables B-2 through B-4). Table 4 shows that for the ToC finished drinking water evaluated in this report, PFOA, PFOS, and PFHxS all had hazard quotients from intermediate exposures greater than 0.1. PFNA and PFBS were not detected and are not carried forward to Tier 2, while PFHpA lacked a health-based CV and was only considered qualitatively.

Table 4. Tier 1 (hazard quotient) analysis of estimated intermediate duration exposure doses from measured PFAS levels in ToC finished drinking water.

PFAS	Highest estimated hazard quotient in any age group†	Was hazard quotient ≥0.1?	More than one age group with hazard quotient ≥0.1?	Include PFAS in Tier 2 mixtures evaluation?

PFOA	0.6	Yes	Yes	Yes
PFOS	3.4	Yes	Yes	Yes
PFHxS	0.3	Yes	Yes	Yes
PFNA	Not detected	No	No	No
PFBS	Not detected	No	No	No

†Hazard quotient is the highest dose in the highest exposed group (children from birth up to one year old with high-end water consumption) divided by the minimal risk level. Individual contaminants with a hazard quotient greater than 0.1 are evaluated further, and PFAS hazard quotient greater than 0.1 are included in the Tier 2 mixtures evaluation.

For Tier 2 analysis, ATSDR estimated combined exposure to measured (Table B-5) levels of PFOA, PFOS, and PFHxS in the ToC finished drinking water. Under an RME scenario, all age groups exceeded a level of combined PFAS consumption that had the potential to cause health effects, with hazard indexes ranging from 1.0 for teenagers to 4.3 for formula fed infants. In the CTE analysis, only formula fed infants exceeded a level of concern for consumption of combined PFAS, with a hazard index of 1.9.

Because ToC finished drinking water had a hazard index greater than 1, ATSDR proceeded with further evaluation. As discussed previously, the toxicological literature suggests that PFOA, PFOS, and PFHxS share sensitive endpoints such as developmental, immunological, and liver effects. The presence of other PFAS (besides those that could be evaluated quantitatively) lends uncertainty to the health evaluation. PFHpA was not included in the PFAS mixture evaluation due to a lack of toxicological information. Other PFAS may have been present in the finished ToC drinking water but were not tested during the April 2017 initial round of testing. The presence of additional PFAS may affect health implications of exposure to the mixture, although it is expected that PFOA, PFOS, and PFHxS contributed most of the potential health risk.

In Tier 3 analysis, ATSDR examined the overall risks from intermediate-duration exposure to the combination of PFAS detected in ToC finished drinking water. Ingestion of the combination of PFAS present in ToC finished drinking water in April 2017 posed a greater risk of immune suppression and other health risks than PFOS alone, although PFOS drove most of the health risk. The presence of PFOA and PFHxS adds to the concern for the potential of this water to cause health effects in children under 6, particularly infants, and raises the possibility that other age groups might also be affected. The risk of toxicity of the PFOA, PFOS, and PFHxS mixture was approximately 27% higher than the risk of toxicity discussed above for PFOS alone. PFHpA and other untested PFAS may further contribute to the toxicity of the mixture of PFAS present in ToC finished drinking water at around that time.

The qualitative analysis of PFOS toxicity for infants and other children under 6, discussed above, is not significantly altered by the inclusion of PFOA and PFHxS, as the doses were already high enough to cause concern. For most teenagers and adults, who were exposed to lower doses and were not at sensitive stages for immunotoxicity, the combined PFAS levels were still not high enough to cause a health concern. Children ages 6 to <11, pregnant and breastfeeding women, and older adults (65 and up) are at stages of their lives where the immune system may be at particular risk of immune disruption [Simon 2015] and/or where PFAS might be anticipated to have an increased health effect. In addition, others may be at elevated health risks due to conditions that suppress the immune system. Although the doses of PFOS alone were not high enough to raise concerns for health effects, for some individuals from high risk groups, the combined PFAS mixture likely poses a risk of health effects from intermediate-duration exposures.

5.2.2.5 Chronic Exposures to Individual Compounds

Although PFAS were present in the April 2017 finished ToC drinking water at levels of potential health concern from chronic-duration exposure, we do not know when the exposure started. The higher levels of PFAS in ToC shallow production wells when sampling of the wells resumed in 2020 suggest that a PFAS-containing groundwater plume had not fully reached the shallow production wells in April 2017, in which case earlier PFAS concentrations would likely be lower. The April 2017 ToC finished drinking water had concentrations for PFOA, PFOS, and PFHxS above their respective chronic exposure duration screening values (MCLs). PFHpA was detected but does not have a health-based comparison value or reliable scientific studies for comparison. Given the trends of increasing PFAS concentrations in the well data, the doses calculated above for intermediate duration exposures likely represent the worst-case scenario for chronic duration exposure doses and can provide context for the potential for health effects from chronic PFAS exposure through the ToC finished drinking water. The actual chronic duration exposure doses of PFAS from consuming ToC finished drinking water prior to April 2017 are expected to be no higher than what is discussed below and may be lower.

PFOS

For PFOS, chronic exposure doses estimated from April 2017 finished drinking water concentrations, ranging from 1.6×10^{-6} to 6.7×10^{-6} mg/kg/day for various age groups with high-end water consumption rates (more than 95% of their age group), exceeded those where health effects in human epidemiology studies were observed (Table B-6). A brief summary of the PFOS doses that caused developmental, immune system, heart, and liver effects, the primary effects observed in humans exposed to PFOS, is presented below:

- Developmental effects. Decreased birth weights for infants exposed *in utero* to PFOS at a dose of 1.3×10^{-6} mg/kg/d [Wikström et al 2020].

- Immune effects. Decreased antibody response for diphtheria vaccines measured at age 7 after measuring PFOS concentration at age 5 [Budtz-Jørgensen and Grandjean 2018] which continued through adolescence monitored through age 12 [Timmermann et al 2021] at doses in the range of 1.03×10^{-6} to 5.21×10^{-6} mg/kg/d.

- Heart effects. Increased total cholesterol was observed in national testing at doses ranging 1.2×10^{-6} [Dong et al 2019] to 8.51×10^{-6} mg/kg/d [Lin et al 2019].

- Liver effects. Elevated ALT in blood indicating mild liver damage at doses ranging 1.94×10^{-6} [Nian et al2019] to 7.27×10^{-6} mg/kg/d [Gallo et al 2012].

High end doses of PFOS in April 2017 were similar to, or higher than, doses where human health effects have been observed in epidemiology studies, presumably from chronic duration exposure. Although earlier exposures were likely to lower concentrations of PFOS, there was likely an elevated risk of health effects for sensitive groups, especially for breastfed infants exposed during gestation and breastfeeding as a result of their mothers' chronic PFOS exposure. For teenagers and adults with healthy immune systems, the risk of health effects from chronic duration exposures cannot be estimated.

PFOA

For PFOA, chronic exposure doses estimated from April 2017 finished drinking water concentrations, ranged from 3.7×10^{-7} to 1.7×10^{-6} mg/kg/day for various age groups with high-end water consumption rates (more than 95% of their age group), which exceeded the estimated doses where health effects for epidemiological studies were observed (Table B-7). A brief summary of the PFOA doses that caused developmental, immune system, heart, and liver effects, the primary effects observed in humans exposed to PFOA, is presented below:

- Developmental effects. Decreased birth weights for infants exposed *in utero* to PFOA at doses ranging from 2.92×10^{-7} mg/kg/day [Wikström et al 2020] to 1.21×10^{-6} mg/kg/day [Sagiv et al 2018].

- Immune effects. Decreased antibody response for diphtheria vaccines ranging 2.20×10^{-7} mg/kg/day [Timmermann et al 2021] to 2.92×10^{-7} mg/kg/day [Budtz-Jørgensen and Grandjean 2018]. Decreased response for tetanus antibody concentrations were observed in the range of 3.34×10^{-7} mg/kg/day [Timmerman et al 2021] to 3.05×10^{-7} mg/kg/day [Budtz-Jørgensen and Grandjean 2018].

- Heart effects. Increased total cholesterol was observed in national testing in the range 2.75×10^{-7} mg/kg/day [Dong et al 2019] to 5.10×10^{-7} mg/kg/day [Steenland et al 2009].

- Liver effects. Elevated ALT in blood indicating mild liver damage were observed in the dose range 4.51×10^{-7} mg/kg/day [Nian et al 2019] to 7.92×10^{-6} mg/kg/day [Darrow et al 2016].

High end doses of PFOA in April 2017 were similar to, or higher than, doses where human health effects have been observed in epidemiology studies, presumably from chronic duration exposure. Although earlier exposures were likely to lower concentrations of PFOA, there was likely an elevated risk of health effects for sensitive groups, especially for breastfed infants exposed during gestation and breastfeeding as a result of their mothers' chronic PFOA exposure. For teenagers and adults with healthy immune systems, the risk of health effects from chronic duration exposures cannot be estimated.

PFHxS

For PFHxS, chronic exposure doses estimated from April 2017 finished drinking water concentrations ranged from 1.4 x 10^{-6} to 6.4 x 10^{-6} mg/kg/day for various age groups with high-end water consumption rates (more than 95% of their age group), which exceeded the estimated doses where immune effects for epidemiological studies were observed (Table B-8). A brief summary of the PFHxS doses that caused effects on the immune system and thyroid, the primary effects observed in humans or animals exposed to PFHxS, is presented below:

- Immune effects. Decreased antibody response for tetanus vaccines in children exposed to 1.16 x 10^{-8} mg/kg/day [Budtz-Jørgensen and Grandjean 2018]. Decreased response for diphtheria antibody concentrations were observed at 1.23 x 10^{-8} mg/kg/day [Budtz-Jørgensen and Grandjean 2018].

- Thyroid effects. Decreased serum T4 levels were observed in rat pups administered a human equivalent dose of 2.45 x 10^{-5} mg/kg/day in a multigenerational study [Ramhøj et al 2020]

Doses of PFHxS in April 2017 were similar to, or higher than, doses where immune suppression has been observed in epidemiology studies, presumably from chronic duration exposure. They also approached doses where thyroid toxicity had been observed in a multigenerational rat study. Although earlier exposures were likely to lower concentrations of PFHxS, there was likely an elevated risk of health effects for sensitive groups, especially for breastfed infants exposed during gestation and breastfeeding as a result of their mothers' chronic PFOA exposure. For teenagers and adults with healthy immune systems, the risk of health effects from chronic-duration exposures cannot be estimated.

5.2.2.6 Chronic Exposure to PFAS Mixture

Given the uncertainty regarding the duration of exposure and the doses of PFAS consumed from ToC finished drinking water before April 2017, the health risks from chronic-duration exposure to the mixture of PFAS compounds were qualitatively assessed. The combination of PFAS present in the April 2017 ToC finished drinking water would pose a greater risk of chronic-duration exposure related health effects than any individual compound alone. PFOA, PFOS, and PFHxS share most of the same outcomes, and exposure to the combination of the three together is anticipated to increase the risks of health effects caused by each of the individual compounds alone. Much less is known about PFHpA toxicity, but based on what is known, the concentration of PFHpA found in ToC finished drinking water would not be expected to substantially increase the health risks already posed by the other three PFAS.

Overall, the mixture of PFAS present in ToC finished drinking water in the months to years leading up to April 2017 would have increased the risk of chronic-duration exposure related health effects compared to the risk from any individual PFAS compound alone. Overall, the levels of the combined PFAS compounds present in ToC finished drinking water through April 2017 likely posed a health risk to sensitive individuals, particularly infants, young children, and women who became pregnant during this time. We are not able to evaluate whether there was a chronic-duration exposure related health risk for non-sensitive populations.

5.2.2.7 Cancer effects

The concentrations of PFAS, particularly PFOA, found in ToC finished drinking water in April 2017 increase the potential risk for the development of cancer with an extended duration of exposure. Levels of PFAS in the ToC shallow production wells from November 2020 through July 2022 were approximately two or more times as high as the levels of PFAS measured in April 2017. This suggests that the plume had not yet fully reached the shallow production wells during the first sampling event and thus that the duration of exposure to PFAS was likely much shorter than the time frames that ATSDR typically uses to assess cancer risk (12 and/or 33 years). The uncertainty regarding the duration of exposure complicates efforts to quantify how PFAS exposure affected cancer risk among exposed ToC residents.

Based on available information, EPA has concluded that PFOA is likely to be carcinogenic in humans (EPA 2024b). The International Agency for Research on Cancer (IARC) has classified PFOA as carcinogenic to humans (Group 1) based on strong mechanistic evidence in humans and sufficient evidence for cancers in experimental animals [IARC 2025; Zahm et al. 2023]. For PFOS, EPA has concluded that it is also likely to be a human carcinogen [EPA 2024a]. IARC has classified PFOS as possibly carcinogenic to humans (Group 2B) based on strong evidence that it has properties of a carcinogen in exposed humans and limited evidence it causes cancer in laboratory animals [IARC 2025]. Limited to no information is currently available on the carcinogenicity of PFHxS or other PFAS.

EPA has established cancer slope factors, which are used to estimate how much of an increase in cancer rates is possible from a given dose of a chemical, for PFOA and PFOS [EPA 2024b; EPA 2024a]. EPA's prediction of how much cancer rates would increase following PFOA exposure is high enough that chronic-duration exposure to PFOA in drinking water at the MCL would be expected to meaningfully increase the risks of cancer. Given that there was at least some exposure to PFOA through ToC finished drinking water prior to April 2017, a protective approach would predict that cancer rates may have increased, even with an exposure of less than 12 years. However, given that we are unable to estimate the duration of the exposure, we are not able to assess the potential for PFOA to cause cancer. PFOS at the detected concentrations would not be expected to meaningfully affect cancer rates among residents.

5.3 Evaluation of Surface Water, Sediment, and Biota

5.3.1 Screening Analysis

Surface water, sediment, and biota (fish, shellfish, and crops) were considered potential exposure pathways. Please see Table A-1 for description of exposure pathway analysis for this evaluation.

ATSDR used surface water and sediment data from the Preliminary Assessment and Site Investigation Work Plan for Per- and Polyfluoroalkyl Substances. The maximum detected PFAS levels in surface water and sediment from Little Mosquito Creek, Jenneys Gut, and Boat Basin are presented in Table 5. The Little Mosquito Creek maximum PFOS sediment concentration (5.9 µg/kg) was at the upstream location, not the two locations at the mouths of NASA outfalls/drainage channels (LMC-SD04 at 4.4 µg/kg and LMC-SD07 at 2.9 µg/kg).

PFAS have been detected in surface water and sediment on-base and near WFF at levels either near or below drinking water and soil health-based CVs. Surface water and sediment exposures are generally much lower than drinking water or soil exposures, and there is no evidence of frequent recreational use of these water bodies. ATSDR concludes that direct contact with surface water and sediment in the creeks and other water bodies surrounding WFF is not a health concern.

Table 5. Maximum detected PFAS levels in surface water (ng/L) and sediment (µg/kg) from Little Mosquito Creek, Jenneys Gut, and Boat Basin.

PFAS	Little Mosquito Creek Surface water; sediment	Jenneys Gut Surface water; sediment	Boat Basin Surface water; sediment	Corresponding drinking water or soil CV
PFOA	5.5 ng/L; ND	1.8 ng/L; ND	2.6 ng/L; ND	0.21 ng/L; 1.6 µg/kg
PFOS	21 ng/L; 5.9 µg/kg	2.4 ng/L; 0.88 µg/kg	5.4 ng/L; ND	0.71 ng/L; 5.2 µg/kg
PFBS	1.8 ng/L; ND	0.24 ng/L; ND	0.85 ng/L; ND	2,100 ng/L; 16,000 µg/kg
PFDA	0.36 ng/L; ND	ND; 0.62 µg/kg	ND; ND	Not available
PFHpA	3.2 ng/L; ND	1.0 ng/L; ND	1.8 ng/L; ND	Not available
PFHxS	6.4 ng/L; ND	ND; ND	3.9 ng/L; ND	140 ng/L; 1,000 µg/kg
PFHxA	4.8 ng/L; ND	1.4 ng/L; ND	3.1 ng/L; ND	Not available
PFNA	2.0 ng/L; 0.14 µg/kg	0.78 ng/L; 0.19 µg/kg	ND; ND	21 ng/L; 160 µg/kg
PFTA	0.58 ng/L; ND	ND; ND	ND; ND	Not available
PFUnA	ND; 0.13 µg/kg	ND; 0.17 µg/kg	ND; ND	Not available

ND = non detect; For PFAS chemical names see Abbreviation and Acronym list in front material. ATSDR's public health assessment site tool PHAST [ATSDR 2023b] is the source of soil and drinking water CVs. Soil and drinking water CVs are more than protective for sediment and surface water exposure.

There are no data on PFAS levels in biota. A particular concern of residents is the PFAS levels in fish and shellfish located in the area. There are no biological accumulation factors or other approaches that would allow us to estimate the potential for exposure from PFAS in this situation. ATSDR could not evaluate ingestion of biota as a potential pathway.

5.4 Biomonitoring

ATSDR is not aware of biomonitoring data of people in the site area using ToC public drinking water and/or living or working in the vicinity or at the NASA WFF site. Therefore, biomonitoring data were not evaluated in this document. As discussed below, residents had questions about PFAS testing in serum, but ATSDR does not conduct biomonitoring as part of the public health assessment process.

5.5 Contributions from Other Sources

We do not have enough information to identify individual exposure sources or to estimate the background PFAS exposure levels among residents of ToC and WFF. Non-drinking water sources might include PFAS-contaminated food, hand-to-mouth transfer from surfaces previously treated with PFAS-containing stain protectants (carpet being most significant for infants and toddlers), inhalation of volatile precursor compounds, or eating food packaged in material containing PFAS.

5.6 Susceptible Populations: Persons with Pre-existing Health Conditions and Early Development

ATSDR is committed to considering potential health effects of exposure to all groups, including those that might be unusually susceptible to environmental contamination. Pregnant women, the developing fetus, infants, children, and people of all age groups with certain pre-existing conditions might be unusually vulnerable to harmful health effects from PFAS exposure.

- Epidemiological studies suggest an association between serum PFOA levels and pregnancy-induced high blood pressure or pre-eclampsia [ATSDR 2021]. Increased PFOA or PFOS levels in pregnant women's blood serum suggested an association with decreases in their babies' birth weights.

- Infants may be exposed to PFAS through their mother's milk. ATSDR has developed information that summarizes scientific knowledge about PFAS and breastfeeding (Available at: https://atsdr.cdc.gov/pfas/prevent-exposure/breastfeeding.html). Breastfeeding provides many health benefits to a child, including reduced risk of ear and respiratory infections, asthma, obesity, and sudden infant death syndrome. Breastfeeding can also help lower a mother's risk of high blood pressure, type 2 diabetes, ovarian cancer, and breast cancer from presence of chemical toxicants in breast milk (Available at: https://www.cdc.gov/breastfeeding/php/faq/faq.html). The American Academy of Pediatrics states that a mother's exposure to low-level environmental chemical agents is not a contraindication to breastfeeding (Available at: https://www.aap.org/en/patient-care/breastfeeding/breastfeeding-overview/). A woman's decision to breastfeed is a personal choice, often made in consultation with her healthcare provider. ATSDR has developed information to guide clinicians in this decision-making process (Available at: https://atsdr.cdc.gov/pfas/hcp/clinical-overview/index.html).

- Infants may also be exposed to PFAS through formula made with contaminated water. In addition to exposure from water, infants could have additional exposure, such as from hand-to-mouth behavior after contacting carpets or other household items previously treated with PFAS-containing products. In this report, ATSDR based its public health decisions on infants, which would have the highest dose because of their higher water intake and smaller body weight compared to other age groups. In children, PFAS exposure may decrease antibody responses to childhood vaccines [ATSDR 2021].

- People of all age groups with certain pre-existing conditions could be more susceptible to harm from PFAS exposures. For example, exposure to certain PFAS can increase cholesterol levels [ATSDR 2021]. The consequences of this would likely be worse if the person exposed already has high cholesterol or other risk factors for cardiovascular disease. Similarly, PFAS exposure could disproportionately affect people who already have compromised immune systems or liver function or who have high blood pressure. More research is needed to understand how exposure to PFAS might affect people with pre-existing risk factors for cardiovascular and other diseases.

5.7 Addressing Community Concerns

5.7.1 Evaluation of Risks to Visitors

For those exposed for a shorter time (e.g., visitors, vacationers, summer workers), ATSDR estimates the exposure dose using a fraction that represents how many days per week of exposure. For example, a full-time resident, week-long and/or month-long vacationer is exposed for 7 days a week while a weekend visitor is exposed for 2–3 days per week. This shorter-term exposure calculation reflects the actual amount of time a visitor would be exposed per week, which translates to a fraction, such as 2 days in a weekend out of 7 days per week (2/7 days or about 28–29% or 3/7 days or about 43% of a full week exposure scenario as shown in Table 6). Exposure doses (mg/kg/day) represent the amount of PFAS (mg) per unit of body weight (kg) per day. Estimated exposure doses and health risks are directly proportional — a higher exposure dose results in a higher estimated theoretical health risk.

Table 6. Estimated PFOS exposure doses (mg/kg/day) for measured PFOS (0.047 ppb) in ToC finished drinking water for the CME and RME birth to one-year old age group.

Days of exposure per week	PFOS Estimated Exposure Dose – CTE (0.047 ppb)	PFOS Estimated Exposure Dose – RME (0.047 ppb)	CTE Hazard Quotient	RME Hazard Quotient
1/7	5.1E-07	9.5E-07	0.26	0.48
2/7	2.9E-07	1.9E-06	0.51	0.95

3/7	1.5E-06	2.9E-06	0.77	1.4*
4/7	2.0E-06	3.8E-06	1.0*	1.9*
5/7	2.6E-06	4.8E-06	1.3*	2.4*
6/7	3.1E-06	5.7E-06	1.5*	2.9*
7/7	3.6E-06	6.7E-06	1.8*	3.3*

Notes: * = Hazard quotient exceeds 1

For an exposure up to two -days per week, the estimated exposure doses to the combined PFAS mixture (or individual PFAS) are below the doses that would increase risk for developmental and immune effects for all CTE and RME age groups. As such, any visitor spending every weekend or 1 week per month or less consuming ToC finished drinking water would not be anticipated to have adverse health effects based on the concentrations measured in April 2017. For exposures greater than two days per week, the hazard quotient exceeds one for the highest exposed group (birth to one year old for RME scenario). Thus, there is the potential for development of immune effects for infants who spent 3 days or more per week consuming ToC finished drinking water, based on the April 2017 PFAS levels. However, given that there are no data available measuring PFAS levels using ToC finished drinking water during the summer before the shallow wells were taken offline, it is possible that actual exposure levels differed from those predicted from the April 2017 measurements. ATSDR did not compare these exposure doses to the chronic RfDs because intermittent scenarios were assumed to be less than 365 days of total exposure.

5.7.2 Biological PFAS Sampling Questions

Community concerns/questions requesting that CDC/ATSDR conduct PFAS testing (i.e., blood and/or urine) throughout the ToC community have been raised. ATSDR does not recommend that community wide PFAS biological testing be conducted in the ToC community at this time. Given that exposures to PFAS in drinking water at concentrations that would be expected to meaningfully increase PFAS exposure relative to other sources of PFAS ended in April 2017 when the shallow wells were taken offline, it would be unclear whether or how present PFAS levels in serum reflect exposure from ToC drinking water contamination. Even if there were no other sources of PFAS exposure, measurements taken so long after exposure stopped from one source would be difficult to interpret. Many factors including variables affecting PFAS clearance would make it difficult to determine the total amount of past PFAS exposure for an individual.

If you are concerned and choose to have your blood tested, test results will tell you how much of each PFAS is in your blood, but they would not predict your overall risk of health effects, as the health outcomes associated with PFAS exposure also have many other contributing factors. In addition, blood testing for PFAS is not a routine test offered by most doctors or health departments or typically covered by health insurance. If you would like to have your or your children's blood tested, talk to your health care provider. You can also seek guidance and how to interpret blood test results from your regional

Pediatric Environmental Health Specialty Unit (PEHSU). ATSDR has recently published guidance including available clinical resources to help physicians discuss PFAS exposures with patients, including the results of blood tests, which is available at https://atsdr.cdc.gov/pfas/hcp/resources/.

Please note that PFAS are found in the blood of humans and animals worldwide. Most people in the United States have one or more PFAS in their blood, especially PFOS and PFOA.

5.8 Summary of Limitations and Uncertainties

There are important limitations and uncertainties that affect efforts to evaluate human health risks from PFAS exposures in drinking water. These are discussed in detail below.

5.8.1 Multiple Exposure Sources

In addition to drinking water exposures, community members likely have exposures to PFAS from other sources. These could include food, dust, air, and consumer products. Exposures might also occur when people touch surfaces treated with a stain protector then touch their mouths or food. All sources add to the amount of chemicals in the body and potential health effects. Early life exposures (i.e., in-utero and breast feeding) were not specifically estimated or included in this evaluation, but these exposures may have contributed to a baby's body burden and added to the risk for adverse health effects from exposures prior to 2017.

5.8.2 Uncertainty Regarding Exposure to Breastfed Newborns

As discussed above, ATSDR does not assess exposures through breastmilk. For PFAS, exposure to breastfed infants likely exceeds that of the formula-fed infants that are the basis of ATSDR's exposure assumptions. However, the benefits of breastfeeding are well established and thus nursing mothers can continue to breastfeed.

5.8.3 Lack of Historical Exposure Data

We do not know exactly how long people drank PFAS contaminated water, how much they drank, or the PFAS concentrations adults and children were exposed to in ToC finished drinking water prior to April 2017. Historical sampling data are unavailable. Exposures may have occurred for an unknown duration of time prior to filtration because of PFAS movement in groundwater, but estimating exact past exposures is not possible. PFAS accumulate and remain in the body for years before elimination. Past and current exposures contribute to the overall health risks from PFAS.

The only two samples of ToC water before steps were taken to address PFAS were collected on consecutive days in April 2017, which may not have been representative of other times of the year. The ToC shallow wells provided a baseline production volume throughout the year, while the ToC deeper wells made up the difference between the production from the shallow wells and consumer demand. Thus, in January, when demand was lowest, the shallow wells made up a higher percentage of the overall production than in April, during the shoulder season when tourists were more likely to be present, while the shallow wells made up a lower percentage of the total during the peak summer months when the highest numbers of tourists were visiting. These seasonal changes and their effects on drinking water source contributions may have impacted the amount of PFAS in the ToC finished drinking water. This difference means that the actual exposure during other times may have been to lower or higher concentrations of PFAS than is represented in this analysis.

Further complicating the analysis, the available data suggest that the PFAS concentrations in the shallow wells may have been increasing at the time of the first sampling event in April 2017. Between April 2017 and the next time the shallow wells were sampled, in November 2020, there was a significant increase in PFAS levels, after which point concentrations were fairly steady. This suggests the presence of a PFAS-contaminated groundwater plume that had not fully reached the shallow ToC production wells when they were shut down. It is therefore difficult to assess when exposure to PFAS through ToC finished drinking water first started. We assume that the April 2017 data are representative of exposures that occurred in the weeks to months before the shallow wells were shut down, but they likely do not represent PFAS levels in drinking water dating back a year or more.

5.8.4 Other General Limitations

Humans and experimental animals differ in how their bodies absorb and react to PFAS. These discrepancies leave questions about how relevant the effects seen in animals are to humans. The health consequences of PFAS in the body are uncertain. Significant uncertainty remains about the lowest concentration at which toxic effects might occur in people exposed to PFAS for many years. Therefore, people exposed for many years could be at increased health risk.

ATSDR calculated the health-based CVs for PFAS using the best scientific information available at this time. The CVs allow us to assess the potential health risk from ToC finished drinking water exposures. ATSDR bases the CVs and MRLs on the most current PFAS science; however, overall scientific knowledge on PFAS is still evolving. Toxicity information for some PFAS compounds is limited.

5.8.5 Incomplete information on the type of AFFF used at NASA/WFF and specific PFAS formulations.

Challenges to evaluating exposures from an AFFF source include that we do not know all the PFAS constituents and that these constituents have changed over time. Data on AFFF-contaminated groundwater indicate that about 25 percent of the PFAS species remain unidentified [Houtz et al. 2013]. A 2017 study by Barzen-Hanson et al. resulted in adding over 240 individual PFAS chemicals to the previous list associated with AFFF. Little is known regarding the surface-subsurface transport and toxicity of the newly discovered PFAS [Barzen-Hanson et al. 2017]. The complex geology, hydrogeology, and historic site use and water use further complicate exposure assessment.

6. Conclusions

ATSDR evaluated the potential exposure to PFAS through releases to groundwater and surface water from NASA's WFF and reached the following conclusions.

Conclusion 1

ATSDR is unable to conclude whether there are ongoing risks of noncancer or cancer health effects from ingestion of PFOA, PFOS, and PFHpA in WFF finished drinking water or ToC finished drinking

water for a year or more after April 2017. Any ongoing increased risk is expected to be minimal compared to other sources of environmental exposure to PFAS. The levels of PFBS and PFHxA detected in ToC finished drinking water since April 2017 are not expected to harm people's health.

Basis for Conclusion

PFOA and/or PFOS were occasionally detected in WFF drinking water production wells and in ToC drinking water production wells and finished drinking water while the contaminated wells were not in use, between April 2017 and April 2021, at levels above the ATSDR health-based comparison values (CVs). However, each compound was only detected in less than 10% of samples. As a result, it is not possible to calculate an exposure point concentration for water from the WFF system or from ToC after April 2017. There were no detections of PFAS in ToC finished drinking water after the installation of granular activated carbon treatment in April 2021 through the last set of data reviewed, from July 2022.

Because chronic exposure to PFOA and PFOS has the potential for health effects at concentrations below the laboratory limits of detection, we cannot rule out health effects from these compounds. However, any increased risk of health effects from drinking ToC finished drinking water after April 2017 or WFF finished drinking water is expected to be well below background risks from other sources of PFAS exposure.

Other PFAS, particularly PFHxA and PFHpA, were also detected in WFF water and in ToC samples collected after April 2017. PFBS and PFHxA concentrations were orders of magnitude lower than corresponding CVs and thus these compounds are not expected to contribute to health risks from drinking water. Very limited research is available on PFHpA health effects, which prevents ATSDR from making conclusions about risks from exposure to this compound, although the PFHpA levels detected were very low.

Conclusion 2

Although no data are available for PFAS in ToC prior to April 2017, conclusions were developed based on exposure at the levels measured during the initial round of testing. These conclusions may overestimate actual risk. ATSDR concludes that past daily exposure to PFOS alone or to the PFAS mixture in ToCs drinking water at the levels detected in April 2017 for 15–365 days (i.e., an intermediate exposure duration) could have harmed people's health. Exposures of over two weeks could cause immune suppression for children under 6 and may be a health risk for other particularly susceptible individuals, such as those with suppressed immune systems or those at highest risk of heart attacks. Visiting infants under 1 year old who averaged three days a week or more drinking ToC water would likely also have been at risk of immune suppression. These risks would have been expected to be present for the 2016–2017 winter and early spring. ATSDR cannot conclude whether there were risks from earlier exposures to PFAS in drinking water given the limited available data.

ATSDR concludes that past PFAS exposure through drinking ToC finished drinking water for a year or more before mitigation efforts began in April 2017 could have harmed people's health. Chronic

exposures to low levels of PFAS are associated with noncancer health effects that include immune system, developmental, liver, and cardiovascular toxicity.

ATSDR is unable to evaluate whether exposure to PFAS in ToC finished drinking water before April 2017 could have led to a higher risk of cancer in residents.

Basis for Conclusion

To estimate past exposure, ATSDR used the maximum concentrations for individual PFAS from two finished drinking water samples collected on consecutive days in April 2017 before mitigation was implemented. PFAS levels were likely increasing in the ToC drinking water wells when they were first detected, and thus earlier well concentrations are predicted to have been lower than those measured in April 2017. A higher percentage of ToC water was coming from the affected wells over the 2016-2017 winter, so PFAS concentrations in finished water may have been as high or possibly higher than measured in April 2017 for four to six months, even if well concentrations were lower. However, during peak summer months, ToC used less water from the affected wells. Therefore, resident exposures before October 2016 were likely to lower concentrations of PFAS.

ATSDR assessed whether past exposures to PFAS in drinking water at the levels found in ToC drinking water during the initial testing in April 2017 would result in harmful health effects for intermediate duration exposures (more than two weeks up to a year). Maximum PFOS exposure doses for children under 6 years old and average exposure doses for children under 1 year old were above ATSDR's minimal risk level (MRL), which is based on developmental and immune effects. Maximum PFOS doses for formula-fed infants under 1 year old were close to human equivalent doses that resulted in immune suppression during intermediate duration studies in mice. Children, particularly infants, are at a sensitive stage of development for immune suppression and the immunological studies were not done at a sensitive stage in mouse development, suggesting more potential harm than was observed in those studies. The presence of PFOA and PFHxS in the drinking water further contributed to the overall PFAS risk from intermediate duration exposures, although neither was present alone at levels that are known to cause toxicity following exposures of less than a year. The dose of PFOS reached a level of concern when infants consumed high-end volumes of ToC drinking water at least three out of seven days per week. Because we do not know when exposure to PFAS first started, and because the available data suggest that PFAS levels were increasing when they were first detected, we cannot evaluate intermediate-term exposures to PFAS more than 6 months before April 2017.

Based on average drinking water ingestion rates in humans, the concentration of PFAS detected in ToC finished drinking water in April 2017 resulted in estimated doses for all age groups that exceeded adverse health effect levels associated with noncancer adverse health effects in human studies. These human health studies are assumed to involve PFAS exposures of over a year. With data only available for two samples collected on consecutive days in April 2017, it is very difficult to predict the concentrations of PFAS going back more than a year from that time. However, the measured levels of PFOS, PFOA, and PFHxS were each orders of magnitude higher than the corresponding concentrations of health concerns for exposures of over a year. Even with potentially much lower concentrations in the months and years before sampling data are available, it is likely that PFAS were present at levels of potential health concern in ToC finished drinking water for more than a year before the contaminated shallow ToC drinking water production wells were removed from service following the detection of PFAS in April 2017. Adverse health effects that can result from chronic PFAS exposures include decreased vaccine efficacy, decreased birth weight, increased cholesterol, and increased risk of liver damage [EPA 2024a; EPA 2024b].

To evaluate the risk of cancer from an exposure, ATSDR needs to estimate when the exposure first started. ATSDR does not know when PFAS first reached the contaminated shallow ToC drinking water production wells that were removed from service in April 2017. Levels of PFAS found in monitoring of the shallow wells from November 2020 through July 2022 were approximately double or more compared to concentrations that were initially measured in April 2017. The substantial increase in PFAS levels in the shallow wells between 2017 and 2020 suggests that PFAS had not fully reached the wells in April 2017 when those wells were shut down. Therefore, the duration of exposure was likely much shorter than the durations assumed in ATSDR's standard exposure scenarios for cancer. There is no way to address the lack of data available for past exposures to PFAS in ToC finished drinking water. Given that EPA has estimated that PFOA increases the risk of cancer even at very low doses, it is possible that PFOA present in finished drinking water could meaningfully increase cancer risks at concentrations below those detected in April 2017. However, with the uncertainty in the duration and dose of the exposure, ATSDR cannot evaluate whether the PFOA levels in finished ToC drinking water were high enough for long enough to increase residents' cancer risk. EPA's estimate of the increase in cancer risk from an increase in PFOS dose is much lower than PFOA; therefore, PFOS is not expected to significantly impact the estimated increased cancer risk from the PFOA dose.

Conclusion 3

ATSDR is unable to determine whether a health concern exists for consumption of fish or shellfish from the waters surrounding or downstream from WFF.

Basis for Conclusion

ATSDR is not aware of any PFAS biota data (i.e., shellfish or finfish) collected near WFF. PFAS readily bioaccumulate, so even with very low or non-detect concentrations in water or sediment, it is not possible to evaluate health risks associated with fish or shellfish without PFAS measurement in those organisms.

Conclusion 4

Based on available information, ATSDR concludes that inhalation, ingestion, and/or skin contact with PFAS in off-site groundwater, surface water, or soil are not expected to harm people's health.

Basis for Conclusion

NASA investigated off-site migration of PFAS by installing monitoring wells and sampling both the monitoring wells and private wells to the west and north of NASA WFF. Based on review of environmental data collected to date, private wells outside the boundaries of WFF have not been contaminated with PFAS. ATSDR reviewed the limited surface water and sediment data from three offsite surface water bodies (Little Mosquito Creek, Jenneys Gut, and the Boat Basin). PFAS have been detected in surface water and sediment a short distance from WFF. Surface water levels were higher than drinking water comparison values but were below levels that would be expected to be a concern from wading or swimming. Sediment levels were below soil comparison values for intermediate-duration exposures.

7. Recommendations and Public Health Action Plan

ATSDR supports reducing PFAS exposures, especially exposures for persons who may be more susceptible to the effects of PFAS.

Current scientific information suggests that the health and nutritional benefits of breastfeeding outweigh the potential risks associated with PFAS in breastmilk [ATSDR 2024b]. Studies have shown that infants can be exposed to PFAS during pregnancy by transfer through the mother to the fetus and through breastfeeding. However, breastfeeding provides clear health and nutritional benefits, including a reduced risk for ear and respiratory infections, asthma, obesity, and sudden infant death syndrome. Breastfeeding can also help lower a mother's risk for high blood pressure, type 2 diabetes, and ovarian and breast cancer [AAP 2012]. In general, the Center for Disease Control and Prevention (CDC) and the American Academy of Pediatrics [AAP 2012] recommend breastfeeding despite the potential presence of chemical contaminants in breast milk.

(see https://www.atsdr.cdc.gov/pfas/about/health-effects.html).

ATSDR recommends the following actions:

- While the wells are in use, ToC/NASA monitor drinking water quality and maintain the drinking water filtration system to remove harmful contaminants.
- While the wells are in use, ToC/NASA monitor PFAS concentrations in raw and finished water on a routine basis to ensure contaminant removal effectiveness.

- NASA support efforts by the State of Virginia Departments of Environmental Quality and Health to conduct testing for PFAS in shellfish and finfish from Jenneys Gut, Little Mosquito Creek, Mosquito Creek, and/or Simoneaston Bay to determine if consumption may pose a health risk. The decision to test should be inclusive of health and welfare concerns from the affected community, including those who harvest fish and shellfish.

- Residents concerned about their past exposure to PFAS discuss their concerns with their health care provider. ATSDR has information for health care providers and the public at https://atsdr.cdc.gov/pfas/resources/index.html. ATSDR also provides guidance and tools for reducing stress and building resilience in communities during public health responses to environmental contamination at its Community Stress Resource Center at https://atsdr.cdc.gov/community-stress-resource-center/index.html

- Nursing mothers can continue to breastfeed and contact their healthcare providers with specific concerns. ATSDR is available to provide information to healthcare providers as needed.

- ATSDR's [2024a] current information on evaluation of patients exposed or potentially exposed to PFAS for clinicians https://atsdr.cdc.gov/pfas/hcp/resources/ is available as a resource for informing patients and guiding treatment.

7.1 Public Health Action Plan

Completed Actions

The ToC, NASA WFF and VADEQ have designed and constructed a water treatment system using carbon filtration of the mixed water from the shallow and deep wells as a remedy to reduce exposure to PFAS through ToC public drinking water. The treatment system began operational testing in August 2020 with treated finished drinking water being sent to ToC starting on April 27, 2021.

NASA has taken steps to reduce the discharge of PFAS from WFF to surrounding waterways:

- In 2022, NASA identified a groundwater seep that was discharging PFAS to surface water. They installed a treatment system that captures water and removes PFAS before it reaches surface water.
- NASA identified two manhole covers and a broken wastewater line as contributing factors for contaminated groundwater entering wastewater collection systems that discharged to surface water. After repairs were conducted in 2023, the PFAS entering the wastewater system was reduced by over 80%.

ATSDR provided health education information related to PFAS in drinking water to community members and the general public. General information related to PFAS in drinking water for residents, community members, and health professionals is available from: https://www.atsdr.cdc.gov/PFAS/.

Ongoing Actions

PFAS levels in the ToC PWS treated/finished drinking water are being monitored monthly. The treatment system began operation in April 2021 and prevents current and future exposures. This treatment system will be adjusted as necessary to provide the most effective removal of PFAS contaminants. There are two filtration systems running in parallel, each consisting of two tanks of granular activated carbon. If PFAS start breaking through one tank, it will be taken off-line and the media replaced, while the other system continues to provide filtration.

PFAS levels in the NASA WFF area groundwater are being periodically monitored by sampling shallow and deep monitoring wells. The flow of PFAS from groundwater to surface water is being investigated through sampling of outfalls and surface water. As routes of contamination of surface water are identified, NASA will take steps to mitigate them.

NASA WFF continues to investigate potential PFAS contaminant source areas and PFAS migration pathways to determine the most effective groundwater contaminant containment and mitigation strategies. This investigation is focused on environmental fate and transport outside of the drinking water pathway (i.e., surface water). The *Preliminary Assessment and Site Investigation Work Plan for Per- and Poly-fluoroalkyl Substances at Goddard Space Flight Center Wallops Flight Facility Wallops Island, Virginia* [NASA 2019] summarizes ongoing actions and plans. It can be found at https://www.nasa.gov/sites/default/files/atoms/files/final_nasa_wff_pfas_pa-si_wp.pdf. In addition, the most up-to-date information about ongoing actions and plans will be on NASA's website: https://www.nasa.gov/wallops/pfas/.

Future Actions

ATSDR recommends that NASA support efforts by the Commonwealth of Virginia to conduct testing for PFAS in shellfish and finfish from Jenneys Gut, Little Mosquito Creek, Mosquito Creek, and/or Simoneaston Bay to determine if consumption may pose a health risk. The decision to test should be inclusive of health and welfare concerns from the affected community, including those who harvest fish and shellfish. ATSDR is available to advise Virginia and NASA on a testing plan and data interpretation.

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Appendix A: Brief Summary of ATSDR's Public Health Assessment (PHA) Process

ATSDR follows the PHA process to find out:

- Whether people living near a hazardous waste site are being exposed to toxic substances.
- Whether that exposure is harmful.
- What must be done to stop or reduce exposure.

The PHA process is a step-by-step consistent approach during which ATSDR:

- Establishes communication mechanisms, including engaging communities at the beginning of site activities and involves them throughout the process to respond to their health concerns.
- Collects many different kinds of site information.
- Obtains, compiles, and evaluates the usability and quality of environmental and biological sampling data (and sometimes modeling data) to examine environmental contamination at a site.
- Conducts four main, sequential scientific evaluations.
    - Exposure pathways evaluation to identify past, present, and future site-specific exposure situations, and categorize them as completed, potential, or eliminated.
    - Screening analysis to compare the available sampling data to media-specific environmental screening levels (ATSDR comparison values [CVs] and non-ATSDR screening levels). This identifies potential contaminants of concern that require further evaluation for completed and potential exposure pathways.
    - Exposure Point Concentrations (EPCs) and exposure calculations for contaminants flagged as requiring further evaluation in completed and potential exposure pathways. It involves calculating EPCs, using the estimated EPCs to perform exposure calculations, and determining which site-specific scenarios requires an in-depth toxicological effects analysis.
    - In-depth toxicological effects evaluation, if necessary, based on the three previous scientific evaluations. This step looks more closely at contaminant-specific information in the context of site exposures. This evaluation can also help determine if there is a potential for non-cancer or cancer health effects.
- Summarizes findings and next steps, while acknowledging uncertainties and limitations.
- Provides recommendations to site-related entities, partner agencies, and communities to prevent and minimize harmful exposures.

The sequence of steps can differ based on site-specific factors. For instance, health assessors might define an exposure unit before or after the screening analysis.

For more detail on the PHA process, please visit Explanation of ATSDR's PHA Process Evaluation. Readers can also refer to ATSDR's Public Health Assessment Guidance Manual for all information related to the step-wise PHA process.

Appendix B – Additional Figures, Tables, and Equations

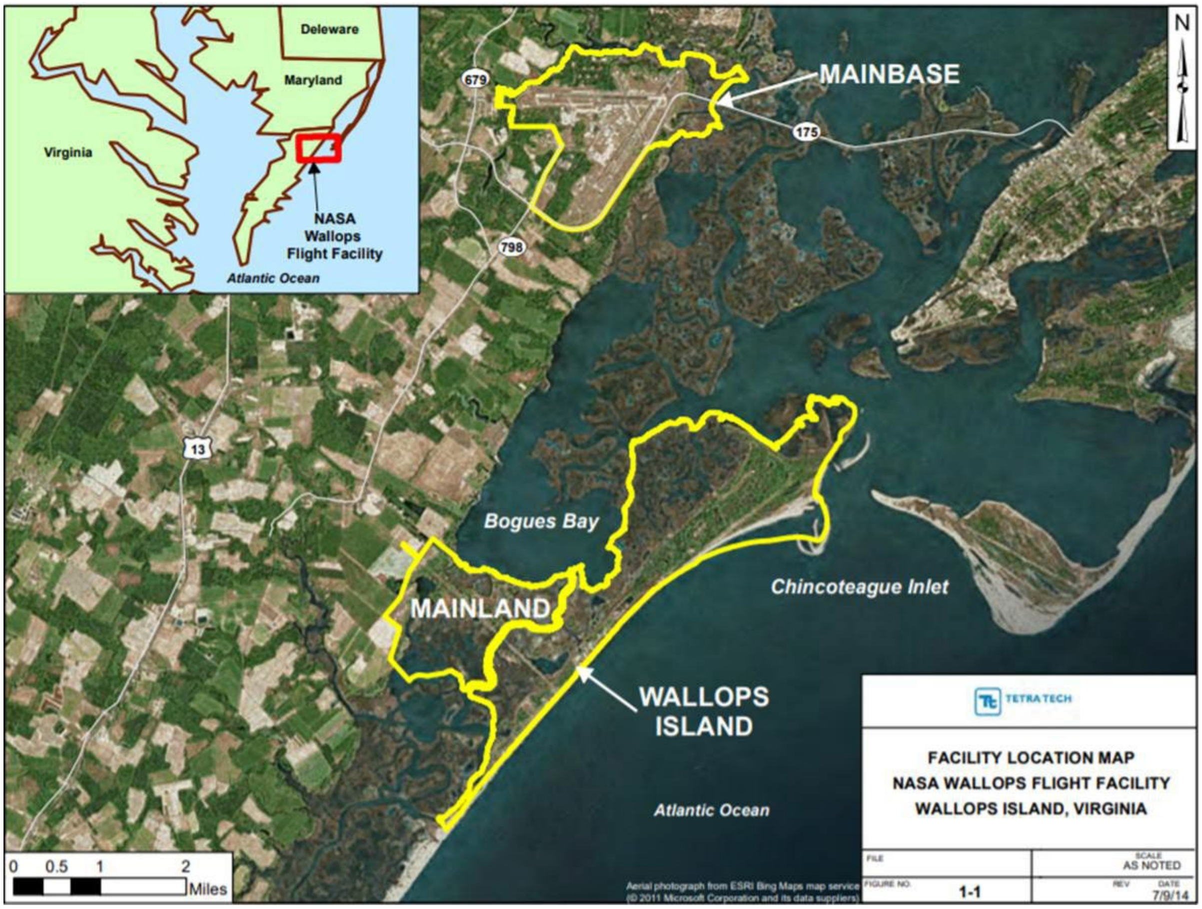

Figure B-1. Location and vicinity of Town of Chincoteague PWS wells (on NASA WFF main-base), Wallops Island, Virginia [NASA 2019].

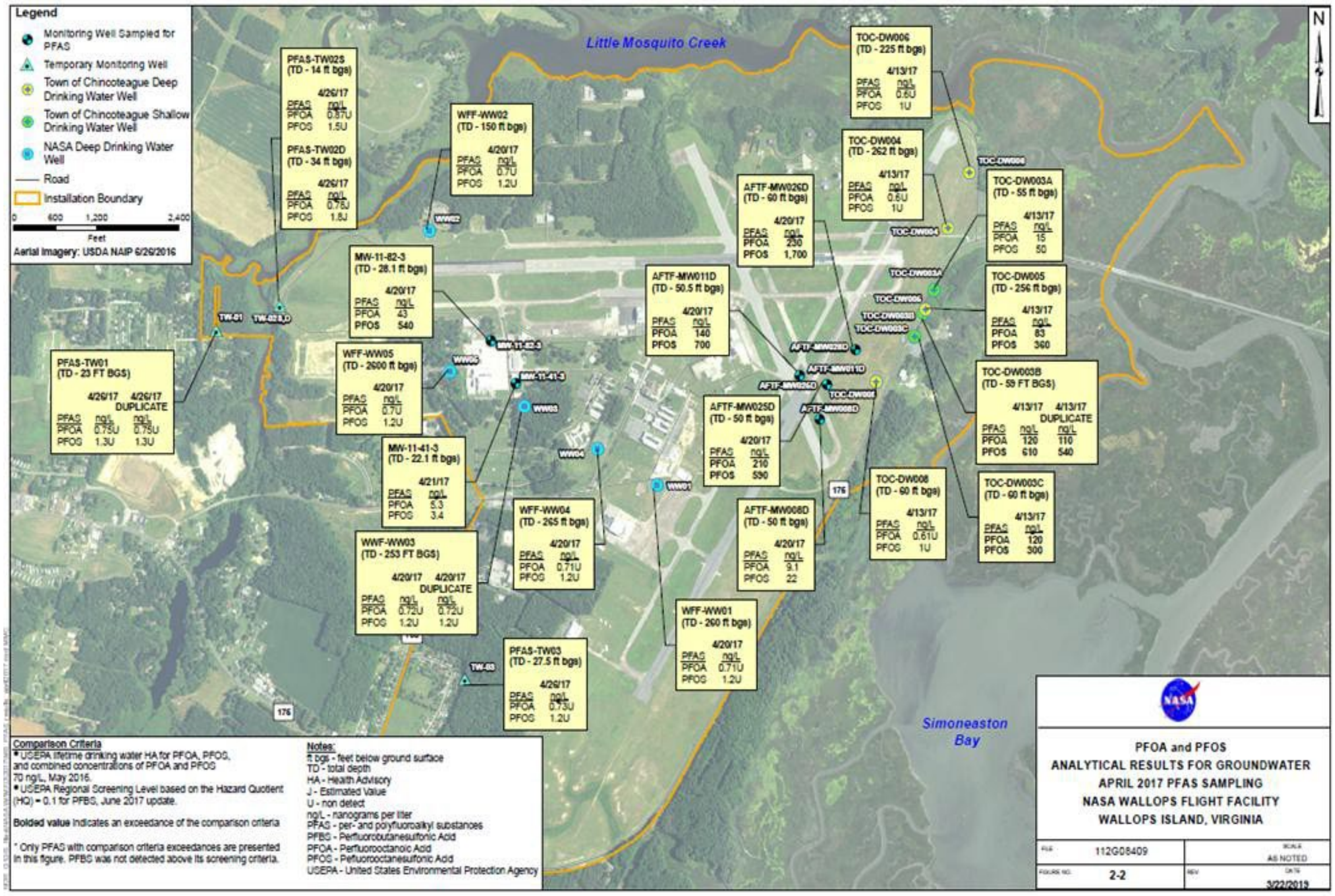

Figure B-2. NASA WFF April 2017 PFAS Groundwater sampling locations and results. Source: NASA 2019.

Table B-1. Exposure Pathways Related to NASA WFF PFAS Groundwater Contamination, including Town of Chincoteague Public Water System (ToC PWS), Chincoteague, Virginia

Pathway	Source	Media	Exposure Point	Exposed Population	Exposure Route	Time	Pathway Status
Town of Chincoteague Public Water Supply	On-base shallow groundwater	Water	ToC water supply distribution points	Residents and visitors of ToC	Ingestion, dermal, inhalation	Past, present, and future	Completed*†‡
Off-site private wells	Off-site groundwater	Water	Water taps	Residents with private wells	Ingestion, dermal, inhalation	Past, present, and future	Incomplete eliminated**
Surface water	Off-site surface water runoff	Water	Little Mosquito Creek	Recreational visitors	Ingestion, dermal, inhalation	Past, present, and future	Potential eliminated**
Sediment	Off-site sediment migration	Sediment	Little Mosquito Creek	Recreational visitors	Ingestion, dermal	Past, present, and future	Potential eliminated**
Crops	Soil or groundwater in surrounding areas	Biota	Food grown in nearby areas	Residents, commercial	ingestion	Past, present, and future	Potential eliminated**
Fish or shellfish	Off-site surface water or sediment	Biota	Fish or shellfish in surrounding waterways	Residents, visitors, commercial	Ingestion	Past, present, and future	Potential
NASA WFF workers, tenants	On-base groundwater	Drinking water	WFF distribution points	Workers, tenants, and visitors	Ingestion, dermal, and inhalation	Past, present, and future	Completed, minimal

* Exposure to PFAS via drinking water was stopped in April 2017 when the ToC shallow production wells were closed and NASA WFF provided drinking water. Treatment system to remove per- and polyfluoroalkyl substances from ToC PWS production wells began operational testing in August 2020 with treated finished drinking water being sent to ToC starting on April 27, 2021. Per- and polyfluoroalkyl substances occasionally detected at very low levels. Treatment system will be adjusted to maximize removal of per- and polyfluoroalkyl substances.

†Dermal and inhalation exposure routes contributed negligible additional intake based on past concentrations in drinking water.

‡Water treatment system is removing PFAS to either non-detect levels or very low concentrations. The ToC public drinking water contributes negligible ongoing exposure based on current concentrations in the treated finished drinking water.

** NASA WFF will continue to monitor on-site groundwater, sediment, and surface water to ensure off-site migration of PFAS does not occur.

Perfluorooctane sulfonic acid (PFOS)

Table B-2. Residential: Default exposure doses for intermediate exposure to perfluorooctane sulfonic acid (PFOS) measured in April 2017 finished drinking water at 4.7E-05 mg/L along with non-cancer hazard quotients*

PHAST Public Health Assessment Site Tool **Exposure Group**	**CTE Dose (mg/kg/day)**	**CTE Noncancer Hazard Quotient**	**RME Dose (mg/kg/day)**	**RME Noncancer Hazard Quotient**
Birth to < 1 year	3.6E-06	1.8 †	6.7E-06	3.3 †
1 to < 2 years	1.0E-06	0.51	2.7E-06	1.4 †
2 to < 6 years	9.1E-07	0.46	2.3E-06	1.2 †
6 to < 11 years	6.7E-07	0.34	1.9E-06	0.93
11 to < 16 years	4.7E-07	0.23	1.5E-06	0.73
16 to < 21 years	4.7E-07	0.24	1.5E-06	0.73
Adult	7.7E-07	0.39	1.9E-06	0.95
Pregnant Women	7.5E-07	0.37	1.9E-06	0.94
Breastfeeding Women	9.6E-07	0.48	2.0E-06	0.99

Source: [NASA 2017]
Abbreviations: CTE = central tendency exposure (typical); mg/kg/day = milligram chemical per kilogram body weight per day; mg/L = milligram chemical per liter water; RME = reasonable maximum exposure (higher)
* The calculations in this table were generated using ATSDR's PHAST v1.8.0.0. The non-cancer hazard quotients were calculated using the intermediate (two weeks to less than 1 year) minimal risk level of 2E-06 mg/kg/day.
† Indicates the hazard quotient exceeds the non-cancer health guideline, which ATSDR evaluates further.

Perfluorooctanoic acid (PFOA)

Table B-3. Residential Site-specific exposure doses for intermediate exposure to perfluorooctanoic acid (PFOA) measured in April 2017 finished drinking water at 1.2E-05 mg/L along with non-cancer hazard quotients*

PUBLIC HEALTH ASSESSMENT SITE TOOL PHAST Exposure Group	CTE Dose (mg/kg/day)	CTE Noncancer Hazard Quotient	RME Dose (mg/kg/day)	RME Noncancer Hazard Quotient
Birth to < 1 year	9.2E-07	0.31	1.7E-06	0.57
1 to < 2 years	2.6E-07	0.086	6.9E-07	0.23
2 to < 6 years	2.3E-07	0.077	5.9E-07	0.20
6 to < 11 years	1.7E-07	0.057	4.7E-07	0.16
11 to < 16 years	1.2E-07	0.040	3.7E-07	0.12
16 to < 21 years	1.2E-07	0.040	3.7E-07	0.12
Adult	2.0E-07	0.066	4.8E-07	0.16
Pregnant Women	1.9E-07	0.063	4.8E-07	0.16
Breastfeeding Women	2.5E-07	0.082	5.0E-07	0.17

Source: [NASA 2017]

Abbreviations: CTE = central tendency exposure (typical); mg/kg/day = milligram chemical per kilogram body weight per day; mg/L = milligram chemical per liter water; RME = reasonable maximum exposure (higher)

* The calculations in this table were generated using ATSDR's PHAST v2.1.0.0. The non-cancer hazard quotients were calculated using the intermediate (two weeks to less than 1 year) minimal risk level of 3E-06 mg/kg/day.

Perfluorohexane sulfonic acid (PFHxS)

Table B-4. Residential Site-specific exposure doses for intermediate exposure to perfluorohexane sulfonic acid (PFHxS) measured in April 2017 finished drinking water at 4.5E-05 mg/L along with non-cancer hazard quotients*

PHAST Public Health Assessment Site Tool Exposure Group	CTE Dose (mg/kg/day)	CTE Noncancer Hazard Quotient	RME Dose (mg/kg/day)	RME Noncancer Hazard Quotient
Birth to < 1 year	3.4E-06	0.17	6.4E-06	0.32
1 to < 2 years	9.7E-07	0.048	2.6E-06	0.13
2 to < 6 years	8.7E-07	0.044	2.2E-06	0.11
6 to < 11 years	6.4E-07	0.032	1.8E-06	0.089
11 to < 16 years	4.5E-07	0.022	1.4E-06	0.070
16 to < 21 years	4.5E-07	0.023	1.4E-06	0.070
Adult	7.4E-07	0.037	1.8E-06	0.091
Pregnant Women	7.1E-07	0.036	1.8E-06	0.090
Breastfeeding Women	9.2E-07	0.046	1.9E-06	0.094

Source: [NASA 2017]

Abbreviations: CTE = central tendency exposure (typical); mg/kg/day = milligram chemical per kilogram body weight per day; mg/L = milligram chemical per liter water; RME = reasonable maximum exposure (higher)

* The calculations in this table were generated using ATSDR's PHAST v2.1.0.0. The non-cancer hazard quotients were calculated using the intermediate (two weeks to less than 1 year) minimal risk level of 2E-05 mg/kg/day.

Table B-5. Combined perfluorohexane sulfonic acid (PFHxS), perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS) intermediate-duration hazard index (HI) for ToC PWS users, Chincoteague, VA from measured drinking water concentrations April 2017.

Age group	CTE (L/day)	RME (L/Day)	Body weight kg	CTE HI	RME HI
Birth to <1 year	0.36	0.80	7.8	**1.9**	**4.3**
1 to <2 years	0.22	0.64	11.4	0.8	**2.3**
2 to <6 years	0.27	0.70	17.4	0.6	**1.7**
6 to <11 years	0.37	1.00	31.8	0.5	**1.3**
11 to <16 years	0.46	1.41	56.8	0.3	**1.0**
16 to <21 years	0.55	1.75	71.6	0.3	**1.0**
Adults (≥21 years)	0.88	2.21	80	0.5	**1.2**
Pregnant women	0.62	1.85	73	0.4	**1.1**
Lactating women	1.19	2.56	73	0.7	**1.5**

Abbreviations: µg/L = micrograms per liter; CTE = central tendency exposure; Hazard index (HI) for combined hazard quotient for PFHxS, PFNA, PFOA and PFOS; kg = kilogram; L = liter; RME = reasonable maximum. Notes: Bold = exceedance of an HI of 1. Estimated exposure doses assume 100% of PFAS exposure is from drinking water ingestion.

Equations

Equation 1. Reasonable maximum exposure concentration calculation approach (example: 7/7 days for ToC resident or week-long visit while a weekend visitor would be proportional for example 2/7 for a 2-day visit).

$$\text{Reasonable maximum exposure} = \frac{\frac{7}{7} \times \text{Upper percentile drinking water intake } \left(\frac{\text{L}}{\text{day}}\right) \times \text{Exposure point concentration } \left(\frac{\mu\text{g}}{\text{L}}\right)}{\text{Body weight (kg) } \times 1{,}000}$$

Equation 2. Central tendency exposure concentration calculation approach (example: 7/7 days for ToC resident or week-long visit while a weekend visitor would be proportional for example 2/7 for a 2-day visit).

$$\text{Central tendency exposure} = \frac{\frac{7}{7} \times \text{Mean drinking water intake } \left(\frac{\text{L}}{\text{day}}\right) \times \text{Exposure point concentration } \left(\frac{\mu\text{g}}{\text{L}}\right)}{\text{Body weight (kg) } \times 1{,}000}$$

Table B-6. Residential Default exposure doses for chronic exposure to perfluorooctanoic acid (PFOA) in drinking water at 1.2E-05 mg/L along with noncancer hazard quotients*

PHAST Public Health Assessment Site Tool Exposure Group	CTE Dose (mg/kg/day)	CTE Noncancer Hazard Quotient	RME Dose (mg/kg/day)	RME Noncancer Hazard Quotient
Birth to < 1 year	9.2E-07	31 †	1.7E-06	57 †
1 to < 2 years	2.6E-07	8.6 †	6.9E-07	23 †
2 to < 6 years	2.3E-07	7.7 †	5.9E-07	20 †
6 to < 11 years	1.7E-07	5.7 †	4.7E-07	16 †
11 to < 16 years	1.2E-07	4.0 †	3.7E-07	12 †
16 to < 21 years	1.2E-07	4.0 †	3.7E-07	12 †
Adult	2.0E-07	6.6 †	4.8E-07	16 †
Pregnant Women	1.9E-07	6.3 †	4.8E-07	16 †
Breastfeeding Women	2.5E-07	8.2 †	5.0E-07	17 †

Source: [NASA 2017]
Abbreviations: CTE = central tendency exposure (typical); mg/kg/day = milligram chemical per kilogram body weight per day; mg/L = milligram chemical per liter water; RME = reasonable maximum exposure (higher); yrs = years
* The calculations in this table were generated using ATSDR's PHAST v2.4.1.0. The noncancer hazard quotients were calculated using the chronic (lifetime) reference dose of 3E-08 mg/kg/day.
† Indicates the hazard quotient is greater than 1, which ATSDR evaluates further.

Table B-7. Residential Default exposure doses for chronic exposure to perfluorooctane sulfonic acid (PFOS) in drinking water at 4.7E-05 mg/L along with noncancer hazard quotients*

PUBLIC HEALTH ASSESSMENT SITE TOOL PHAST Exposure Group	CTE Dose (mg/kg/day)	CTE Noncancer Hazard Quotient	RME Dose (mg/kg/day)	RME Noncancer Hazard Quotient
Birth to < 1 year	3.6E-06	36 †	6.7E-06	67 †
1 to < 2 years	1.0E-06	10 †	2.7E-06	27 †
2 to < 6 years	9.1E-07	9.1 †	2.3E-06	23 †
6 to < 11 years	6.7E-07	6.7 †	1.9E-06	19 †
11 to < 16 years	4.7E-07	4.7 †	1.5E-06	15 †
16 to < 21 years	4.7E-07	4.7 †	1.5E-06	15 †
Adult	7.7E-07	7.7 †	1.9E-06	19 †
Pregnant Women	7.5E-07	7.5 †	1.9E-06	19 †
Breastfeeding Women	9.6E-07	9.6 †	2.0E-06	20 †

Source: [NASA 2017]

Abbreviations: CTE = central tendency exposure (typical); mg/kg/day = milligram chemical per kilogram body weight per day; mg/L = milligram chemical per liter water; RME = reasonable maximum exposure (higher); yrs = years

* The calculations in this table were generated using ATSDR's PHAST v2.4.1.0. The noncancer hazard quotients were calculated using the chronic (lifetime) reference dose of 1E-07 mg/kg/day.

† Indicates the hazard quotient is greater than 1, which ATSDR evaluates further.

Table B-8. Residential Default exposure doses for chronic exposure to perfluorohexane sulfonic acid (PFHxS) in drinking water at 4.5E-05 mg/L*

PUBLIC HEALTH ASSESSMENT SITE TOOL PHAST Exposure Group	CTE Dose (mg/kg/day)	CTE Noncancer Hazard Quotient	RME Dose (mg/kg/day)	RME Noncancer Hazard Quotient
Birth to < 1 year	3.4E-06	8,600†	6.4E-06	16,000†
1 to < 2 years	9.7E-07	2,400†	2.6E-06	6,500†
2 to < 6 years	8.7E-07	2,200†	2.2E-06	5,500†
6 to < 11 years	6.4E-07	1,600†	1.8E-06	4,500†
11 to < 16 years	4.5E-07	1,100†	1.4E-06	3,500†
16 to < 21 years	4.5E-07	1,100†	1.4E-06	3,500†

Exposure Group	CTE Dose (mg/kg/day)	CTE Noncancer Hazard Quotient	RME Dose (mg/kg/day)	RME Noncancer Hazard Quotient
Adult	7.4E-07	1,800†	1.8E-06	4,500†
Pregnant Women	7.1E-07	1,800†	1.8E-06	4,500†
Breastfeeding Women	9.2E-07	2,300†	1.9E-06	4,700†

Source: [NASA 2017]

Abbreviations: CTE = central tendency exposure (typical); mg/kg/day = milligram chemical per kilogram body weight per day; mg/L = milligram chemical per liter water; RME = reasonable maximum exposure (higher); yrs = years

* The calculations in this table were generated using ATSDR's PHAST v2.4.1.0. The noncancer hazard quotients were calculated using the chronic (lifetime) reference dose of 4E-10 mg/kg/day.

† Indicates the hazard quotient is greater than 1, which ATSDR evaluates further.