

Removal of PFOA, PFOS and Other PFAS Substances Using Ion Exchange
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ABSTRACT

Recent ten-fold reduction in US EPA lifetime health advisory levels for PFOA and PFOS to <70 ppt underscores the public's increasing concern for safe drinking water. Individual states and cities have proposed even lower levels down to non-detect levels. Granular activated carbon (GAC) has been used for remediation over the years with frequent change-outs and large footprints. Recently developed selective ion exchange (IX) resins have been shown to effectively reduce such PFAS chemicals to non-detect levels with fewer change-outs and smaller footprints. This paper compares the performance and cost of IX and GAC and provides system design guidelines for use of IX technology.

INTRODUCTION

Growing health concerns persist across the globe regarding the presence of trace levels of organo-fluorine chemicals in drinking water supplies. Made up of two broad categories - perfluorinated and poly-fluorinated chemicals, they are known collectively as PFASs and commonly referred to as PFCs. In 2012 the US EPA published its first lifetime health advisories (LHA) for two of these chemicals, perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS), at 400 ppt and 200 ppt respectively. Just four years later, the combined advisory level for these two chemicals was reduced about ten-fold to 70 ppt. Individual states have pursued their own agenda, with Vermont at 20 ppt for PFOA, and Minnesota setting new advisories in May 2017 of 35 ppt for PFOAS and 27 ppt for PFOS. New Jersey and Delaware are considering limits of 14 ppt and 6 ppt for PFOA, respectively. The cities of Horsham, Warminster and Warrington in Pennsylvania, where contamination of public and private wells is most prominent, have gone a step further by setting non-detect goals for such chemicals in their drinking water supplies.

For convenience, PFCs are divided into two groups – “long chain” and “short chain” PFCs. Long chain includes carboxylic (-COOH) types such as PFOA and PFNA with ≥ 8 carbons and sulfonic type PFOS with ≥ 6 carbons.

[Table 1: Typical Short and Long Chain PFASs](#)

A study conducted by the Water Research Foundation (2016) concluded that conventional water treatment processes such as coagulation and filtration were largely ineffective in removing PFASs from water. The study concluded that NF and RO membranes were the most effective treatment technologies with greater than 90% removal efficiency, followed by granular activated carbon (GAC) and anion exchange resins with removal efficiencies ranging from 10 to 90 percent, depending on the specific PFC chemical. The study also recognized the high cost of membrane based treatment systems and the large volume of water that must be wasted.

But it should be apparent that 90% reduction as per the WRF report is not enough to achieve the non-detect (< 5 ppt) goals of consumers as concentrations in contaminated drinking water supplies can range up to 2,000 ppt and even higher. In such a case, greater than 99.5% reduction will be needed.

FIELD DATA ON PFAS REMOVAL WITH ION EXCHANGE RESIN

Fortunately, since publication of the above report, new high capacity selective resins capable of reducing PFCs to non-detect levels have recently been developed and are now in commercial use.

Pilot #1 – VOC and PFC Plume Control Well

This pilot, which started in June 2016, has been operating for over one year at time of writing of this paper and is still running.

The purpose of the pilot was to compare the performance of a proprietary selective resin developed and manufactured specifically for PFAS remediation (herein referred to generically as PFC4 resin) versus Mastercarb 1240C coconut shell based granular activated carbon (GAC) that was in use at the site at time of startup of the pilot. At the start of the ion exchange pilot, an emergency containerized mobile GAC system was already in use, treating a total water flowrate of 140-165 gpm. The total flow was first passed through an air stripper and then split to feed two trains of lead-lag GAC vessels, each 4-ft. diameter vessel containing 32 cubic feet of GAC. Total empty bed contact time (EBCT) through the first pair of GAC vessels amounted to an average 3.4 minutes, and a total of 6.8 minutes EBCT combined for all four GAC vessels. Several months after the start of the ion exchange pilot, the mobile GAC system was replaced by a permanent larger lead-lag GAC pair of vessels, each vessel containing 138 cubic feet of GAC, allowing for additional evaluation of GAC at EBCTs of 6.8 and 13.6 minutes using coconut shell GAC.

The ion exchange pilot was designed to allow comparison of three options:

1. Coconut shell GAC followed by PFC4 resin (6.8 and 1.5 minutes EBCT respectively)
2. Standalone PFC4 selective resin (2 to 3 minutes EBCT)
3. Layered bituminous GAC / PFC4 (EBCTs of 6 and 1.5 minutes respectively)

Fig. 1 is a sketch of the system in which air is injected into the well and poly-phosphoric acid is dosed for scale and corrosion control. The pilot columns are stainless steel and have a 2-inch diameter with 2 liters of media per column. Flow is controlled by needle valve and monitored and adjusted as needed for all columns by the city operator. For the polisher resin configuration, flow is taken directly from the permanent system lead GAC vessel sampling outlet and was taken from the temporary system lag GAC vessel sampling outlet. For the stand-alone resin and layered GAC/resin configurations, flow is taken from the air stripper outlet before the lead GAC vessel after initial filtration with 25 and 5 μm cartridge filters. Flow is confirmed monthly on a manual basis and totalizers are used for the polisher and standalone resin configurations.

[Fig. 1 – Pilot #1 – Resin / GAC treatment options](#)

A relatively short contact time of 1.5 minutes was chosen for the polisher resin in Option (a) to evaluate the suitability of resin for improving the performance of the existing GAC system and for later consideration in point of entry (POE) applications. Since the installation used coconut-shell GAC for its normal operation (Option a), bituminous GAC was used for Option (c) in the layered GAC/resin configuration to compare the efficiency of both types of carbon. The volumetric ratio selected for bituminous GAC to resin was 4 to 1. This would be useful for later design of commercial systems using a true layered bed as tested, or retrofitting an existing GAC system by installing a smaller lower cost polisher vessel with selective resin.

The inlet water chemistry contained six measured PFAS compounds with a total concentration of approximately 1440 ng/L (ppt) as shown in Table 2 below. A survey by the US EPA (1991) entitled “Air Stripping of Aqueous Solutions” indicates that VOC strippers typically operate at greater than 98 to 99% efficiency. So, based on the water quality shown in Table 2, the residual VOCs after the stripper can be as high as 1,000 ppt, assuming 99% removal efficiency. Therefore, compared to approximately 1,500 ppt of PFAS compounds present in the water, residual VOC can be expected to pose significant competition versus PFAS adsorption on the same micro-pore sites of the GAC.

[Table 2: Inlet water parameters for Pilot #1](#)

Water Research Foundation Report #4440 (Summers, R, et al, (2015) entitled “Removal of Volatile Organic Contaminants (VOCs) From the Groundwater Sources of Drinking Water via Granular Activated Carbon Treatment” concludes that competing solutes can negatively impact VOC breakthrough capacities by about 12% while the presence of dissolved organic matter (DOM) can reduce operating capacities for VOCs by as much as 39%. Since GAC adsorbs VOCs, similar negative impact on operating capacities for PFAS compounds can be expected.

Results of Pilot #1:

Fig. 2 shows the results for the coconut shell GAC over the latest cycle from the permanent GAC installation, which operates with EBCTs of 6.8 and 13.6 minutes for the lead and lag GAC vessels, respectively. Bed volumes shown at 6.8 minutes EBCT are based on the volume of GAC in the lead vessel while bed volumes at 13.6 minutes EBCT are based on the combined volume of GAC in the lead and lag vessels. The city’s operating philosophy for this well is to change both the lead and lag charges of GAC prior to reaching a combined level of PFOA and PFOS of 70 ppt in the effluent from the lag vessel. As can be seen, a total of approximately 10,000 bed volumes were processed before the effluent rose to 37 ppt at which point the charges of GAC in both vessels were changed out. Since startup, the GAC charges have been changed out roughly every 3 months.

[Fig. 2 - Coconut-shell GAC](#)

Fig. 3 compares the GAC results with the performance of the standalone PFC4 resin.

The PFC4 resin was initially operated at 2 minutes EBCT up to 20,000 BV when an upset in analytical results occurred, with one data point recorded at 6 ppt. At that point, a decision was taken to increase the EBCT to 6 minutes as a precaution to regain control. After the analyzed results returned to <1 ppt for two subsequent readings, a decision was taken to shorten the EBCT to 3 minutes for the duration of the test. The resin has been operating for over one year now, having treated over 155,000 bed volumes of water. Effluent leakage has started to rise, with the last result showing a 7 ppt combined level of PFOA and PFOS. Examination of the detailed data showed that PFOS was at non-detect (ND) levels for all data values, indicating all breakthrough values were due to PFOA.

[Fig. 3 - Capacity of GAC and stand-alone resin](#)

Fig. 4 shows the results of all pilot options: GAC, standalone PFC4 resin, GAC followed by polisher PFC4 resin and the layered bituminous GAC over PFC4 resin. As can be seen, the polisher resin which is downstream of the lead GAC vessel, operates at 1.5 minutes EBCT, and has treated 312,000 bed volumes of water so far, with the last data point showing the combined level of PFOA and PFOS rising to 7 ppt. Examination of the leakage values for PFOA and PFOS ex the lead GAC showed that the loading on the polisher resin was on average about 104 ppt or about 12% of the total load. The polisher resin has so far treated the effluent water from four batches of GAC. At time of writing, the resin was still running.

The layered bed consists of bituminous GAC loaded on top of PFC4 resin at a volumetric ratio of 4 to 1 and EBCTs of 6 and 1.5 minutes, respectively. At time of writing, the PFC4 resin component had treated over 216,000 bed volumes of water, while the corresponding volume of water treated by the GAC component was 54,000 bed volumes. All effluent values for combined PFOA and PFOS values were reported at less than 1 ppt.

While remediation of PFOA and PFOS is currently a prime objective, use of these two chemicals have been largely discontinued in recent years in favor of shorter chain PFASs which are also currently found in AFFF contaminated ground and surface water. Hence there is growing interest in removal of short chain compounds as well.

[Fig. 4 - Capacity of GAC, stand-alone, polisher and layered GAC/resin](#)

The ability of coconut shell GAC and the PFC4 selective resin to remove other PFASs was also evaluated. Both media successfully reduced concentrations of long-chain PFNA and PFHxS and short chain PFHpA and PFBS to ND levels. GAC capacities for the short chain PFASs ranged from 10,000 to 15,000 BV while capacities for the long chain PFASs ranged from 18,000 to 20,000 BV. At time of writing, the PFC4 resin had successfully treated 155,000 BV of water with PFNA, PFHxS and PFBS successfully reduced to ND levels for all samples. In the case of PFHpA, 131,000 BV was treated with leakage of less than 5 ppt. PFHpA was removed from 155,000 BV before leakage rose to 10 ppt. Interestingly, sulfonic acid type PFBS, was still at ND levels after 155,000 BV had been treated – see Fig.5. In summary, the PFC4 resin clearly outperformed the coconut shell based GAC for all six PFASs evaluated, showing at least 8 to 20 times higher capacity to non-detect levels while operating at about ¼ to ½ of the EBCT used for GAC.

[Fig. 5 - Capacity of GAC and stand-alone PFC4 resin for PFBS](#)

Municipal Drinking Water System #1 (Horsham):

A combination of bituminous GAC and PFC4 resin are used to remove PFASs from drinking water wells at City of Horsham, PA. Pennsylvania Department of Environmental Protection (DEP) has issued the first permit for such treatment in which PFC4 resin has been in use as a polishing step in water treated by GAC since early 2017. The polisher resin was installed to help the city achieve its declared goal of supplying all drinking water supplies to consumers at non-detect levels for PFASs. Based on successful piloting of the PFC4 resin at 1.5 minutes EBCT at another facility, a similar range of EBCT was chosen for the design and operation of this system.

Well water flowing at an average of 53 to 58 gpm is first passed through 5 μ m cartridge filters then through two 2.5-ft diameter vessels in series each containing 20 cubic feet of bituminous GAC (B GAC) followed by a single 2.5-ft diameter vessel containing 20 cubic feet of PFC4 resin – see Fig. 6. EBCT for the two GAC vessels combined is 5.6 minutes while sample points placed at the mid-point and exit of the resin bed allow for resin evaluation at EBCTs corresponding to 1.4 and 2.8 minutes, respectively.

[Fig. 6 – Flow Diagram for Municipal Drinking Water #1 \(Horsham\)](#)

Seven PFASs are present in the inlet water supply with total concentration of approximately 104 ng/L (ppt) as shown in Table 3 below:

[Table 3: Inlet water parameters](#)

Results for Municipal Drinking System #1 (Horsham):

Fig. 7 shows treatment results for the lead and lag GAC vessels and the PFC4 polisher resin. Note that bed volumes for the lead GAC vessel are based on the volume of GAC in the lead vessel while bed volumes shown for the lag GAC vessel are based on the combined volume of GAC in both vessels, with operation at 2.8 and 5.6 minutes average EBCT, respectively. Approximately 19,000 bed volumes were treated by the combined volume of GAC before the combined concentration of PFOA and PFOS rose to 4.6 ppt in the effluent of the lag GAC vessel (76 days operation). Under the non-detect criteria adopted by the city, it would have been necessary at that point to replace both charges of GAC. But, with the polisher resin in place, a decision was taken to continue operation of the GAC vessels without changing out the GAC charges. So far, 47,000 BV of water has been by the combined volume of GAC. The concentration of PFOA + PFOS has risen to 30 ppt in the effluent from the lag GAC vessel, amounting to about 50% breakthrough based on combined influent level of 61 ppt.

At the same time, non-detect levels for PFOA and PFOS were still being measured at both the mid-point and exit points of the resin bed, corresponding to EBCTs of 1.4 and 2.8 minutes and to bed volumes treated of 168,000 and 84,000, respectively.

Removal of other PFASs was also measured. After 19,000 bed volumes had been treated by the combined volume of GAC, leakages were measured at 7%, 14%, 19% and 33% for PFHxS, PFBS, PFHpA, and PFHxA, respectively. Simultaneously, leakage for each of these PFAS compounds was at ND levels, from both the mid-point and effluent sample points of the resin bed.

[Fig. 7 – B GAC and PFC4 resin performance](#)

DISCUSSION OF RESULTS

Pilot #1, demonstrated a capacity for PFOA+ PFOS removal of approximately 10,000 BV when using coconut shell GAC in a lead-lag pair of vessels with a total of 13.6 minutes EBCT to a 35 ppt breakthrough point. In contrast, the single vessel of PFC4 resin, operating with an average of 2 to 3 minutes EBCT, treated approximately 155,000 BV to 7 ppt breakthrough.

If the resin is installed in a similar pair of lead-lag vessels as used for the GAC system, we expect additional operating and cost advantages. The lead resin vessel can be operated to a higher breakpoint, or the lag resin vessel can be operated to achieve non-detect leakage while the operating capacity of the lead vessel can be optimized. By monitoring leakage from the lead vessel, resin change-out from the lead vessel can be scheduled while maintaining non-detectable leakage from the lag vessel. Extrapolation of the pilot data indicates a capacity close to 240,000 bed volumes can be obtained when operating to a 35 ppt breakpoint. Such design and operation would represent a fairer comparison of GAC and resin, with both media using a similar lead-lag configuration.

Bituminous GAC in the municipal drinking water system, at 5.6 minutes EBCT, was shown to treat 19,000 BV of water before breakthrough of PFOA and PFOS at 4.6 ppt combined. In general, the higher operating capacity of bituminous over coconut shell GAC seems to agree with the findings of others.

As indicated previously, short chain PFAS compounds may eventually become treatment targets due to health concerns. GAC operating capacities were shown to be lower than for PFOA and PFOS. Capacity for PFHpA was 9,600 BVs to 8% break, while capacity for PFHxS was 8,000 BVs to 1% leakage.

In contrast, PFC4 resin showed about 10 to 15 times higher operating capacity than for GAC, with 109,000 BVs for PFHpA to 8% leakage and more than 155,000 BVs for PFHxS and PFBS.

DESIGN GUIDELINES

The design of a PFAS remediation system using selective ion exchange resin must be both cost-effective and efficient at reducing PFASs to target values. Since the concentrations of PFASs in contaminated water vary widely, (e.g. 50 to 100,000 ppt), piloting is usually recommended to verify the effectiveness of a particular option. Since piloting can consume considerable time and resources, reliable modeling of the process can allow quicker assessments and fast decisions.

The authors have started the development of such a model for selective resins in which inlet water quality parameters are used to predict operating capacity and leakage. In the case of PFASs, input of the anion composition of the water along with concentrations of the individual PFASs are essential inputs.

Fig. 8 is an example of such modeling for a relatively high concentration of 2000 ppt of PFOA. If targeting removal of PFOA down to 70 ppt in the treated water, it is necessary to determine how many vessels of resin must be placed in series to efficiently reduce PFOA to the target value. It is also important to balance capital and operating cost for the system. Hence, modeling of the type being discussed, can be quite helpful in optimizing the capital and operating costs. For example, from Fig. 8, it is easy to see that it would be possible to reduce PFOA to about 70 ppt if the first vessel is operated to about 50% breakpoint, while the second vessel is used to polish the PFOA concentration to <70 ppt. If the designer is targeting non-detect concentration of PFOA in the treated water, another choice would be to operate the first vessel to 20% breakpoint. At that point, the effluent from the lag vessel is predicted to be close to non-detect level. These two assessments indicate that it will likely cost about 20% more to operate to a non-detect level versus to 70 ppt.

Once the minimum number of vessels to be placed in series is determined, the design for each vessel is straightforward like that used for general ion exchange applications. Fig. 9 shows the typical configuration with acceptable linear velocities ranging from 6 to 12 gpm/ft² of resin bed area (15 to 30 m/h) and with resin bed depth at a minimum of 36 inches (or about 0.9 m).

Actual height of the resin will depend in part on the desired EBCT and desired service life of each charge of resin. An example design for a flowrate of 200 gpm with a desired EBCT of 3 minutes will help clarify. For 3 minutes EBCT, the volume of resin per vessel = 200 gpm x 3 minutes / (7.48 gallons/ft³) = 80 ft³. Choosing a linear velocity of approximately 10 gpm/ft² would equate to a vessel cross-sectional area of approximately 200 / 10 = 20 ft². The nearest commercial diameter is 5 feet with a cross-sectional area of 19.63 ft². Therefore, resin bed depth would equate to 80 / 19.63 = 4 feet.

[Fig. 8 – Proprietary modeling software for PFAS remediation](#)

Fig. 10 shows a design option for using GAC in the lead vessel and resin in the lag vessel as a polisher. This design assumes a smaller resin polisher vessel is used compared to the GAC vessel. Typical design linear velocity for ranges from 2 to 6 gpm/ft² of bed area, therefore the diameter of the GAC vessels will normally be significantly larger, say 1.5 to 2 times larger diameter than used for the resin.

GAC system design routinely provides an extra storage tank and extra pumps for use during periodic backwashing of the GAC. These are usually needed because the linear velocity needed for backwashing can be about 4 to 5 times higher than the linear velocity used during the service phase (e.g. 15 gpm/ft² vs 4 gpm/ft²). This adds extra cost and requires a larger footprint. Routine backwashing is not recommended as this is known to destroy the chromatographic loading profile of the targeted contaminant and potentially lead to early breakthrough. Only at start-up is backwash needed to

properly classify the resin bed and so minimize pressure drop across the resin bed during the service phase. Installation of an appropriately sized bag filter ahead of the ion exchange vessels is highly recommended for control of any incoming suspended solids.

For retro-fitting resin into an existing GAC treatment systems, it is important to verify that the bottom distributor is fitted with slot sizes that are no greater than 60 mesh (250 μm) so as not to lose IX resin. If incoming TOC is relatively high (e.g. 2 to 6 ppm), consideration can be given to installing 20x40 mesh GAC layered on top of the resin in the same vessel with care being taken to properly backwash and classify the resin and carbon components, recognizing that resin needs about 5 times lower linear velocity to achieve the typical 50% expansion of the bed.

[Fig. 9 – Typical Lead-Lag Vessel Design for PFAS remediation using Selective Resin](#)

[Fig. 10 – System Design with GAC in Lead and resin in the Lag vessel](#)

COST COMPARISON

Table 4 below provides a comparison of lead-lag vessels containing (a) GAC >> GAC, (b) GAC >> PFC4, and (c) PFC4 >> PFC4 resin. Capacity values are based on results from Pilot #1. In options (a) and (c), when the lead vessel is exhausted, the lag vessel is moved into the lead position, and the exhausted media is replaced by fresh media.

The vessel with fresh media is placed in the lag position. For option (b), both the GAC and the resin are replaced when the polisher resin is exhausted. The cost comparison is for a flow of 500 gpm, with inlet PFAS concentration of 1500 ppt, and with a target of reducing the PFAS content of the treated water to < 70 ppt. Capital and operating cost to treat 1000 gallons of water was lowest for option (c) at \$0.40 while option (b) is second lowest in cost at \$0.58.

Operating cost for option (c) was \$0.82, or about 50% higher than the resin-only option. While option (c) is the lowest cost option, attention should also be paid to option (b) since this option allows for retrofit of an existing GAC system with resin used as polisher.

[Table 4: Cost Comparison Example, 500 gpm, 263 MM gal/yr.](#)

SUMMARY

Pilot and commercial testing showed remarkably higher operating capacity and faster kinetics for the PFAS selective resin, PFC4, compared to coconut shell and bituminous type GAC. Coconut shell GAC operating at 13.6 minutes EBCT was shown to treat 10,000 bed volumes of water before a breakpoint of 35 ppt for combined PFOA and PFOS. The PFC4 resin operating at 4.5 times shorter EBCT (i.e. 3 minutes) treated 155,000 bed volumes to 7 ppt break. By extrapolation, about 240,000 bed volumes were expected to be treated to 35 ppt break, representing 15 to 24 times higher operating capacity than GAC.

Bituminous GAC, operating at 5.6 minutes EBCT, showed a capacity of 19,000 bed volumes to a 4.6 ppt break. The PFC4 resin, installed as a polisher to the bituminous GAC, with EBCT of 1.4 minutes, had treated 168,000 bed volumes of water to non-detect levels at the time of writing. The bituminous GAC, which was left running, had at that point treated 47,000 bed volumes of water to a 30 ppt break. Thus, the capacity of the GAC was extended to about 2.5 times its standalone capacity by installing the PFC4 resin as a polisher.

Capital and operating cost comparison of various system designs showed that a lead-lag pair of vessels with PFC4 resin was the most cost-effective solution for the waters evaluated. The second most cost effective would be a lead-lag pair of vessels, with GAC in the lead and PFC4 resin as a polisher, costing about 45% more to operate. Least cost effective was a lead-lag pair of GAC vessels, costing 100% more to operate vs the option with resin only.

With GAC, the extra footprint and headspace required can be 50% or higher versus a selective resin like PFC4. In crowded residential neighborhoods, space restrictions and aesthetic considerations can make a more compact longer-running resin based system more desirable. Another important consideration is that GAC systems are usually designed with extra pumps and storage vessels for routine backwashing since backwashing is usually done at linear velocities that are about 3 to 5 times higher than the velocities during service. With resin, only initial backwashing is needed at startup to classify the resin, as bag filters are generally used ahead of the vessels to control suspended solids. Even so, the linear velocity for the backwash is about $\frac{1}{4}$ of that needed during service (e.g. 2.5 vs 10 gpm/ft²), making it unnecessary to add extra pumps and storage tanks, simplifying the design and reducing cost.

For existing GAC systems, it may be more cost-effective to retrofit by installing a much smaller polisher resin vessel downstream of the GAC system, or alternatively by replacing the charge of GAC in the lag vessel with PFC4. If short chain PFASs like PFBS and PFHpA become targets for remediation in the future, then PFC4 would be an ideal solution compared to GAC. The cases presented here show that in general the PFC4 resin is more cost-effective than GAC, with 8 to 20 times higher operating capacities.

Note: The generic name “PFC4” used in this paper refers to Purofine[®] PFA694E resin.

REFERENCES

AWWA (2016). Perfluorinated Compounds - Prevalence and Assessment in Drinking Water. AWWA,
<https://www.awwa.org/Portals/0/files/resources/water%20knowledge/rc%20healtheffects/AWWAPFCFactSheetPrevalenceandAssessment.pdf>

Remediation and Reuse Focus Group (2015, August). Perfluorinated Chemicals (PFCs): Perfluorooctanoic Acid (PFOA) & Perfluorooctane Sulfonate (PFOS). Interstate Technology & Regulatory Council.

Russell, H., Matthews, J., and Sewell, G. (1992). TCE Removal from Contaminated Soil and Ground Water. EPA 540-S-92-002.

<https://www.epa.gov/remedytech/technical-support-project-cleaning-contaminated-sites-issue-papers>.

Summers, R., Kempisty, D., Dougherty, T., and Knappe, D. (2015). Removal of Volatile Organic Contaminants (VOCs) From the Groundwater Sources of Drinking Water via Granular Activated Carbon Treatment. Water Research Foundation, Report #4440. Retrieved from <http://www.waterrf.org/PublicReportLibrary/4440.pdf>

United States Environmental Protection Agency (1991). Control of Air Emissions From Materials Handling During Remediation. USEPA, Engineering Bulletin. Retrieved from: <https://semspub.epa.gov/work/05/100066.pdf>

United States Environmental Protection Agency (July 2017). PFOA Stewardship Program. Retrieved from <https://www.epa.gov/assessing-and-managing-chemicals-under-tsca/risk-management-and-polyfluoroalkyl-substances-pfass#tab-3>

Dickenson, Eric, C.V., and Higgins, Christopher (2016). Treatment Mitigation Strategies for Poly- and Perfluoroalkyl Substances. Water Research Foundation. Project Report #4322. Retrieved from: <http://www.waterrf.org/PublicReportLibrary/4322.pdf>

Xindi C. Hu, et al. (2016). Detection of Poly- and Perfluoroalkyl Substances (PFASs) in U.S. Drinking Water Linked to Industrial Sites, Military Fire Training Areas, and Wastewater Treatment Plants. *Sunderland Environmental Science & Technology, Letters* 2016 3 (10), 344-350 DOI: 10.1021/acs.estlett.6b00260