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# PFAS in Drinking Water

by

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**PFAS Overview**

Per- and polyfluoroalkyl substances are known as PFAS or PFASs. They are a group of synthetic organofluorine chemical compounds that have multiple fluorine atoms attached to an alkyl chain. The arrangement makes them last an extremely long time (>1000 years) in a variety of environments. Hence, PFAS are known as persistent organic pollutants or “forever chemicals.”

PFAS also have superior water-resistant and heat-resistant properties. The combination of appealing properties makes PFAS a popular choice for materials, coatings, and a variety of consumer products. See Figure 1 for examples. Actually, I should say PFAS **was** a popular choice, until a couple decades ago when it was linked to serious health problems in humans and other animals. Since then, PFAS production has slowed.



Figure 1: Left) PFAS coated fabric. Right) PFA tubing.

Source: Left) commons.wikimedia.org/wiki/File:A\_water\_droplet\_DWR-coated\_surface2\_edit1.jpg, Brocken Inaglorly, CC-BY-SA-3.0  
Right) commons.wikimedia.org/wiki/File:Pfa\_tubing.jpeg, Bushytails, CC-BY-SA-3.0

PFAS also has a surfactant property, so was used in foam products for firefighting. The foam is sprayed on a surface which creates an aqueous film blanket with low surface tension. The PFAS foam efficiently covers the fuel surface, blocks oxygen supply, and suppresses fuel vapors. The fire stops and cant spread on the sprayed surface for a very long time.

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PFAS in the Environment

PFAS has slowly accumulated in the environment and is now readily found in these places:

- Surface water
- Groundwater
- Ocean
- Sediment
- Soil
- Plants
- Animals on land and water (see Figure 2)
- Air (short-chain PFAS, settles within a few weeks)

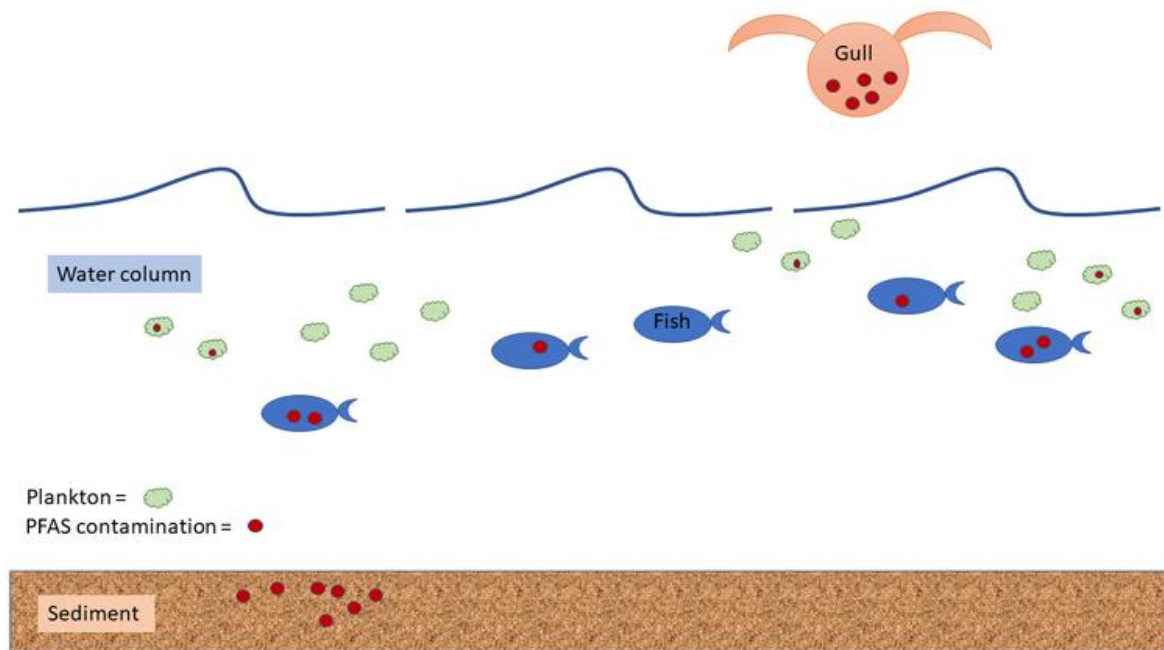


Figure 2: PFAS in sediments and water accumulating in marine organisms.

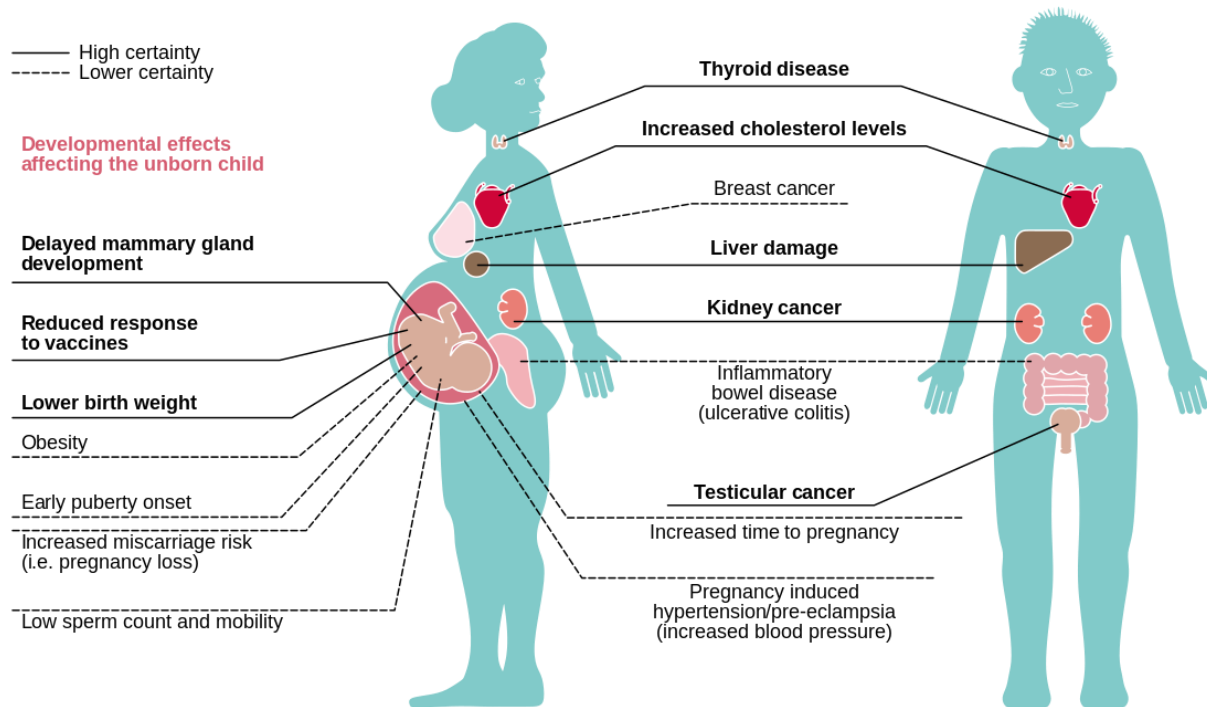
Animals higher on the food chain tend to accumulate more PFAS.  
 Source: commons.wikimedia.org/wiki/File:PFAS\_Biomagnification.png, Yanishevsky, CC-BY-SA-4.0

PFAS concentrations tend to increase over time since they last hundreds or thousands of years. Fortunately, in the last 20 years, most companies have slowed or stopped producing PFAS and turned to alternatives.

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**Health Concerns**

It is difficult to study the long-term health impacts of chemicals like PFAS. However, many medical studies, some going back to the 1970's, have shown direct links between many common types of PFAS chemicals and health problems. Figure 3 shows the main health impacts with high certainty items in bold.



**Figure 3: Health effects of exposure to PFAS in women, men, and fetuses.**

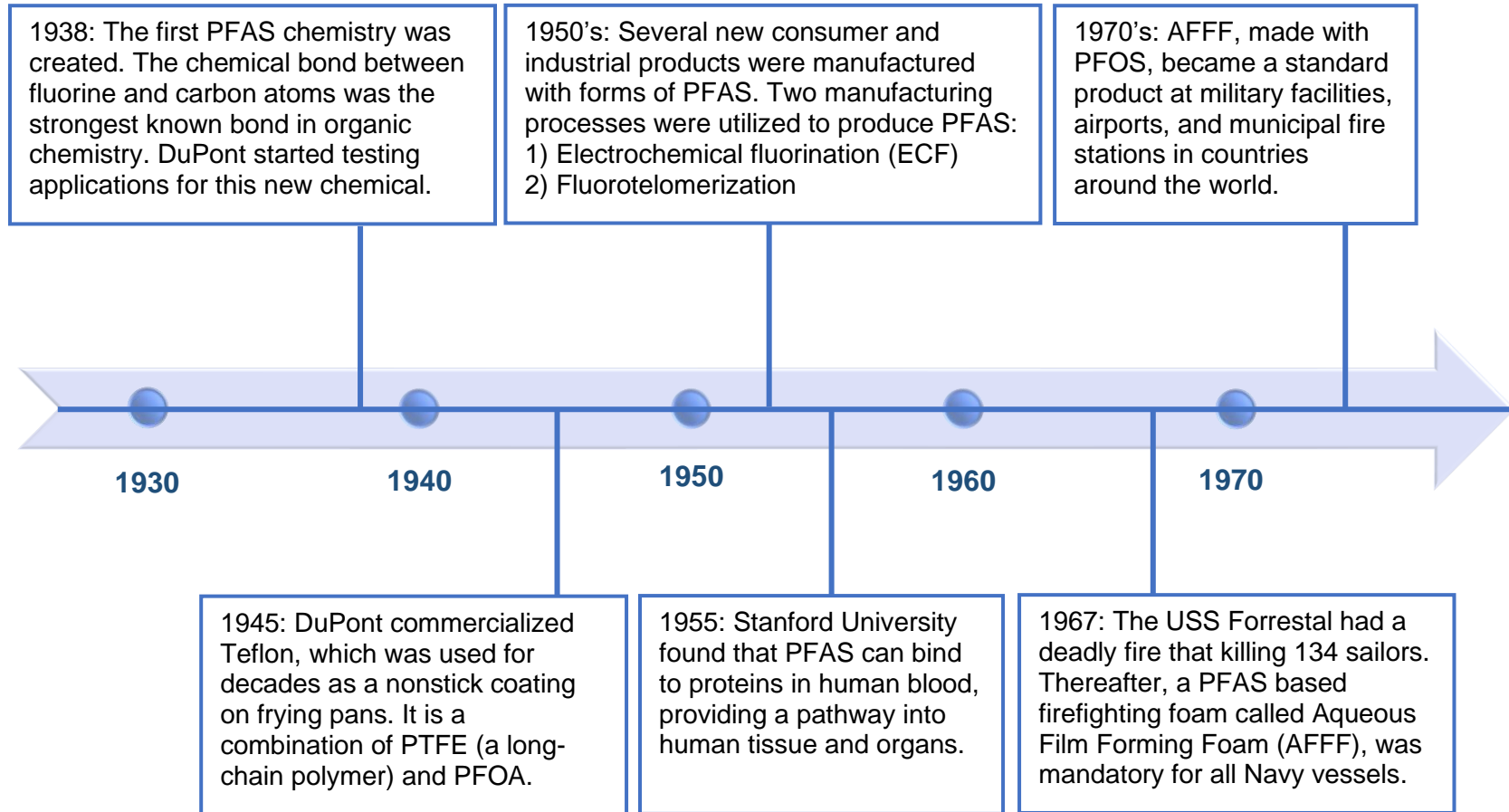
Source: en.wikipedia.org/wiki/File:Effects\_of\_exposure\_to\_PFASs\_on\_human\_health.svg, European Env. Agency, CC-BY-SA-4.0

One of main ways PFAS can enter the human body is through consuming food or liquid with PFAS. The regular drinking of water with PFAS results in PFAS molecules being absorbed into the body and accumulates in human tissue, especially the liver and kidneys. Therefore, private and public drinking water is commonly tested for PFAS levels. Treatment techniques to remove PFAS from potable water supplies are becoming increasingly common.



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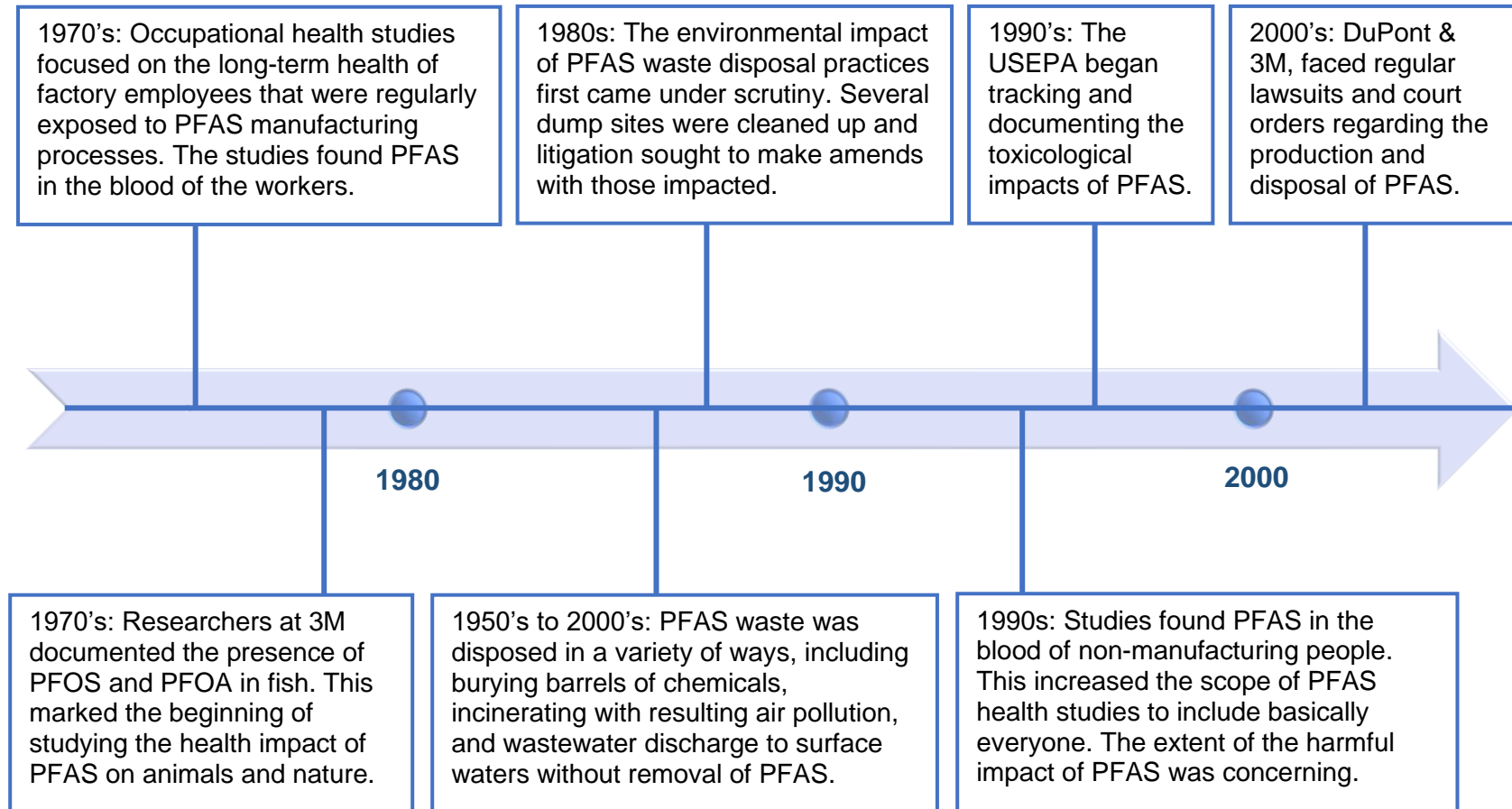
**History**



See the next section for an explanation of different types of PFAS.

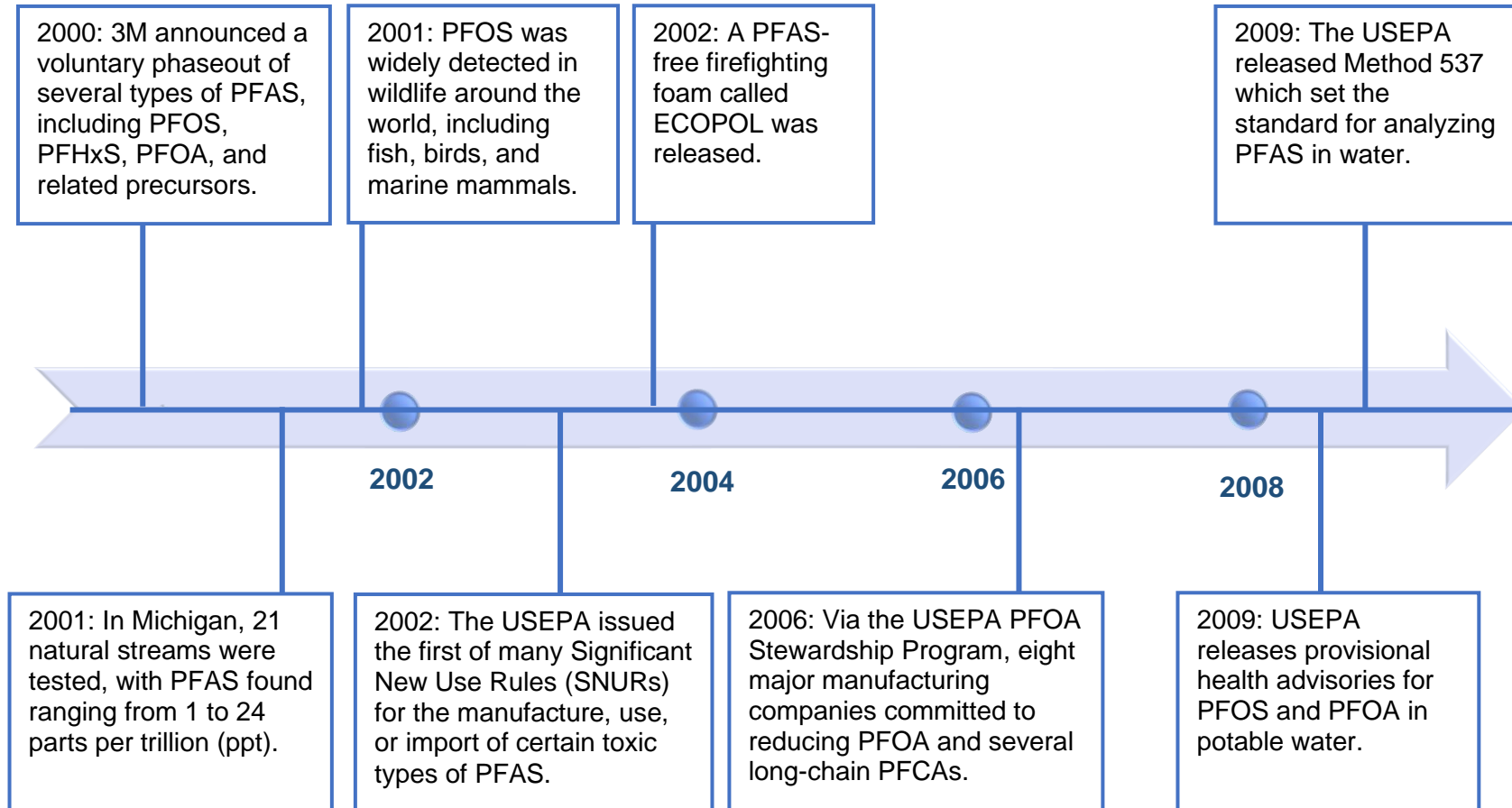


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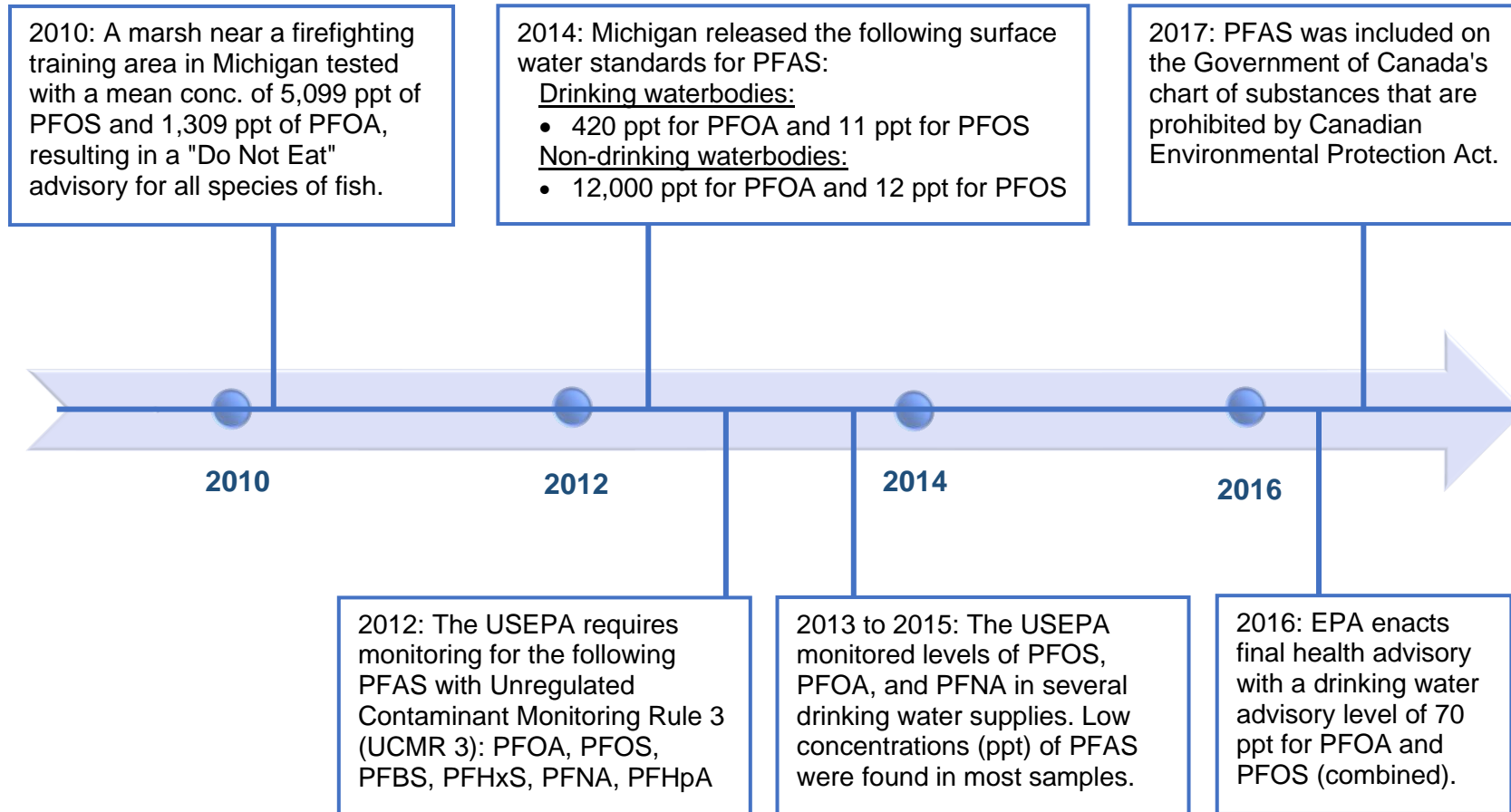






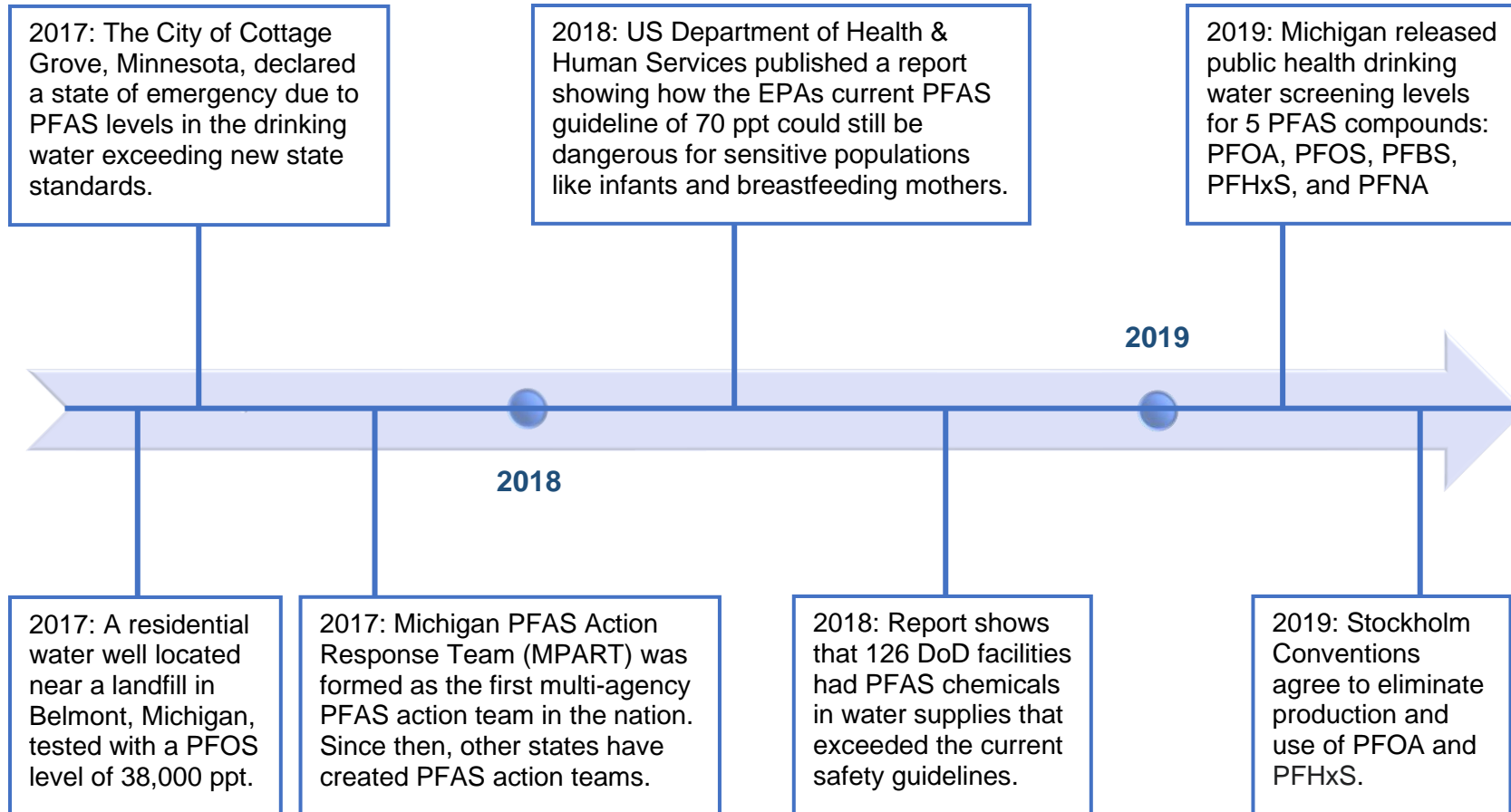
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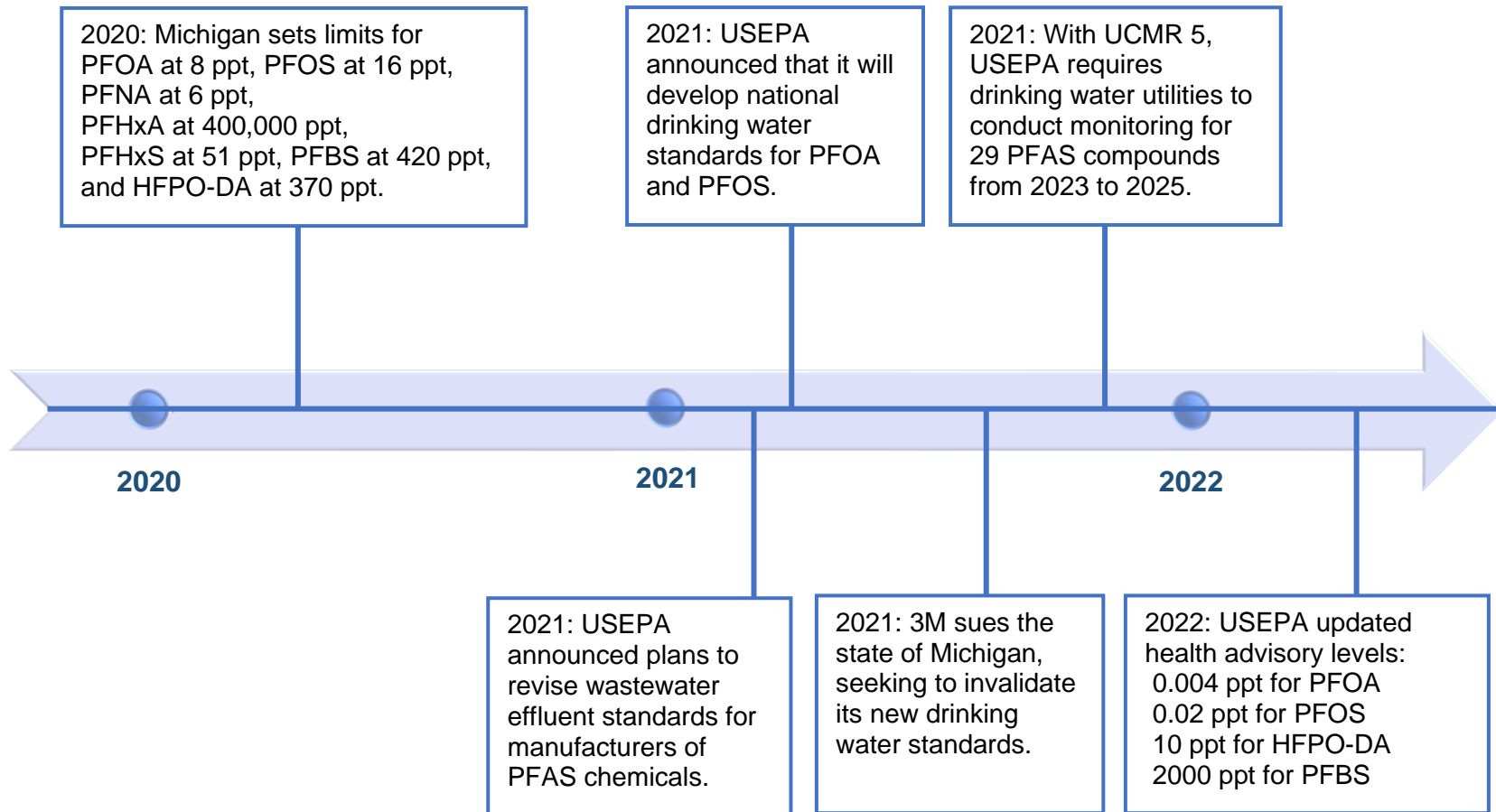


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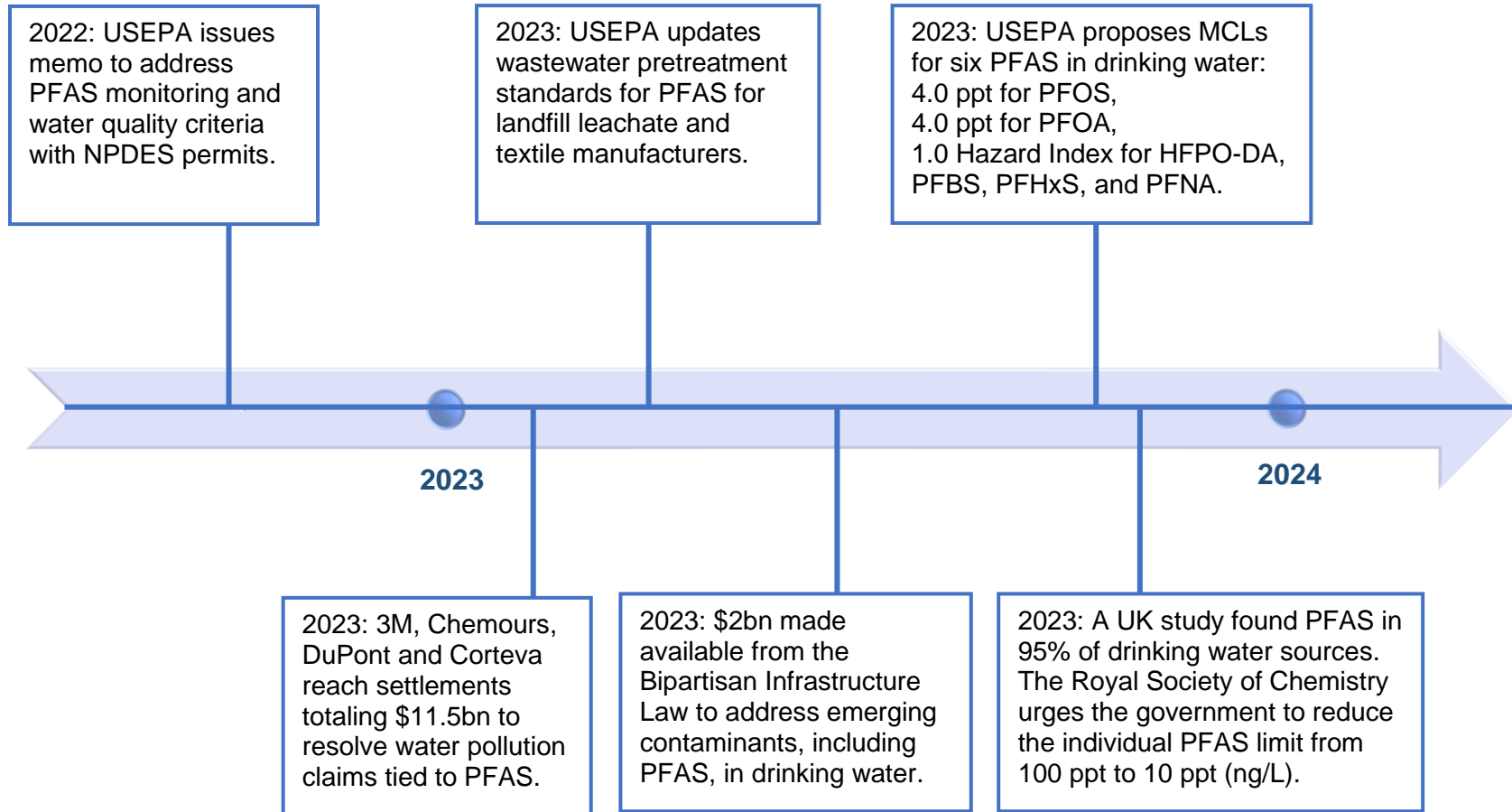


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**Types of PFAS**

There are thousands of different types (or compounds) of PFAS chemicals. The EPA toxicity database, DSSTox, lists 14,735 unique PFAS chemical compounds. Drinking water standards focus on a select few of the most common and most hazardous forms of PFAS. Figure 4 shows common PFAS chemicals in a triangle format, with carboxylate forms on the left and sulfonate forms on the right.

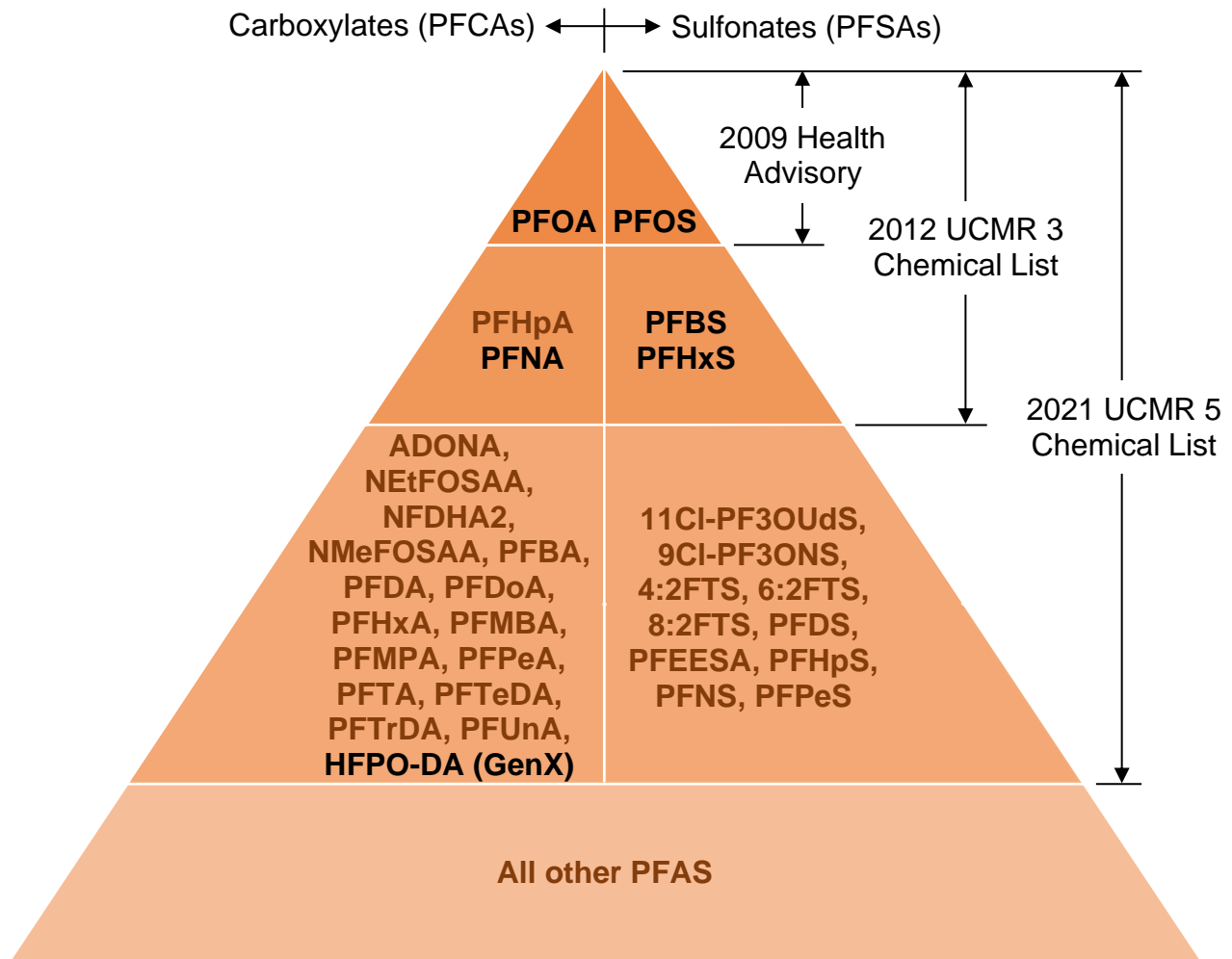


Figure 4: Triangle of PFAS forms with those given earlier attention on top. The PFAS in **black** are in the USEPA proposed MCLs in 2023.

Source: Author

All PFAS have a string of carbon atoms, each bonded with two fluorine atoms. It is these strong fluoride bonds that make the compounds last so long.

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### Head Difference

For perfluoroalkyl carboxylic acids (PFCAs), or carboxylates, the head is a  $-\text{CO}_2$  ion.

For perfluoroalkyl sulfonic acids (PFSA), or sulfonates, the head is a  $-\text{SO}_3$  ion.

See Figure 5 for the most common examples of each.

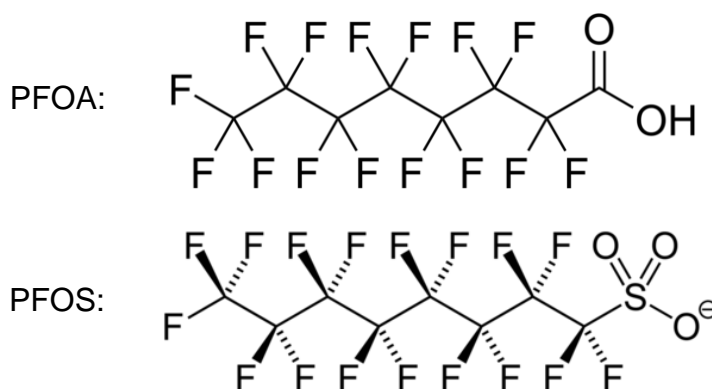


Figure 5: Top) Example carboxylate, PFOA, with a  $-\text{CO}_2$  head on right.  
Bottom) Example sulfonate, PFOS, with a  $-\text{SO}_3$  head on right.  
Note that the carbon atoms are at junctions without a letter, as is customary.  
Source: public domain

### Per- and Poly-

PFAS chemicals can also be grouped into “per-” (fully) and “poly-” (partly) forms.

Perfluoroalkyl have carbon chains that are fully fluorinated (carbon-fluorine bonds only).

Polyfluoroalkyl have carbon chains that are not fully fluorinated (contains some carbon-hydrogen bonds or carbon-oxygen bonds). The “per-” forms tend to be stronger, more toxic, and more heavily regulated. See Figure 6 for examples.

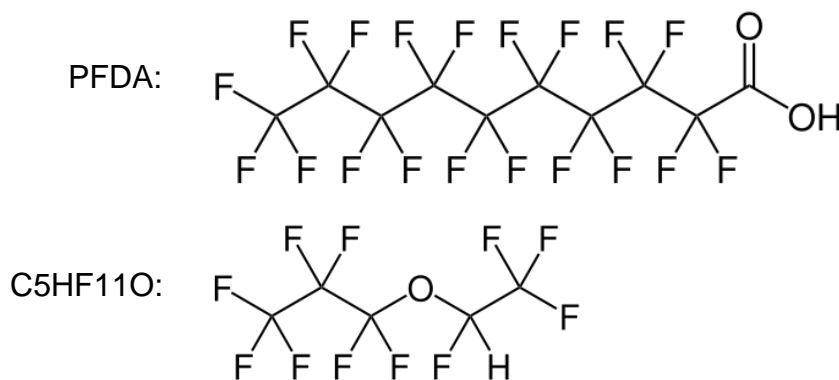


Figure 6: Top) Example “per-” form with fully fluorinated chain.  
Bottom) Example “poly-” form with an oxygen bond in an otherwise fluorinated chain.  
Source: public domain

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Polymer PFAS

PFAS chemicals can also be grouped into polymers and non-polymers. Polymers have chains with  $\geq 15$  carbon atoms for carboxylates (PFCAs) and  $\geq 14$  carbon atoms for sulfonates (PFSA). Examples include fluoropolymers (common for non-stick coatings) and side-chain fluorinated polymers (SCFPs, common for textile finishes). Often polymers are too long to absorb into the human body and thus are not regulated in drinking water. However, they can break down into non-polymer PFAS and thus are still a concern. See Figure 7 for example polymer PFAS.

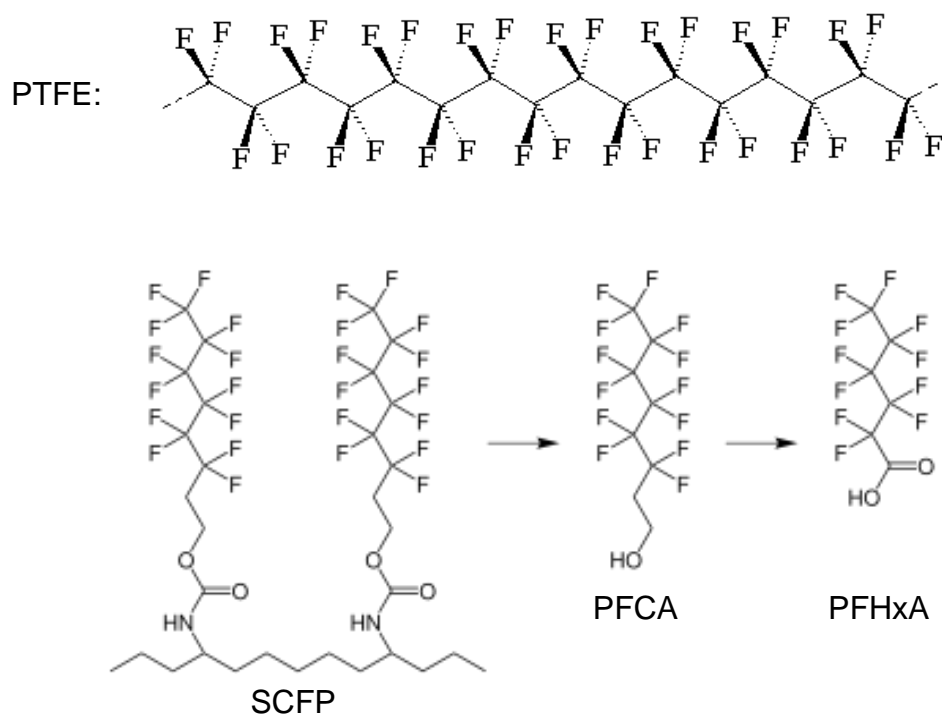


Figure 7: Top) Example fluoropolymer PTFE (Teflon).  
Bottom) Example side-chain fluorinated polymer degrading into PFHxA.

Source: public domain



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Non-Polymer PFAS

Non-polymer “per-” PFAS are grouped into “short-chain” and “long-chain” based on the number of carbon atoms in the chain. Long-chains contain  $\geq 7$  carbons for carboxylates (PFCAs) and  $\geq 6$  carbons for sulfonates (PFSAAs). Carboxylates have an extra carbon in the  $-\text{CO}_2$  head, so the transition to long-chain is one carbon atom higher. Table 1 lists common short-chain and long-chain PFAS based on the number of carbons in the chain. The two **red** PFAS are from the 2009 Health Advisory. The six **bold** PFAS are from the 2012 UCMR3. The six **orange** PFAS are often considered ultrashort-chain.

| No. of Carbons | Carboxylates (PFCAs) |              | Sulfonates (PFSAAs) |              |
|----------------|----------------------|--------------|---------------------|--------------|
| 1              | Short-chain          | -            | Short-chain         | TFMS         |
| 2              |                      | TFA          |                     | PFEtS        |
| 3              |                      | PFPPrA       |                     | PFPPrS       |
| 4              |                      | PFBA         |                     | <b>PFBS</b>  |
| 5              |                      | PFPeA        |                     | PFPeS        |
| 6              |                      | PFHxA        |                     | <b>PFHxS</b> |
| 7              | Long-chain           | <b>PFHpA</b> | Long-chain          | PFHpS        |
| 8              |                      | <b>PFOA</b>  |                     | <b>PFOA</b>  |
| 9              |                      | <b>PFNA</b>  |                     | PFNS         |
| 10             |                      | PFDA         |                     | PFDS         |
| 11             |                      | PFAUnA       |                     | PFAUnS       |
| 12             |                      | PFADoA       |                     | PFADoS       |
| 13             |                      | PFATrDA      |                     | PFATrDS      |
| 14             |                      | PFATeDA      |                     | PFATeDS      |
| 15+            | Polymer              | Various      | Polymer             | Various      |

Long-chain PFAS tend to strongly repel water (hydrophobicity) which makes them commercially attractive. Long-chain PFAS are more highly regulated than short-chain or polymer types of PFAS. Long-chain and polymer types of PFAS are easier to remove from drinking water by membrane filtration. Figure 8 depicts how ultrashort and short-chain PFAS are physically smaller than long-chain PFAS, and thus require smaller openings for membrane removal.



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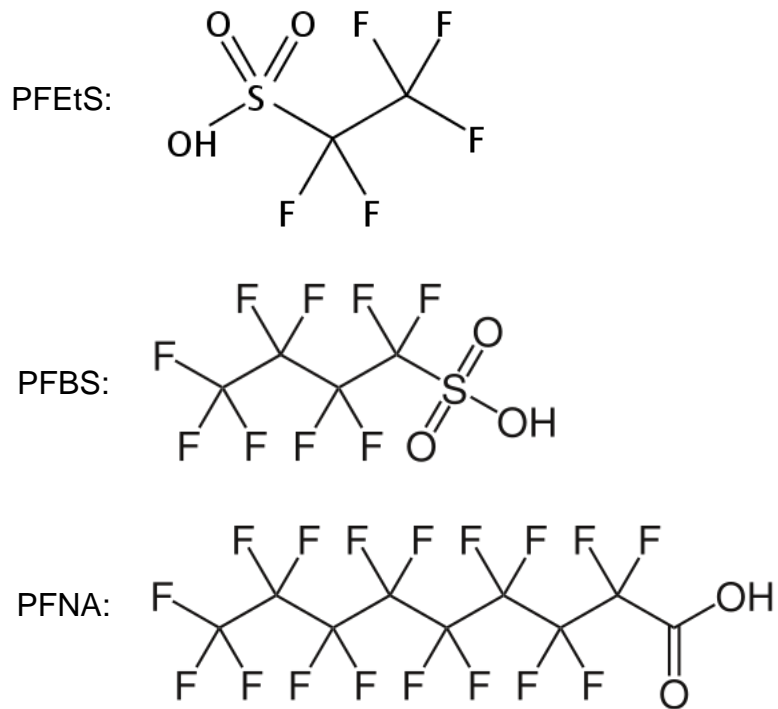


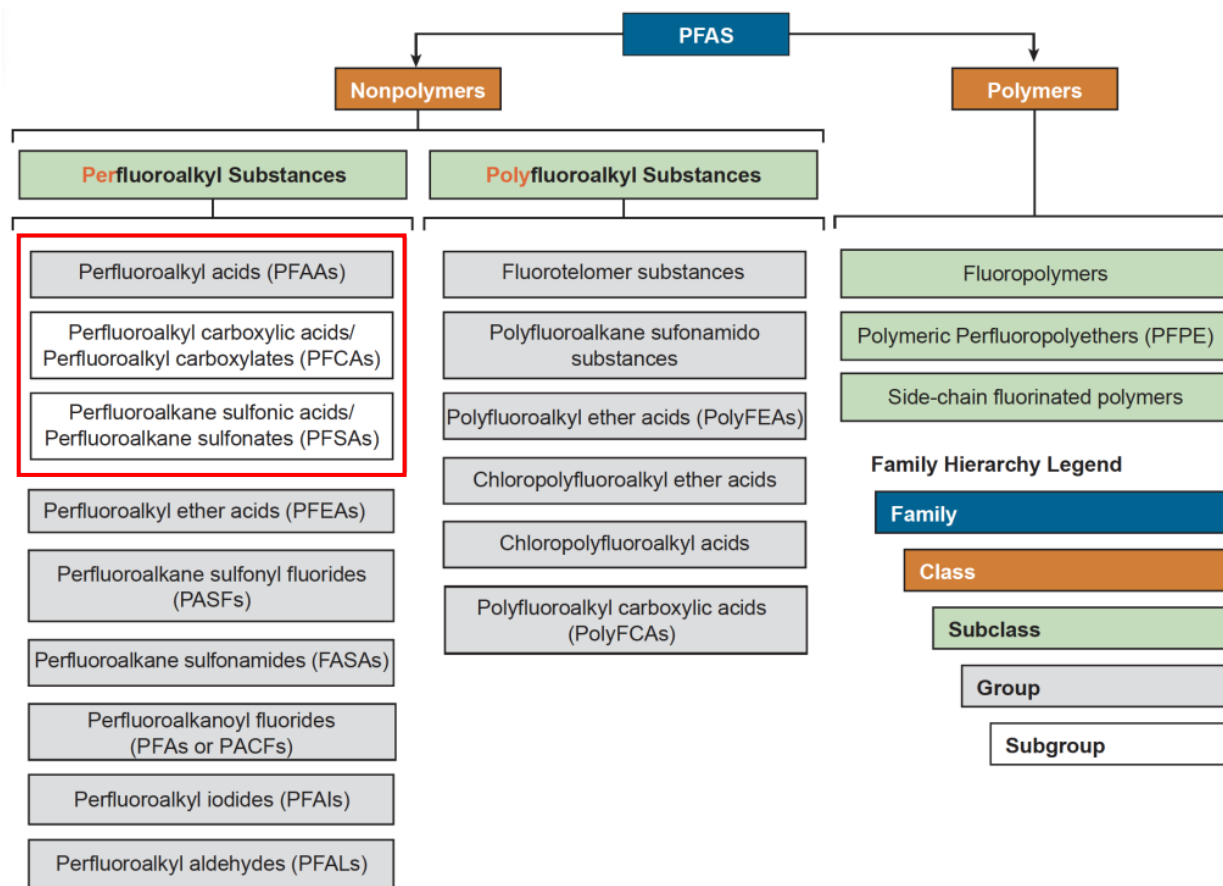
Figure 8: Top) Example ultrashort-chain PFAS (2 carbons).  
 Middle) Example short-chain PFAS (4 carbons).  
 Bottom) Example long-chain PFAS (9 carbons).

Source: public domain

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**PFAS Family Tree**

A comprehensive family tree with types of PFAS is presented in Figure 8. The individual PFAAs boxed in red are listed previously in Table 1.



**Figure 8: PFAS family tree with a red box around the group that is given the most focus in drinking water regulations.**

Source: <https://pfas-1.itrcweb.org/2-2-chemistry-terminology-and-acronyms>, Interstate Technology and Regulatory Council



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### Drinking Water Limits

Currently there is no national enforceable limit on PFAS in drinking water in the United States. The 2021 USEPA UCMR 5 included requirements for monitoring for 29 types of PFAS, but with no enforceable limits. The 2022 USEPA Health Advisory (HA) included very low levels for PFOA, PFOS, HFPO-DA (GenX), and PFBS, but was issued as a warning only. In 2023, the USEPA proposed the following maximum contaminant levels (MCLs), which are yet to be enacted:

- 4.0 ppt for PFOS
- 4.0 ppt for PFOA
- 1.0 Hazard Index for HFPO-DA, PFBS, PFHxS, and PFNA

Once the proposed rule is finalized, water systems will have three years to comply with the MCLs. National and state grants and loans will likely be issued at that time to upgrade treatment facilities and utilize new water sources. Compliance is determined by calculating annual averages at each sampling point (each water source or entry point into the distribution system). Sampling frequency is either quarterly (every 3 months) or biannual (twice a year, minimum 90 days apart) as indicated in Table 2.

| Water Source  | No. of Customers | Frequency (Months) |
|---------------|------------------|--------------------|
| Groundwater   | ≥10,000          | 3                  |
|               | <10,000          | 6*                 |
| Surface Water | N/A              | 3                  |

Note: (\*) Twice a year, min. 90 days apart

### State Limits

In the absence of enforceable national standards, several states have set their own limits. See the states in red in Table 3. The states in black have PFAS limits that require notification to the public and other actions if the limit is exceeded. Note that several states are considering adding or changing their limits, so this table may not reflect the latest state requirements.



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| Table 3: PFAS Levels by State (as of Jan 2024)                                |   |            |                                     |       |                |         |                         |
|---|---|------------|-------------------------------------|-------|----------------|---------|-------------------------|
| Red are MCLs (required); Black are non-mandatory; Units in (ppt, ng/L) u.n.o. |   |            |                                     |       |                |         |                         |
| States  | PFOA  | PFOS       | PFNA                                | PFHxS | HFPO-DA (GenX) | PFBS    | Other                   |
| All, USEPA HA '22   | 0.004   | 0.02       | -                                   | -     | 10             | 2,000   | -                       |
| All, USEPA Prop. MCLs '23   | 4   | 4          | 1.0 Hazard Index (see next section) |       |                |         | -                       |
| Alaska  | 70 (total)  |            | -                                   | -     | -              | -       | -                       |
| California  | 5.1   | 6.5        | -                                   | 3     | -              | 500     | -                       |
| Colorado  | 70 (total)  |            |                                     | 700   | -              | 400,000 | -                       |
| Connecticut   | 16  | 10         | 12                                  | 49    | 19             | 760     | 6 others                |
| Delaware  | 70 (total)  |            | -                                   | -     | -              | -       | -                       |
| Hawaii  | 12  | 7.7        | 12                                  | 1,900 | 12             | 1,700   | 12 others               |
| Illinois  | 2   | 14         | 21                                  | 140   | -              | 2,100   | 3,500                   |
| <b>Maine</b>  | <b>20 (total of PFOA, PFOS, PFHxS, PFNA, PFHpA, and PFDA)</b> |            |                                     |       |                |         |                         |
| Maryland  | -   | -          | -                                   | 140   | -              | -       | -                       |
| <b>Massachusetts</b>  | <b>20 (total of PFOA, PFOS, PFHxS, PFNA, PFHpA, and PFDA)</b> |            |                                     |       |                |         |                         |
| Michigan  | 8   | 16         | 6                                   | 51    | 370            | 420     | 400,000 PFHxA           |
| Minnesota   | 35  | 15         | -                                   | 47    | -              | 100     | 200 PFHxA<br>7,000 PFBA |
| Nevada  | 667 (total)   |            | -                                   | -     | -              | 667,000 |                         |
| <b>New Hampshire</b>  | 12  | 15         | 11                                  | 18    | -              | -       | -                       |
| <b>New Jersey</b>   | 14  | 13 (total) |                                     | -     | -              | -       | -                       |
| New Mexico  | 70 (total)  |            | -                                   | -     | -              | -       | -                       |
| <b>New York</b>   | 10  | 10         | -                                   | -     | -              | -       | -                       |
| North Carolina  | -   |            | -                                   | -     | 140            | -       | -                       |
| Ohio  | 70 (total)  |            | 21                                  | 140   | 25             | 140,000 |                         |
| Oregon  | 30 (total)  |            |                                     |       | -              | -       | -                       |
| <b>Pennsylvania</b>   | 14  | 18         |                                     |       |                |         |                         |
| Rhode Island  | 20 (Total of PFOA, PFOS, PFHxS, PFNA, PFHpA, and PFDA)        |            |                                     |       |                |         |                         |
| <b>Vermont</b>  | <b>20 (Total of PFOA, PFOS, PFHxS, PFNA, and PFHpA)</b>       |            |                                     |       |                |         |                         |
| Washington  | 10  | 15         | 9                                   | 65    | -              | 345     | -                       |
| <b>Wisconsin</b>  | <b>70 (Total)</b>   |            | -                                   | -     | -              | -       | -                       |



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Group Limits

In 2020 Massachusetts set a standard in the northeast when it established an MCL of 20 parts per trillion for the total of six toxic PFAS compounds known as the “MA 6”, consisting of PFOS, PFOA, PFDA, PFHpA, PFHxS, & PFNA. This requires testing for each PFAS chemical and then summing the values. Maine, Rhode Island, and Vermont followed with similar group limits.

Group limits bring the focus on decreasing the total PFAS rather than individual types. For example, compare these two cities:

- 1) City A only has PFOS at 16 ppt and no other PFAS present (16 ppt total PFAS).
- 2) City B has PFOS, PFOA, PFDA, & PFHxS at 15 ppt each (60 ppt total PFAS).

City B has drinking water with a greater potential for health impact from PFAS. However, with only individual MCLs at 15 ppt for each type of PFAS, City B would pass while City A would fail. The group PFAS approach at 40 ppt total would force City B to address the elevated levels.

The USEPA acknowledged the benefit of the group approach, but also recognized that some PFAS are worse for human health than others. Thus, the USEPA developed the “Health Hazard” approach whereby the sum of the PFAS concentrations takes into account the relative health impact of each type of PFAS (see the next section).



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### **Hazard Index**

The Hazard Index (HI) is a USEPA approach that quantifies the combined effect of multiple chemicals. As applied to PFAS, the HI considers PFNA, PFHxS, PFBS, and HFPO-DA (GenX). Each of these has a different health-based value, which is the concentration determined not to have significant health effects. The health-based values are as follows:

- PFHxS = 9 ppt (most toxic)
- PFNA = 10 ppt
- GenX = 10 ppt
- PFBS = 2,000 ppt (least toxic)

The HI is the sum of the measured concentration divided by the health-based value for each of four PFAS. A value greater than 1.0 is considered over the proposed MCL. The USEPA HI formula is as follows:

$$\text{Hazard Index} = \left( \frac{[\text{GenX}_{\text{water}}]}{[10 \text{ ppt}]} \right) + \left( \frac{[\text{PFBS}_{\text{water}}]}{[2000 \text{ ppt}]} \right) + \left( \frac{[\text{PFNA}_{\text{water}}]}{[10 \text{ ppt}]} \right) + \left( \frac{[\text{PFHxS}_{\text{water}}]}{[9.0 \text{ ppt}]} \right)$$

The annual HI value is calculated based on averaging the quarterly or biannual sampling at each sampling point over a 1-year period. Values below the practical quantitation level (PQL) are considered to be zero, so that analytical errors don't result in a false overage. PQLs are provided in Table 4.

| Compound       | PQL |
|----------------|-----|
| PFOS           | 4.0 |
| PFOA           | 4.0 |
| PFHxS          | 3.0 |
| GenX (HFPO-DA) | 5.0 |
| PFNA           | 4.0 |
| PFBS           | 3.0 |



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Example Problem 1

The City of Fetna compliance point is sampled quarterly for PFOS with the following results: 3.0, 5.5, 2.0, and 6.5 ppt. What is the PFOS value to report and is it in compliance with the USEPA proposed MCL of 4.0 ppt?

Solution:

The PFOS value to report is the average of the quarterly PFOS values, which is calculated by summing and dividing by 4. However, the values in the first and third quarters (3.0 and 2.0) are below the PQL of 4.0 and thus not included:

$$\text{PFOS value} = (0 + 5.5 + 0 + 6.5) / 4 = 12 / 4 = 3.0 \text{ ppt}$$

In this case the PFOS value to report is less than the MCL of 4.0 ppt, and thus in compliance.



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Example Problem 2

The City of Fetna also has a surface water compliance point that is sampled twice a year for PFAS, with the results in Table 5. What is the HI value to report and is it in compliance with the USEPA proposed MCL?

| Test No. | PFOA | PFOS | PFNA | PFHxS | HFPO-DA (GenX) | PFBS  |
|----------|------|------|------|-------|----------------|-------|
| 1        | 3.0  | 2.6  | 5.2  | 9.8   | 12.2           | 2,300 |
| 2        | 4.0  | 1.1  | 7.8  | 10.6  | 10.5           | 1,200 |

Solution:

The Hazard Index (HI) value to report is the average of the two HI values, one for each test. The HI values are calculated with the four HI PFAS values (the four last columns), which does not include PFOA & PFOS). None of the values are below the PQLs in Table 4, so none need to change to zero.

The calculations are as follows:

Test 1:

$$HI = \frac{\text{GenX}}{10} + \frac{\text{PFBS}}{2000} + \frac{\text{PFNA}}{10} + \frac{\text{PFHxS}}{9} = \frac{2.5}{10} + \frac{350}{2000} + \frac{4.0}{10} + \frac{1.0}{9} = 0.94$$

Test 2:

$$HI = \frac{4.5}{10} + \frac{300}{2000} + \frac{5.0}{10} + \frac{1.0}{9} = 1.21$$

Average:

$$HI = \frac{0.94 + 1.21}{2} = 1.07$$

The HI value to report is greater than the proposed HI MCL of 1.0, and thus is not in compliance.





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**Lab Test Methods**

For official monitoring and reporting of PFAS, a certified laboratory should be utilized for water quality testing. Field testing or test strips are not available for PFAS. USEPA approved methods are listed in Table 6 with example lab prices as of Jan 2024.

| Table 6: USEPA Approved Methods for Testing PFAS  |              |   |                                       |             |             |   |
|---|--------------|---|---------------------------------------|-------------|-------------|---|
| Type of Water   | EPA Method   | Analytical Technique                              | No. of Compounds                      | Cost (2024) | Time (min.) | Notes   |
| Potable   | 537.1        | SPE and LC/MS/MS                                  | 18                                    | \$185       | 40          | Replaces 537 (fast but inconsistent)<br>Low detection limit     |
|   | 533          | Isotope Dilution Anion Exchange, SPE and LC/MS/MS | 25                                    | \$215       | 35          | Targets short-chain   |
|   | TOF Assay    | Combustion Ion Chromatography (CIC)               | 1 (Total Organic Fluorine)            | \$75        | ~120        | Estimate total PFAS, Modified Method 1621                       |
| Non-Potable   | 8327, SW-846 | External Standard Calibration and MRM LC/MS/MS    | 24                                    | \$185       | 21          | Equal to ASTM D8421 (44 compounds)                              |
|   | 1633         | SPE and LC/MS/MS                                  | 40                                    | \$125       | 20          | Recommended for NPDES and pretreatment permits                  |
|   | TOP Assay    | Oxidize all polyfluorinated compounds into PFAAs  | 1 (Total Organic Precursors)          | \$1,000     | >60         | Measures current and potential PFAAs, see EOF & AOF assays      |
|   | 1621         | Combustion Ion Chromatography (CIC)               | 1 (AOF = Adsorbable Organic Fluorine) | \$55        | ~120        | Determines presence of organofluorines, EPA wastewater standard |
| Notes: SPE = Solid phase extraction<br>LC/MS/MS = Liquid chromatography with tandem mass spectrometry<br>MRM = Multiple reaction monitoring |              |   |                                       |             |             |   |



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**Removal Techniques**

The following tables provide details on common treatment methods for PFAS removal.

| Adsorption              |   |  |
|-------------------------|---|--|
| PFAS Removal            | Function  | Configurations   |
| >99% until breakthrough | PFAS are adsorbed (adhered) to the media surface and removed by backwash, regeneration, or disposal. Breakthrough of short-chain PFAS, such as PFBA & PFBS, occur prior to long-chain breakthrough. | <ul style="list-style-type: none"><li>• Fixed-bed</li><li>• Fluid-bed / Fluidized Bed Reactor (FBR)</li><li>• Media: granular activated carbon (GAC), activated alumina, modified clay</li></ul> |



Figure 9: Activated carbon adsorption system for water treatment, with six vessels. Each vessel can be isolated to replace the media inside.

Source: commons.wikimedia.org/wiki/File:Fischer-Deponie\_Aktivkohle-Filter\_033w.jpg, Peter Haas, CC BY-SA 3.0

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| Carbon Filters (Home Use) |   |   |
|---------------------------|---|---|
| PFAS Removal              | Function  | Configurations  |
| ~75% until breakthrough   | PFAS are adsorbed (adhered) to the media surface and removed by filter disposal. Common household filters are designed to be replaced every 6 months. | <ul style="list-style-type: none"> <li>Media: granular activated carbon (GAC)</li> <li>Third-Party Certified</li> </ul> |

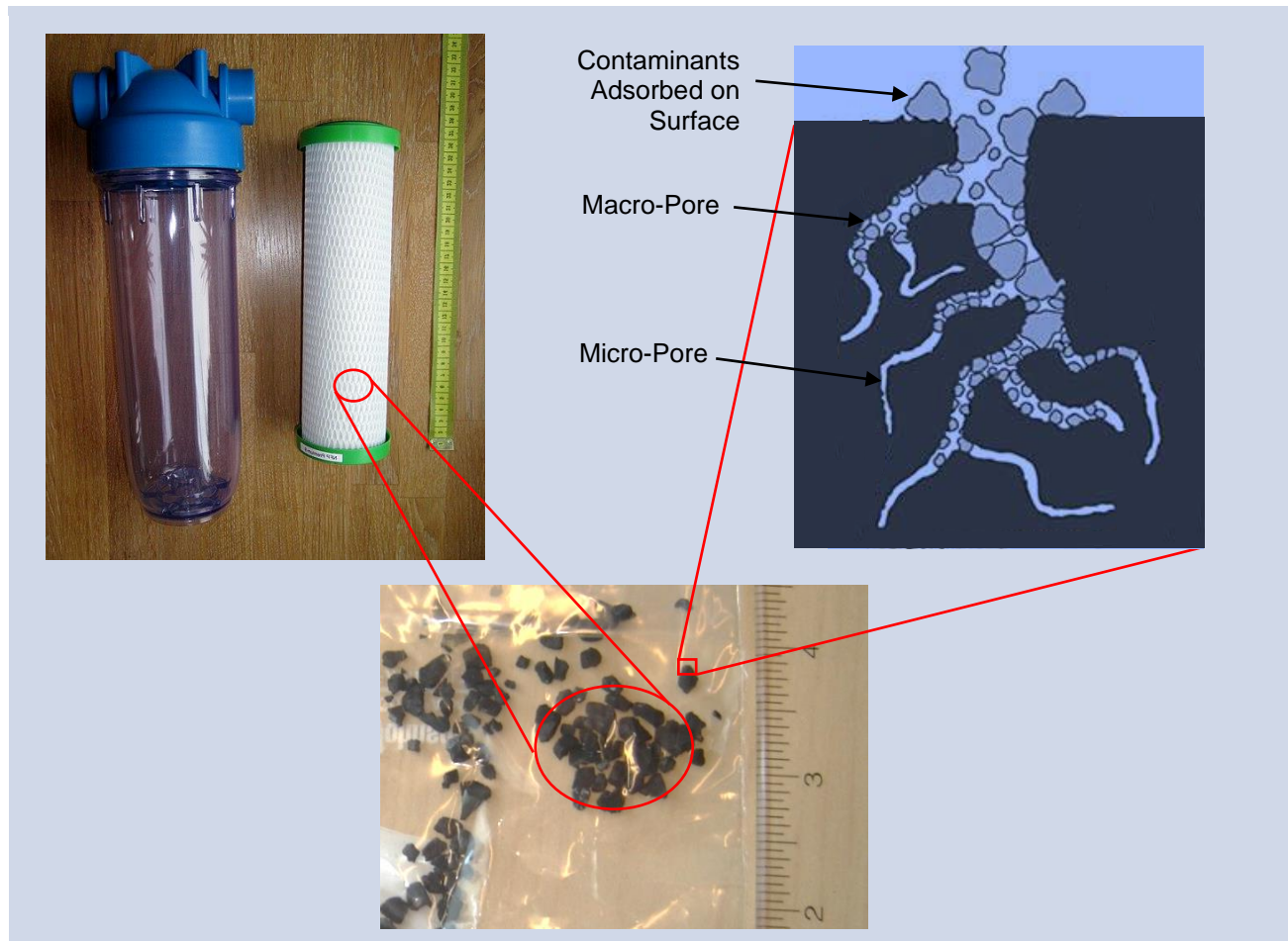


Figure 10: Carbon filter (left) activated carbon inside the filter (bottom), granular media with pores for adsorbing contaminants such as PFAS (right).

Source: Left: commons.wikimedia.org/wiki/File:Wasserfilter\_mit\_Aktivkohle-Filterpatrone.JPG, Cschirp, CC-BY-SA-3.0  
 Bottom: Author; Right: A Citizen's Guide to Activated Carbon Treatment, EPA 542-F-12-001

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| Ion Exchange |  |  |
|--------------|--|--|
| PFAS Removal | Function   | Configurations   |
| >99%         | Special resin exchanges its ions for PFAS molecules and other anions (e.g., nitrates, sulfates, silica). Requires upstream filtration to protect expensive resin from fouling. | <ul style="list-style-type: none"> <li>• Anion resin (media)</li> <li>• Fixed bed</li> <li>• Moving bed/ suspended</li> <li>• Magnetic (MIEX)</li> <li>• One stage or two-stage</li> <li>• Mixed system</li> </ul> |

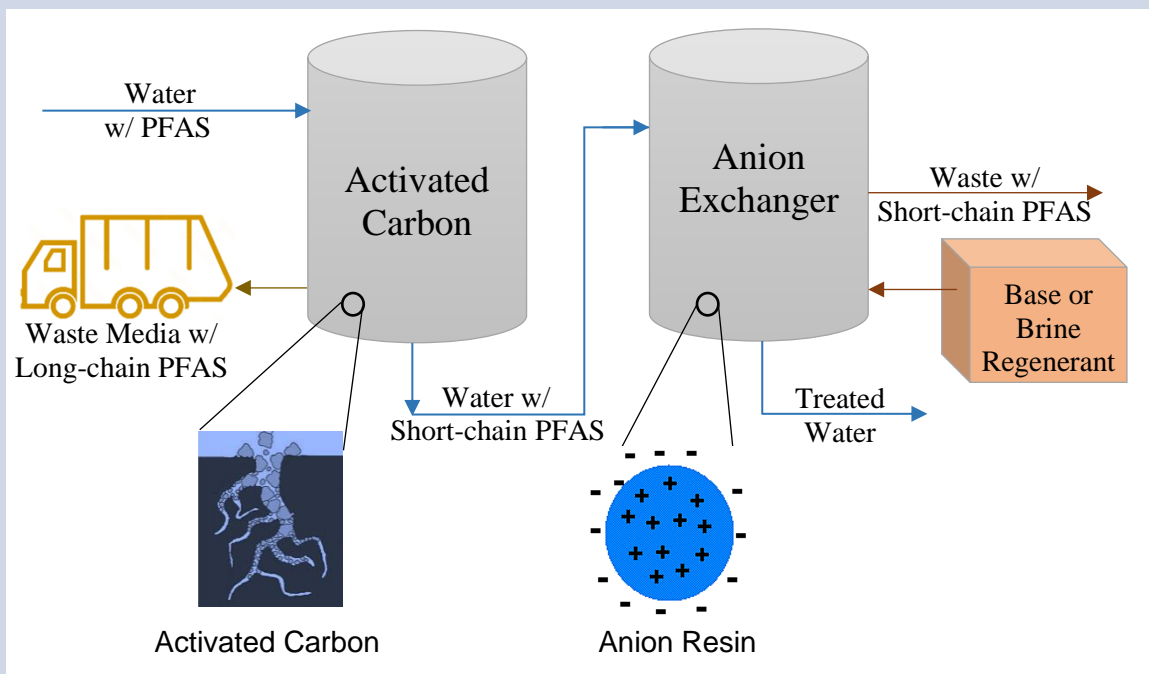


Figure 11: A mixed GAC and ion exchange system, starting with fixed-bed activated carbon (GAC) followed by ion exchange. The GAC focuses on long-chain PFAS while the anion resin polishes any remaining short-chain PFAS. Used GAC is wasted while anion resin is regenerated onsite by soaking media in a strong base or brine regenerant.

Source: Author



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| Nanofiltration (NF) |   |  |
|---------------------|---|--|
| PFAS Removal        | Function  | Configurations   |
| >90%                | Blocks a variety of contaminants, including PFAS, from passing through small openings (1 to 10 nm), and sends them into a concentrate stream. The permeate is very clear water. | <ul style="list-style-type: none"><li>• Nano-filtration (NF)</li><li>• Tubular (shell and tube)</li><li>• Spiral-wound</li><li>• Hollow fiber</li><li>• One or Two Stage</li><li>• Recirculation</li></ul> |



Figure 12: Two skids with ultrafiltration membranes (green tubes) and high-pressure feed pumps (blue).

Source: commons.wikimedia.org/wiki/File:Wastewater\_UF\_membrane\_system,\_Aquabio.jpg, Aquabio Ltd., CC-BY-SA-3.0



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| Reverse Osmosis (RO) |  |  |
|----------------------|--|--|
| PFAS Removal         | Function   | Configurations   |
| >95%                 | Blocks salts, metal ions, carbonates, and a variety of contaminants, including PFAS, from passing through very small openings (0.1 to 1 nm), and sends them into a concentrate stream. The permeate is very clear water. | <ul style="list-style-type: none"><li>• Thin Film Composite (TFC or TFM) membrane</li><li>• Cellulose Triacetate (CTA) membrane</li><li>• Polymeric</li><li>• Ceramic</li><li>• One or Two Stage</li><li>• Recirculation</li></ul> |



Figure 13: Large water plant with four RO skids, each with (81) blue RO tubes. Two upstream cartridge filters are seen in the bottom.

Source: commons.wikimedia.org/wiki/File:Northcapecoral-RO.jpg, Twhair, CC-BY-SA-4.0



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Reverse Osmosis Filtration System (Home Use)

| PFAS Removal            | Function   | Configurations   |
|-------------------------|--|--|
| >99% until breakthrough | Under-sink treatment system with prefilters and RO filter. Blocks contaminants, including PFAS, from passing through very small openings (0.1 to 1 nm), RO concentrate goes to drain. The permeate (clean water) usually routes to a sink drain. | <ul style="list-style-type: none"><li>• GAC prefilter</li><li>• 3 to 7 Stages</li><li>• UV post-disinfection</li><li>• Carbon post-filter</li><li>• Holding Tank</li><li>• Valves and tubing</li><li>• Pressure pump</li></ul> |



Figure 14: 4-Stage 100 gpd RO Water System with (3) prefilters (carbon and sand) at the bottom, a booster pump (silver) and a RO De-Ionizing Filter (white).

Source: commons.wikimedia.org/wiki/File:Rodi.jpg, Kingfish101, CC-BY-SA-3.0



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Comparison of Technologies

Table 7 lists the typical advantages and disadvantages of each of the common PFAS removal techniques for a mid-size water treatment facility (10,000 to 100,000 customers). The table assumes that membrane concentrate cannot be discharged to drain but requires adsorption treatment. For each application, bench-scale or pilot testing is required to confirm PFAS removal, media lifespan, system sizing, and other critical factors.

| Table 7: Comparison of PFAS Removal Technologies<br>for a Water Treatment Facility |  |              |  |  |
|--|--|--------------|--|--|
| Technique  | System Assumptions   | PFAS Removal | Advantages   | Disadvantages  |
| GAC Adsorption   | Upstream filtration, three media vessels, offsite regeneration   | >99%         | <ul style="list-style-type: none"> <li>• Lowest capital cost</li> <li>• Option for onsite regeneration</li> <li>• Media type can be changed or mixed</li> </ul>      | <ul style="list-style-type: none"> <li>• Frequent media change</li> <li>• Frequent media monitoring</li> <li>• Potential for breakthrough</li> <li>• Upstream filtration</li> <li>• Large footprint</li> </ul> |
| Ion Exchange   | Upstream filtration, three media vessels, media disposal offsite | >99%         | <ul style="list-style-type: none"> <li>• Reliable</li> <li>• Low maintenance</li> <li>• Option for onsite regeneration</li> </ul>                                    | <ul style="list-style-type: none"> <li>• Expensive media</li> <li>• High lifecycle cost</li> <li>• Potential for breakthrough</li> <li>• Upstream filtration</li> </ul>  |
| Nano-Filtration  | Two membrane skids, GAC for concentrate                          | >90%         | <ul style="list-style-type: none"> <li>• Pathogen removal credit</li> <li>• Small footprint</li> <li>• Softens water</li> </ul>                                      | <ul style="list-style-type: none"> <li>• Concentrate management</li> <li>• Membrane fouling</li> </ul>   |
| Reverse Osmosis  | Two membrane skids, GAC for concentrate                          | >95%         | <ul style="list-style-type: none"> <li>• Pathogen removal credit</li> <li>• Removes most contaminants</li> <li>• Small footprint</li> <li>• Softens water</li> </ul> | <ul style="list-style-type: none"> <li>• Highest capital cost</li> <li>• Energy intensive</li> <li>• Concentrate management</li> <li>• Membrane fouling</li> </ul>   |





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### **Lifecycle Costs**

When comparing costs of PFAS treatment alternatives, it is important to consider the annual operations and maintenance costs since those can be considerable. With adsorption, the media needs to be replaced often, perhaps annually. With ion exchange, the media is very expensive to replace, so an onsite regeneration is often installed which increases capital costs. Membrane filtration is energy intensive which increases the electricity bill.

Lifecycle cost refers to the total cost of ownership over the life of an asset. This whole-life costing approach includes costs incurred after an asset has been constructed or acquired, such as maintenance, energy usage, operation, and disposal. When comparing alternatives, a time period is selected to apply to all alternatives, such as 20 years. If the system still has value after the time period, that amount, called the salvage value, is subtracted.

The lifecycle cost can be calculated using the present worth approach for annual costs. Present worth accounts for money today being worth more in the future due to interest. The formula is as follows:

$$\text{Lifecycle Cost} = \text{Capital Cost} + \text{Annual O\&M} * \text{PWF} - \text{Salvage Value}$$

where:  $\text{PWF} = \text{Present Worth Factor} = \frac{(1+i)^T - 1}{i * (1+i)^T}$   
 $i = \text{interest rate (adjusted for inflation)}$   
 $T = \text{number of years}$

$$\text{O\&M} = \text{Ongoing Operations and Maintenance Costs}$$



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**Example Project**

The Cape Fear Public Utility Authority (CFPUA) in North Carolina produces drinking water through the Sweeney Water Treatment Plant (WTP). There are 200,000 customers with an average daily flow of 44 million gallons per day (MGD). Raw water comes from the Cape Fear River. About 100 miles upstream on the river was a Chemours and DuPont chemical plant that manufactured PFAS chemicals for decades, resulting in fluctuating PFAS levels in the river.

CFPUA decided to upgrade the existing Sweeney WTP for PFAS removal. Pilot studies were done to test reverse osmosis, ion exchange, and granular activated carbon (GAC) filters. A GAC system was selected, designed, and constructed, with startup in October 2022. The filters contain almost 3 million pounds of GAC in rectangular concrete tanks. Test results are provided on the next page, showing how the finished drinking water is far below the USEPA proposed MCLs.

**Example Problem 3**

For the PFAS removal improvements at Sweeney WTP, capital costs totaled \$43 million and annual operations and maintenance costs are \$5 million (mostly for replacing the GAC media). Calculate the 20-year lifecycle cost, rounded to the nearest million. The interest rate is 5%. Salvage value is estimated to be \$10 million after 20 years.

Solution:

First, calculate the present worth factor, PWF:

$$PWF = \frac{(1 + 0.05)^{20} - 1}{0.05 * (1 + 0.05)^{20}} = \frac{1.65}{0.13} = 12.46$$

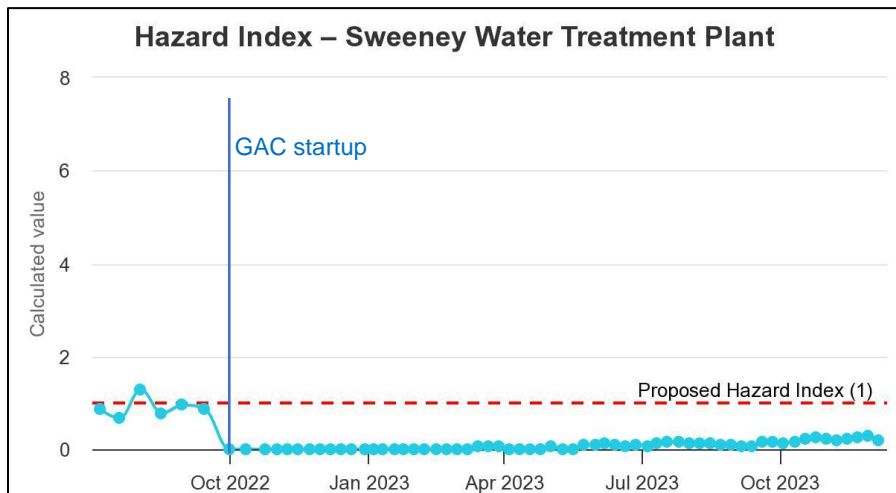
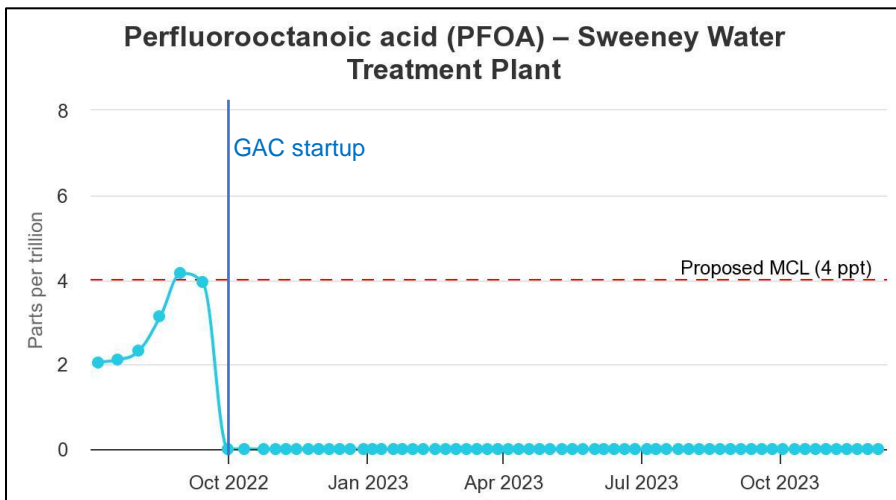
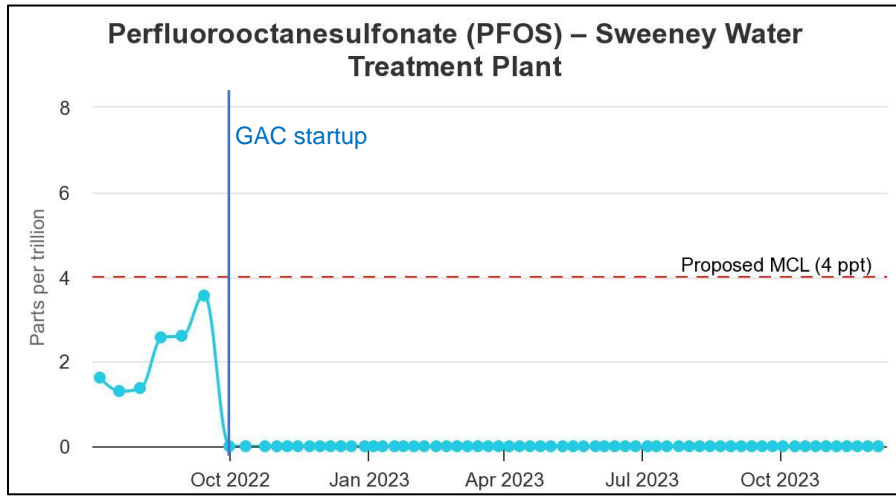
Then use the lifecycle cost formula:

$$Lifecycle\ Cost = Capital\ Cost + Annual\ O\&M * PWF - Salvage\ Value$$

$$Lifecycle\ Cost = \$43M + \$5M * 12.46 - \$10M = \$95M \text{ (rounded)}$$



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### Destruction Techniques

PFAS removed from a water system does not disappear. PFAS lasts hundreds or thousands of years, so if not destroyed, it can continue to negatively impact the environment or human health in the future. Disposal methods such as deep well injection and landfill storage provide long-term protection but do not destroy PFAS.

However, several PFAS destruction technologies do exist and have been implemented at small and large scales. PFAS destruction typically occurs at a dedicated waste management facility which receives PFAS containing solid and liquid waste from a variety of sources such as water treatment plants, wastewater treatment plants, landfills, industrial factories, chemical manufacturing facilities, and environmental cleanup sites.

PFAS destruction technologies include the following:

- Incineration of spent media or dried sludge; can combine with landfill solid waste
- Hydrothermal alkaline treatment
- Photolysis
- High-energy electron beam / radiolytic PFAS
- Electrochemical oxidation
- Advanced oxidation followed by advanced reduction processes (AOP/ARP)
- UV-hydrated electron
- Sonochemical processing / ultrasound sonolysis (see Figure 15)
- Non-thermal plasma (NTP) / electrical discharge plasma (see Figure 16)
- Supercritical water oxidation (SCWO) (see Figure 17)

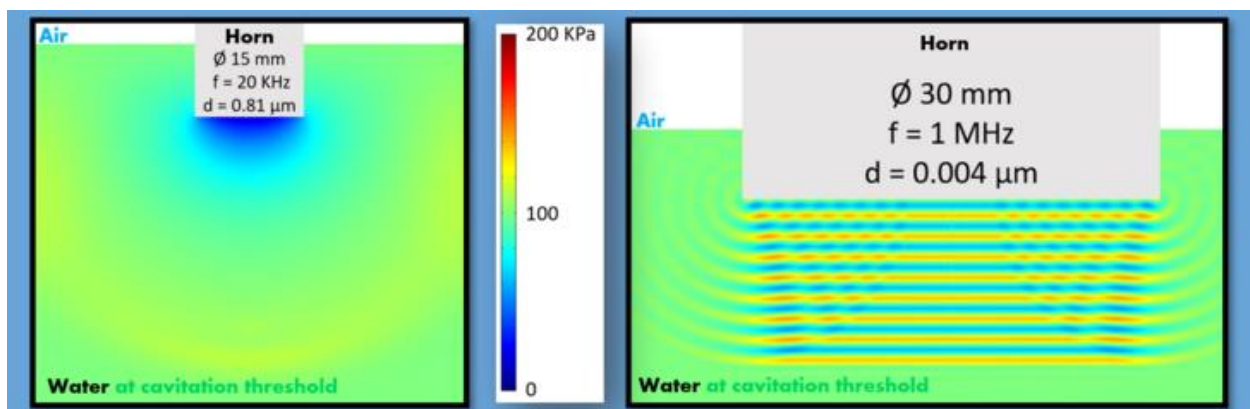


Figure 15: Modeling of ultrasonic horn sonication with better results on the right.

Source: commons.wikimedia.org/wiki/File:Ultrasonic\_horn\_cavitation\_threshold\_dimensionless\_number\_Garcia-Atance\_sonochemistry\_acoustic\_bubbles\_non\_hydrodynamic\_1309px.png, Gongafa, CC-BY-SA-4.0



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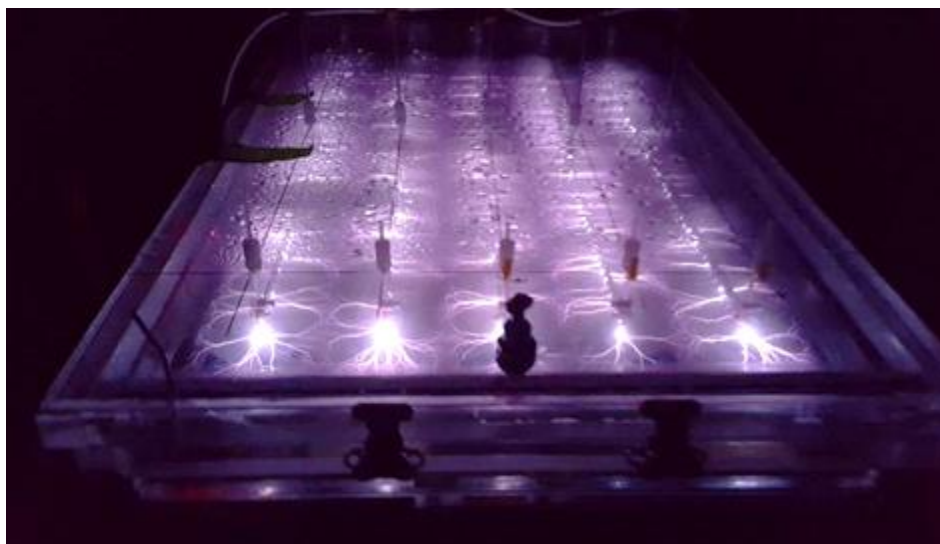


Figure 16: Electrical discharge plasma treatment system with a continuous flow of water through a tank with visible electrical arcs forming plasma.

Source: <https://www.enviro.wiki/index.php?title=File:Plasma4PFASFig2.png>, Plasma Research Laboratory, Clarkson University

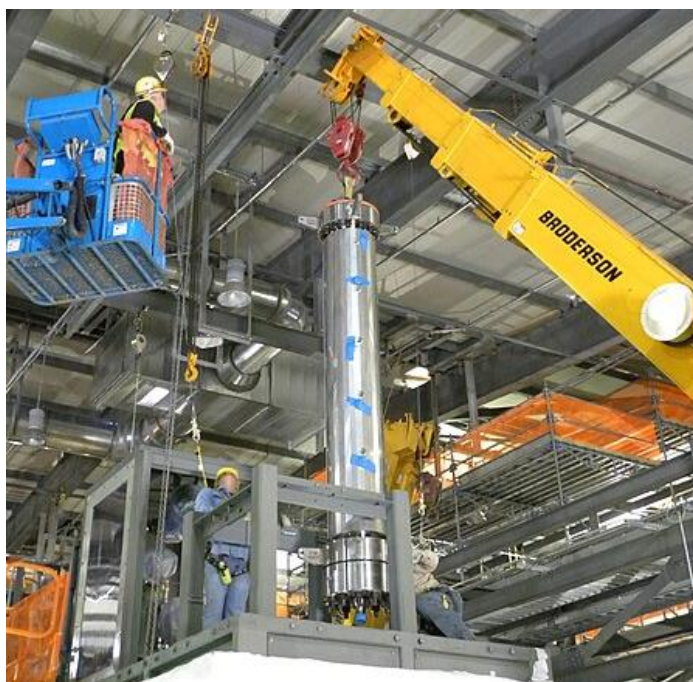


Figure 17: Supercritical water oxidation (SCWO) reactor being lowered into place.

Source: [commons.wikimedia.org/wiki/File:Blue\\_Grass\\_Chemical\\_Agent-Destruction\\_Pilot\\_Plant\\_Supercritical\\_Water\\_Oxidation\\_Processing\\_Building\\_\(12816257943\).jpg](https://commons.wikimedia.org/wiki/File:Blue_Grass_Chemical_Agent-Destruction_Pilot_Plant_Supercritical_Water_Oxidation_Processing_Building_(12816257943).jpg), CC-BY-2.0



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