April 19, 2022

Letter of Transmittal

University of Pennsylvania, School of Engineering and Applied Science Department of Chemical and Biomolecular Engineering 220 South 33rd Street Philadelphia, PA 19104

Dear Dr. Miriam Wattenbarger and Professor Bruce Vrana,

This report proposes two process designs that reduce the concentration of carcinogenic per- and polyfluoroalkyl substances (PFAS) from 4500 parts per trillion to 70 parts per trillion in 2.33 million gallons of water per day. The first process design follows a traditional granular activated carbon (GAC) based treatment scheme wherein PFAS is adsorbed onto carbon particles. The second process design scales up a field scale demonstration of PFAS decomposition using a gas-diffusion enhanced plasma reactor. Both plants are designed to ensure that the health risk to the consumer is minimized.

An economic analysis of this process yields a capital cost estimate of \$6.7MM for the GAC-based design and a capital cost estimate of \$14.8MM for the plasma-based design. However, the annual operating cost of the plasma-based design (\$5.9MM) is slightly lower than that of the GAC-based design (\$6.3MM). Furthermore, the plasma-based design generates 254 fewer metric tons of CO_2e and has the additional environmental benefit of permanently removing PFAS from the hydrologic cycle. Therefore, the plasma-based design is recommended as superior economic and environmental choice in the long run. Potential improvements to plasma technology and increasingly stringent environmental regulations also present future opportunities for improving the cost favorability of the plasma-based design.

Thank you so much for all the assistance with this senior design project. We greatly appreciate your guidance and support throughout this past semester.

Sincerely,

Isabel Gutierrez

Ryan Lam

Daniel Nelson

Replacing Conventional PFAS Water

Treatment by GAC with Plasma

Treatment to Improve Sustainability

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1. Abstract

Per and poly-fluoroalkylated substances (PFAS) are carcinogenic compounds which make their way into water systems and are difficult to remove. Currently, PFAS is removed from drinking water at an industrial scale using granular activated carbon (GAC), a solid particulate which removes PFAS from water through adsorption. However, in recent years, a new method utilizing a plasma reactor to mineralize the PFAS has been designed and tested at small scales. This project aims to increase the scale of existing plasma reactor designs to treat the same volumes of water that traditional GAC plants are capable of treating. A specific well in New Castle County, Delaware was identified as the treatment site, and both processes were designed to treat 2.33 million gallons of water per day by reducing the PFAS concentration from 4,500 parts per trillion to the US EPA health advisory level of 70 parts per trillion. The GAC process was estimated to have a capital cost of \$6.73 million and an operational cost of \$6.32 million each year. The plasma process was estimated to have a capital cost of \$14.8 million and an operational cost of \$5.93 million each year. Based on a number of economic and environmental factors, this project found that the plasma system was a more effective and sustainable method for achieving the desired reduction in PFAS concentration.

Disciplines

Biochemical and Biomolecular Engineering | Chemical Engineering | Civil Engineering | Environmental Engineering | Engineering

2. Introduction and Objective Time Chart

2.1 Project Background

Per- and polyfluoroalkyl substances (PFAS) are a class of anthropogenic chemicals, whose extremely strong carbon-fluorine backbone (C-F) and long environmental half-life have branded them "forever chemicals." In the late 1940s, PFOA, or perfluorooctanoic acid, a class of PFAS created by 3M, was introduced as a component of non-stick cookware due to its thermal stability and waterproofing abilities (3M, 2022). By the 1950s, DuPont was also using PFAS for cookware. Other types of PFAS, including PFOS, PFBS, and PFHxS, also became widely used for products such as ski wax, personal care products, and household cleaning products, with some still in use today.

After a deadly fire in a U.S. Navy aircraft carrier in the late 1960s, however, scientists found an innovative way to use the unique properties of PFAS in firefighting foam (3M 2022). As firefighting foam was dispensed, the PFAS created an aqueous film that was effective in extinguishing fires started from gasoline, oil, and jet fuel. As these PFAS-containing firefighting foams became widely utilized in airports, airplanes, and military bases, bodies of water near these sites subsequently began to show high levels of PFAS contamination. Studies that were conducted on populations surrounding a DuPont Teflon plant showed high numbers of PFOA in their bloodstream showed high rates of various kinds of cancer. Besides affecting human populations, these high levels of PFAS also began to have negative effects on animal populations. Due to concerns from the EPA, many companies began a gradual phase-out of these chemicals in 2002. In 2016, the EPA officially declared regulations for combined PFOA and PFOS levels in water as 70 parts per trillion (ppt), at which point most companies began their

phase-out of PFAS. Apart from federal regulations, various states have also begun setting lower limits; New York has set one of the strictest limits at 10 ppt for each (PFOA and PFOS).

2.2 Project Goals and Scope

This project aims to compare the overall efficiency, cost, and sustainability of two different processes, one existing and one novel, for removing PFAS in water by implementing filtration systems in New Castle, Delaware. Due to its proximity to a commercial airport and military base, the four wells in New Castle County have a concentration of PFOS that reaches 720 parts per trillion (ppt) and a concentration of PFOA that reaches 3780 ppt. The firefighting foams that have been historically used on site were manufactured to only contain PFOA and PFOS (Appendix A). Both PFAS removal designs have been scaled to treat 2.33 million gallons per day.

The existing process in place is Granular Activated Carbon (GAC). GAC is commonly used to remove pollutants from water, as it allows for various pollutants to adsorb to the surface of the GAC. PFAS specifically presents an issue due to its reputation as a "forever chemical." Once the PFAS has been adsorbed onto the surface of the GAC, the GAC reaches a point in which it can no longer adsorb any more PFAS. After this point, the GAC must be thermally regenerated for further use. This thermal regeneration includes heating the used GAC to extremely high temperatures to dissociate the PFAS from the surface. Although this thermally regenerated GAC can be reused, the conditions in which it is heated typically reduce its adsorption capacity upon regeneration. As such, spent GAC can only be regenerated a limited number of times before it must either be sent to a landfill or incinerated, upon which PFAS may then leak back into the hydrologic cycle. The goal of this project is to design a process that would ensure adequate removal of PFAS from the water stream without causing further contamination or adverse environmental effects.

The novel process that the team chose to model involved the use of plasma technology. This technology utilizes argon gas that is bubbled through the PFAS-contaminated water to bring the PFAS to the surface of the water, as PFAS is a surfactant and is uniquely both hydrophobic and hydrophilic. When the electrons of the plasma come into contact with the surface of the PFAS, it is destroyed. Additionally, when the plasma comes into contact with the vaporized water, it creates reductive species which also can destroy the PFAS.

2.3 Objective Time Chart

Figure 2.1 shows the timeline for completion of the project. The team focused on compiling all of the necessary preliminary information needed to begin calculations in January. The team created block flow diagrams, began writing the report, and, at the end of January, began writing their report. By the beginning of February, the team worked on making initial material balances and reviewing these with consultants and faculty in order to ensure that calculations were done correctly and that any assumptions made were justified. Beginning mid-February, the team started to prepare their oral presentations that would be due early in March. Once the oral presentation was completed, feedback was used in order to verify the equipment design chosen. The remainder of March was used to verify final equipment design and complete finances, while simultaneously making sure to work on report writing. The beginning of April, the team focused the majority of efforts on compiling financial information on equipment and other process factors. Finally, the team focused mid-April on making sure to work on and complete report writing by the end of the deadline.

Week of	Objective	Due Dates
17-	an Complete block flow diagram, identify major challenges for future weeks	
24	an Create final report framework/table of contents	
31-	an Verify block flow diagram, begin creating PFD and material balance	
7-F	eb continue research and writing introduction	
14-F	eb Complete base case material balance and computer drawn PFD	
21-F	eb Prepare for oral progress report	Base Case Material Balance and Computer Drawn PFD Due (2/22)
28-F	eb Identify every piece of equipment needed	15 minute Oral Progress Report Due (3/1)
7-N	Iar Verify with equipment identification	
14-N	Iar Work on equipment design	
21-N	lar Work on finances	
28-N	Iar Complete and verify equipment design	Major Equipment Design (3/29)
4-4	pr Complete and verify finances	Finances Completed (4/5)
11-4	pr Writing and editing	
18-4	pr Preparing presentation	Final Written Reports Due (4/19)
25-4	pr Practice presentation	Final Presentations (4/26)

Figure 2.1. Objective Time Chart for the PFAS Water Treatment Process Design Project.

3. Innovation Map



Figure 3.1. Innovation Map for GAC-based and Plasma-based Treatment Designs.

4. Market and Competitive Analysis

Ion exchange resin, granular activated carbon, and reverse osmosis technologies are the current most prominent for removal of PFAS from water on the market, and all were studied for the scope of this project.

In comparing these methods to the plasma reactor, environmental and economic factors were considered. The ion exchange resin method for removal of PFAS in water is one of the emerging technologies for PFAS that has considerable promise for efficient removal. As such, this process has not proven to be efficient for full-scale implementation. Furthermore, it would require the purchase of resin, which is more expensive than GAC on a pound-to-pound basis, but it requires less frequent change-outs. That being said, it has still not proven to be a more cost-effective alternative to GAC as full-scale implementation has not been completed (American Water Works Association, 2020).

The other highly researched process for PFAS removal in water is reverse osmosis technology. This process is more effective than both ion exchange and GAC in removing PFAS from water. Reverse osmosis membranes can remove 99% of PFAS from water. Although efficient in PFAS removal, this process is expensive and creates a highly concentrated waste that cannot be destroyed and must be disposed of as toxic waste. Therefore, in the long term this process is less sustainable.

The last method that we chose for this project scope is the GAC method because in terms of removal, this method is currently the most prominent in the industry. Of the methods, it is the least expensive. Because the project goal was to design a cost effective alternative to a process currently in place for GAC removal.

5. Customer Requirements

The primary goal of this project is to reduce the concentration of PFOS and PFOA to the US EPA's designated health advisory levels of 70 parts per trillion. As of the submission of this report, the state of Delaware follows this non-enforceable concentration limit. However, other states have adopted stricter, enforceable regulations, both in terms of lower concentration limits as well as in terms of additional PFAS species being regulated. For example, Michigan enforces an 6 part per trillion maximum contaminant level (MCL) on perfluorononanoic acid (PFNA), which is another carcinogenic PFAS compound.

6. Competitive Patent Analysis

The following section discusses two pending patent applications with technologies similar to those incorporated within the plasma-based water treatment plant design described within this report. It also discusses an existing patent for a GAC-based water treatment plant design that includes onsite regeneration of GAC.

Patent application number US2020012648 held by Evoqua Water Technologies LLC (Appendix A) describes a PFAS water treatment scheme using where either nanofiltration is used to preconcentrate a PFAS contaminated water stream prior to PFAS destruction. The patent application primarily specifies a nanofiltration preconcentration process and an electrochemical process wherein both the cathode and anode are placed within the liquid phase to promote PFAS destruction. However, it also notes that some embodiments may use ion exchange separation or use plasma-based advanced oxidation processes. Key innovations in this patent include the implementation of a heat exchanger to maintain plasma reactor efficiency as well as the specification of argon gas diffusion enhanced-plasma reactor design. These key innovations are likely sufficient to avoid infringement of Evoqua's patent if it is approved. Regardless, the local governing bodies of New Castle County, Delaware may consider licensing Evoqua's patent or commissioning Evoqua to assist in the design and construction of such a plasma-based treatment plant given their established history and expertise within the water treatment industry.

Patent application number US202017027386 submitted by James Garber describes a method of stacking a plasma treatment system with multiple horizontal channels (Appendix A), similar to the proposed plasma reactor design described in this report. While not yet approved, the licensure of this patent, if necessary, could also prove to be a reasonable method of reducing the amount of areal building footprint required for the plasma reactor.

Patent number US201916698360 held by Onvector LLC describes a PFAS water treatment plant design using GAC based separation technology coupled with on site plasma regeneration of the GAC (Appendix A). While the process of using GAC adsorption columns to remove PFAS from water is similar to the process outlined in this report, the design choice to outsource the GAC regeneration process to Calgon Corporation, which employs thermal instead of plasma regeneration, is sufficient to avoid copyright infringement of this patent. Not only does this avoid additional patent licensure fees but it also reduces the capital overhead required for the construction of onsite GAC regeneration facilities.

7. Preliminary Process Synthesis

Originally, the problem statement considered using thermal regeneration to enable the reuse of the GAC. This process would entail taking the fouled GAC and heating it to a temperature of about 1000 °C. This would allow multiple uses of the fouled GAC. However, after speaking with Sarah Golden, a representative from H2M architects + engineers, it was explained that water treatment plants with GAC units installed in them do not typically complete their own thermal regeneration. Instead, the fouled GAC is sent to the manufacturer, who will then thermally regenerate the GAC and resell it to the consumer.

The other considerations in the GAC process were the other types of adsorption media that could be used. Three types of GAC were researched: wood, bituminous, and coconut GAC. Research has shown that bituminous GAC is most effective in removing PFAS from water. The next important decision was for the best carbon product to choose for the initial concentrations of PFAS. For treatment of PFOA and PFOS at the concentrations listed, the most effective carbon product recommended by the supplier, Calgon Carbon Corporation, is the Filtrasorb-400.

The removal of PFAS through the GAC process occurs in two M12-40 parallel vessels also supplied by Calgon Carbon Corporation. This supplier explained that the industry standard for treatment using GAC is to operate multiple vessels in series, as this maximizes the mass transfer zone. However, the supplier also advised that the volume of water treated in this project scope makes operating the vessels in parallel a preferred choice.

For other projects involving the removal of other contaminants through the GAC process, isotherm data is typically provided by the supplier. This isotherm data is obtained from experimental data, and is then given to the customer to give a carbon adsorption rate based on the concentration of contaminant. Because PFAS is an "emerging contaminant," this isotherm data is

not available, and therefore a bed volume estimate is given by the supplier. This estimate gives the approximate volume of water treated before detection surpassing the acceptable limit of the contaminant in the effluent stream.

Once the pounds of carbon consumed per million gallons of water treated were calculated, the pounds of carbon consumed per day using the volumetric flow rate were determined. This number gave an estimate for the days or years until breakthrough (Appendix B).

A metric used to compare existing and emerging technologies was the environmental impact of each process. The reasoning behind completing in-house thermal regeneration was to be able to trace the PFAS from its source to its elimination. Typically, spent GAC that has adsorbed the maximum amount of PFAS possible is sent to a landfill or incinerator to be disposed of.



Figure 7.1: Block flow diagram for the GAC process.

In the past, research surrounding the treatment of PFAS contaminated drinking water with a plasma degradation reaction fed the water directly into the plasma reactor. However, this project design departs somewhat from that approach due to the scale of operation. Due to the volume of water treated in the water treatment plant, the authors of this report have opted to use a preconcentration stage prior to reactor treatment. In doing so, a smaller, and more concentrated, volume of water is sent to the plasma reactor. Because the cost of treatment scales much more strongly with the volume of water that needs to be treated than with the magnitude of concentration of PFAS, the inclusion of a preconcentration operation results in drastic reduction in electricity requirements and overall cost. Estimates based on Franke et al. (2019) and Nau-Hix et al. (2021) suggest an operational cost savings of 87% with preconcentration as compared to without preconcentration.

In evaluating options for preconcentration of the influent stream to be fed into the plasma reactor, ion exchange resin and reverse osmosis technology were alternatively considered before deciding to pursue nanofiltration as the technology of choice. Both of the alternative options would have been *in-situ* replacements for the nanofiltration unit operation. Using reverse osmosis technology was determined to be a financially inferior choice to nanofiltration. While both membrane filtration technologies would be able to achieve the minimum separation of PFAS from influent water as specified by the USEPA, with nanofiltration achieving PFAS removal of greater than 95% and reverse osmosis achieving PFAS removal of greater than 95% and reverse osmosis achieving PFAS removal of greater than 95% and reverse osmosis technology is much more expensive because of the relatively high operations and maintenance costs due to the influent head pressure required to drive separation (American Water Works Association, 2020). Thus, in accordance with other literature reviews, nanofiltration was selected as the more cost-effective choice among membrane separation technologies (Rahman et al., 2014).

Using a regenerable ion exchange resin has been used successfully in the past to preconcentrate PFAS containing water streams for subsequent degradation treatment with plasma

reactor technology on the field scale (Singh et al., 2020), but it has not yet been shown to be cost effective at the plant scale. While the operations and maintenance cost of the ion exchange columns rival those of nanofiltration technology, in order to destroy the PFAS from IX resin, the resin would need to be washed with a methanol-NaCl solution to desorb the PFAS from the resin. Before this wash solution could be processed by the plasma reactor unit, the solution would require two separate distillation steps – one to remove the alcohol and one to remove the salt (Figure 7.2). Such a distillation train would incur significant energy costs, as tabulated in Table 7.1, making nanofiltration the most cost-competitive option when considering holistic preconcentration costs. Calculations for both ion exchange and nanofiltration systems are normalized to an influent water flow rate of 2.33 million gallons per day. The operation cost of the ion exchange system includes the cost of replacement media, labor, spent media profiling, and regeneration (ITRC, 2020). The operating cost of the nanofiltration system includes the cost of pumping energy, replacement membranes, prefilters, antiscalant, pH adjustment media, and membrane maintenance costs (Franke et al., 2021). Distillation costs were calculated as only equal to the cost of energy which was determined through modeling with ASPEN Plus and assumed to have a cost of 7.42 cents/kWh (Appendix B).



Figure 7.2: Block flow diagram for alternative ion exchange resin preconcentration process. The addition of the distillation columns to remove the methanol and salt make this process less cost-competitive than nanofiltration.

Table 7.1. Summarized operational costs of ion exchange alternative as compared to nanofiltration.

Treatment Option	Operating Cost per Day	Methanol Distillation Cost per Day	Total
Ion Exchange (ITRC, 2020)	\$373	\$1491	\$1864
Nanofiltration (Franke et al., 2021)	\$1005	N/A	\$1005

Thus, given the cheaper operational cost for nanofiltration, the following block flow diagram was chosen to advance the design of this report's plasma-based water treatment plant. The most notable differences in comparing Figure 7.3 and Figure 7.2 include the addition of a heat exchanger to avoid vaporization of water within the plasma reactor and additional holding tanks used to run the plasma reactor as a semi-batch process, as well as the removal of the ion exchange and distillation columns.



Figure 7.3. Final block flow diagram for the plasma-based water treatment design.

8. Assembly of Database

8.1 GAC Hazards

The GAC process provides safe drinking water, but there are precautions necessary when carrying out the process for the safety of plant workers. Wet granular activated carbon depletes oxygen from the atmosphere when it is kept in an enclosed space. Workers should wear an approved respirator in the case that increased risk occurs.

8.2 Plasma Reactor Kinetics

The plasma reactor was assumed to follow pseudo-first order rate kinetics according to the following rate equation (Stratton et al., 2015).

$$-\frac{dC_s}{dt} = \frac{A}{V \cdot \left(\frac{1}{k_m} + \frac{1}{k'}\right)} = k_{obs} \cdot C_s$$

where

While similar plasma reactors treating water with similar levels of PFAS contamination have operated with k_{obs} in the range of .04 to .067 min⁻¹ (Singh et al., 2019; Palma et al., 2021), since

the scaled up reactor design implemented within this report most closely follows that of Nau-Hix et al. (2021), a $k_{obs} = .05 \text{ min}^{-1}$ was used.

8.3 NF90 Specifications

NF90 was chosen as a membrane for preconcentration due to its high rate of rejection of notable PFAS species, as well as its high rate of liquid recovery at achievable pressures.

NF90 has a 99.8% rejection rate of PFOA and PFOS (Soriano et al., 2019), meaning that only 0.02% of the PFAS in the groundwater will enter the untreated permeate stream.

NF90 has a salt rejection rate of 93% (Kreig et al., 2005), which, in this process, will cause a large buildup of salt in the retentate stream.

When at an operating pressure of 15 bar, an NF90 membrane can reach a liquid recovery rate of 70%, meaning that 70% of the liquid feed leaves the system as permeate(Schaefer et al., 2005).

8.4: PFOA and PFOS Safety Hazards

PFOA and PFOS are dangerous chemicals which can cause liver damage and potentially cancer, as well as lead to birth defects in the children of those exposed (Appendix C). High-concentration solutions of PFOA and PFOS, as well as solid matter with adsorbed PFOA and PFOS, should be handled with care, using protective clothing and respirators. Handling should, if necessary, be done in open air rather than in an enclosed space.

8.5: Hydrochloric Acid (HCl) Safety Hazards

HCl is a dangerous acid which is used in the membrane cleaning process and which can pose corrosive danger to both operators and equipment(Appendix C). Protective clothing, including eye protection, should be used while handling, and it should be handled in open air or other well-ventilated conditions. HCl should only be stored in containers which are resistant to acid corrosion, such as the original container, or fiberglass-reenforced plastic containers (S.E.O. Team, 2019).

Hastelloy C is a metal alloy which is high in nickel and chromium, and has a low iron content, making it more resistant to acid corrosion than steel. It is useful for the construction of corrosion resistant, pressure resistant equipment, such as pumps(Scantlebury, 2019)

9. Process Flow Diagram and Material Balance

9.1 GAC



Figure 9.1: Process Flow Diagram for GAC Adsorption. The V-100 and V-101 blocks show both M12-40 vessels. T-100 represents the pre-treatment tank, and T-101 represents the post-treatment tank. Finally, T-102 is the holding tank for the spent GAC.

Stream	S-01	S-02	S-03	S-04	S-05	S-06
Mass Flows (kg/day)	8.82E06	8.82E06	8.82E06	4.41E06	4.41E06	4.41E06
PFOS	3.33E-02	3.33E-02	3.33E-02	1.67E-02	1.67E-02	2.59E-04
PFOA	2.54E-03	2.54E-03	2.54E-03	1.27E-03	1.27E-03	4.94E-05
Water	8.82E06	8.82E06	8.82E06	4.41E06	4.41E06	4.41E06
Mass GAC (kg)	0	0	0	0	0	0
Temperature (°C)	12	12	12	12	12	12
Pressure (psia)	29.4	29.4	140	140	140	140

Table 9.1. GAC Process Stream Table. The table below includes the stream tables and material balances for each stream.

Stream	S-07	S-08	S-09	S-10	S-11
Mass Flows (kg/day)	4.41E06	-	-	8.82E06	8.82E06
PFOS	2.59E-04	1.64-02	1.64E-02	5.19E-04	5.19E-04
PFOA	4.94E-05	1.22E-03	1.22E-03	9.88E-05	9.88E-05
Water	4.41E06	0	0	8.82E06	8.82E06
Mass GAC (kg)	0	18,100	18,100	0	0
Temperature (°C)	12.0	12.0	12.0	12.0	12.0
Pressure (psia)	140	140	140	140	140





Figure 9.2: Plasma Reactor Process Flow Diagram. Figure 9.2 shows the overall process flow diagram for the plasma reactor process, with the nanofiltration process treated as a single-step, single-unit operation for the sake of diagram legibility.

Below are the material flows for each stream indicated on the diagram.



Figure 9.3: Nanofiltration Preconcentration Process Flow Diagram. The first stage holds 36 membranes, the second stage holds 12, the third holds 11 membranes, the fourth holds 4, and the fifth and final stage holds 2 membranes.

Figure 9.3 gives the process flow diagram for the nanofiltration process, such that the permeate outlet becomes stream S-301 in Figure 9.2 and the retentate outlet(S-254) becomes stream S-300. Below are the material flows for each stream indicated.



Figure 9.4: Process flow diagram for the membrane cleaning operation. NF-400 and NF-401 house NF90:400 membranes, while NF-402,403, and 404 house NF90:4040 membranes.

STREAM	S-001	S-210	S-211	S-212	S-213	S-214
Total Mass Flow (tonnes/day)	8,790	251	75.4	176	6,160	2,640
H2O (tonnes/day)	8790	251	75.4	176	6160	2640
PFOA (g/day)	6.36	0.182	0.181	0.000363	0.0127	6.35
PFOS (g/day)	33.2	.950	.948	.019	0.0665	33.2
Ca(kg/day)	634	18.1	16	1.45	50.7	583
SO4(kg/day)	149	4.27	3.97	0.299	10.5	139
F(kg/day)	129	3.69	3.43	0.259	9.05	120
Temperature (°C)	15	15	15	15	15	15
Pressure (bar)	1	15	14	14	14	15

Table 9.2. Stream tables for plasma process.

STREAM	S-220	S-221	S-222	S-223	S-224	S-230
Total Mass Flow (tonnes/day)	240	72.1	168	1,850	792	79.2
H2O (tonnes/day)	240	72.0	168	1,850	791	79.1
PFOA (g/day)	0.577	0.576	0.00115	0.0127	6.33	0.633
PFOS (g/day)	3.02	3.01	0.00603	0.0663	33.1	3.31
Ca(kg/day)	53	49.3	3.71	40.8	543	54.3
SO4(kg/day)	12.6	11.75	0.885	9.73	129	12.9
F(kg/day)	10.9	10.2	0.765	8.42	112	11.2
Temperature (°C)	15	15	15	15	15	15
Pressure (bar)	15	14	14	14	15	15

STREAM	S-231	S-232	S-233	S-234	S-240	S-241
Total Mass Flow (tonnes/day)	23.8	55.4	554	238	79.3	23.9
H2O (tonnes/day)	23.7	55.4	554	237	79.1	23.7
PFOA (g/day)	0.632	0.00127	0.0127	6.32	2.11	2.10
PFOS (g/day)	3.30	0.00662	0.0662	33.0	11.0	11.0
Ca(kg/day)	50.5	3.8	38	505	168	156
SO4(kg/day) 12 0		0.905	9.05	120	40.1	37.3
F(kg/day)	10.4	0.783	7.83	104	34.7	32.2
Temperature (°C)	15	15	15	15	15	15
Pressure (bar)	14	14	14	16	16	15

STREAM	S-242	S-243	S-244	S-250	S-251	S-252
Total Mass Flow (tonnes/day)	55.4	166	71.9	71.9	22.0	49.9
H2O (tonnes/day)	55.4	166	71.2	71.2	21.4	49.9
PFOA (g/day)	0.00421	0.0126	6.31	6.31	6.29	0.0126
PFOS (g/day)	0.222	0.0661	33.0	33.0	32.9E-02	0.0660
Ca(kg/day)	11.8	35.3	469	469	436	32.8
SO4(kg/day)	2.81	8.42	112	112	104	7.83
F(kg/day)	2.43	7.28	96.7	96.7	89.9	6.77
Temperature (°C)	15	15	15	15	15	15
Pressure (bar)	15	15	16	16	15	15

STREAM	S-253	S-254	PERMEATE CLEAN OUTLET
Total Mass Flow (tonnes/day)	49.9	2,140	8,770
H2O (tonnes/day)	49.9	2,140	8,770
PFOA (g/day)	0.0126	6.29	0.0633
PFOS (g/day)	0.0660	32.9	0.331
Ca(kg/day)	32.8	436	197
SO4(kg/day)	7.83	104	45.5
F(kg/day)	6.77	89.9	39.3
Temperature (°C)	15	15	15
Pressure (bar)	15	15	14

STREAM	S-001	S-300	S-310A/B	S-311A/B	S-312	S-313
Total Mass Flow (tonnes/day)	8,790	22.0	22.0	42.0	42.0	41.7
H2O (tonnes/day)	8,790	21.4	21.4	40.8	40.8	40.8
PFOA (g/day)	6.36	6.29	6.29	12.0	12.0	12.0
PFOS (g/day)	33.2	32.9	32.9	62.7	62.7	62.7
Ca(kg/day)	634	441	441	841	841	734
SO4(kg/day)	149	104	104	198	198	1.91
F(kg/day)	129	90	90	171	171	147
Temperature (°C)	15.0	15.0	15.0	15.0	15.0	15.0
Pressure (bar)	1.00	15.0	15.0	1.00	2.51	2.51

STREAM	S-314	S-315	S-320
Total Mass Flow (tonnes/day)	0.172	3,150	2,360
H2O (tonnes/day)	0	3,080	2,240
PFOA (g/day)	0	906	variable
PFOS (g/day)	0	4,740	variable
Ca(kg/day)	56	55400	40400
SO4(kg/day)	103	145	105
F(kg/day)	13	11100	8116
Temperature (°C)	15.0	15.0	15.0
Pressure (bar)	N/A	1.00	1.00

STREAM	S-330	S-331	S-332
Total Mass Flow (g/day)	7.42	7.42	7.42
CO2(g/day)	0.13	0.13	0.13
Ar(g/day)	7.29	7.29	7.29
Temperature (°C)	40.0	20.0	40.0
Pressure (bar)	2.00	1.00	2.00

STREAM	S-321	S-322	S-323/ S-323A	S-324B	S-325	S-326
Total Mass Flow (tonnes/day)	2,360	2,360	2,360	2,360	21.5	21.5
H2O (tonnes/day)	2,240	2,240	2,240	2,240	21.4	21.4
PFOA (g/day)	variable	variable	variable	58.0	0.553	0.553
PFOS (g/day)	variable	variable	variable	29.9	0.285	0.285
Ca(kg/day)	40400	40400	40400	40400	39	39
SO4(kg/day)	105	105	105	105	1	1
F(kg/day)	8120	8120	8120	8120	77	77
Temperature (°C)	40.4	21.4	21.4	21.4	21.4	21.4
Pressure (bar)	1.00	1.00	5.55	5.55	1.00	5.55

STREAM	S-301	S-302	S-303	S-304
Total Mass Flow (tonnes/day)	8,770	8,770	8,770	8,790
H2O (tonnes/day)	8,770	8,770	8,770	8,790
PFOA (g/day)	0.0681	0.0681	0.0681	0.621
PFOS (g/day)	0.341	0.341	0.341	0.627
Ca(kg/day)	193	193	193	578
SO4(kg/day)	46	46	46	47
F(kg/day)	39	39	39	117
Temperature (°C)	15.0	15.0	21.0	15.0
Pressure (bar)	14.0	5.55	5.55	5.55

10. Process Description

10.1 GAC

For the removal of PFAS through the GAC process, stream S-01, running at 1600 gpm, is first put through pre-treatment operations, represented by T-100 in the GAC process flow diagram. Stream S-02 is at 29.4 psia and then brought to a pressure of 139.7 psia using pump P-100. Stream S-03, the pre-treated water stream, is then sent to splitter S-101, which separates the stream in half, running the system in parallel, with water running at 800 gpm in each vessel. The treated water streams are combined in mixer M-01 and put through post-treatment operations, represented by T-102. The water is sent to distribution. Finally, when the GAC has adsorbed the maximum amount of PFAS before detection in the effluent stream, it is placed in the T-101 holding tank for disposal or regeneration. The water is maintained at the same temperature throughout the process, so the only equipment that requires the use of energy is pump P-100.

10.2 Plasma Reactor Process

The treatment of PFAS in the plasma plant design can be broken down into two main sections. First, there is the preconcentration of the influent water stream using a series of nanofiltration membranes. Second, the concentrated stream from the nanofiltration membranes passes through the plasma reactor where the PFAS is degraded. The reactor effluent is mixed with the nanofiltration permeate before discharge to any further post-treatment operations and public distribution.
10.2.1 Nanofiltration Preconcentration

Figure 9.3 shows the process flow diagram for the continuous nanofiltration process. The process inlet(S-001) is divided, over the course of several stages of nanofiltration, into a high-concentration, low volume stream called the retentate(S-254) and a low concentration, high volume stream called the permeate(S-213, 223, 233, 243, 253). Nanofiltration is a membrane separation in which a pressure gradient drives the flow of water across the membrane. NF90 membranes were chosen for their high rejection of PFAS, and for their high liquid recovery. The NF90 membranes used are operated at a pressure differential of 15bar, in order to achieve 70% liquid recovery, and this pressure is provided by a series of pumps.

P-200 is the largest pump in the process, designed to raise the pressure of the process inlet flow(S-001) from atmospheric pressure to a pressure of 15bar. The pump must operate at 1600 gpm of water flow and provides a head of 500 ft. The first stage of membranes is composed of 36 parallel NF90:400 membranes. Of these membranes, 35 will treat 46 gpm of flow, while one membrane will be shut down for cleaning. The retentate streams from the membranes(S-211) are pooled together(S-214) and sent through the next pump(P-201). There is a 15 PSI pressure drop associated with operating the membrane, and the liquid stream must be brought back up to 15 bar in order for the next membrane to reach the desired liquid recovery. The permeate streams from each membrane(S-212) come together(S-213), and later come together with the permeate streams from other stages. This mixture of permeate streams forms the bulk permeate stream in Figure 9.2.

P-201 is a pump block composed of four identical pumps operating in parallel. Each pump operates on 125 gpm of flowing water, creating a head of 500ft, and altogether sending 500 gpm of water through the second stage. The 12 membranes in the second stage of

nanofiltration are NF90:400, and are operated in the same manner as the membranes in the first stage. Again, the permeate(S-222) is united(S-223), as is the retentate(S-221, 224).

P-202 sends the retentate through the third stage of filtration. As the preconcentration progresses, the volume of water treated decreases, and so P-202 must only accommodate 146 gpm of water and impart a 500ft head. In the third stage, the large NF90:400 membranes are replaced by NF90:4040 membranes, which are smaller and treat approximately one third the volume of the NF90:400 membranes. The flow in the third stage is split among 10 membranes, with an eleventh membrane housing built to accommodate the cleaning process. Each membrane will treat 14.5 gpm of water.

P-203 operates on 44 gpm of water. As the volume of water decreases, the concentration of salt increases, leading to an osmotic pressure which must be accounted for. Osmotic pressure was negligible in the first three stages, but by the fourth stage it has reached a point where the pump must provide a larger head in order to make a 15 bar pressure differential in the membrane. P-203, therefore, is designed to impart a 540 ft head to the water which flows to the fourth stage membranes. Three of the four NF90:4040 membranes in stage four operate with a 14.5 gpm feed flow, while the fourth is being cleaned.

P-204 is the final pump in the nanofiltration stage. It operates on a low flow rate compared to the previous stages, the feed to the final NF90:4040 membrane in stage five is only 13 gpm, but the pump must still impart a 540 ft head on the water, and so a reciprocating plunger pump was chosen in order to provide this large head. The final retentate flow rate(S-251, 254) is 3.9 gpm, for a total volume reduction of 99.76%.

10.2.2 Settling Tank

The nanofiltration process leads to a high concentration of salt in the retentate, through the same mechanism that causes the high concentration of PFAS in the retentate. Drinking water in New Castle County contains many ion species, at safe levels, and as the concentration increases, some salt species reach their solubility limit and precipitate out of the liquid phase as crystals. This precipitation is slow, and unlikely to occur during the nanofiltration process, although any precipitated solids will be removed from the nanofiltration membranes during cleaning. Figure 9.2 shows the way in which this solid is removed from the liquid stream prior to treatment in the plasma reactor. In order to allow all of the salt to precipitate out of the retentate(S-300), it is stored in a storage tank(T-300, 301) for eleven hours, in order to allow precipitation to proceed to the point of saturation. After these eleven hours have elapsed, the solid-liquid slurry is sent to a pump-fed rotary drum vacuum filter(F-1), which continuously removes and expels the solid salt precipitate from the liquid water, and sends the water along to wait for the plasma reactor in T-302.

The two salts which are expected to precipitate are calcium fluoride and calcium sulfate. Delaware's water has high calcium concentration, and the calcium pulls a large amount of sulfate and fluoride out of the water in order to form solid salts. Since these salt crystals are the only solids present in this water stream, the rotary drum vacuum filter is to be designed with a scraper for solid discharge, the recommended attachment for this task. The filter is designed in order to treat an entire day's worth of solid-water slurry in twelve hours and 35 minutes, meaning that it is shut down for the other eleven hours of the day, and can be cleaned or repaired as necessary without disrupting the overall process.

10.2.3 Cleaning

Figure 9.4 shows the process flow diagram for the membrane cleaning process which the nanofiltration membranes must undergo. The cleaning rate of the membranes depends on the ratio of solute mass in the feed over membrane area. For this reason, the membranes in stages further along the nanofiltration process must be cleaned more frequently than those in the early stages. Each day, the membranes which had been cleaned the previous day are inserted into the five empty slots in the preconcentration process, and the five membranes below them are moved to cleaning. In this way, the first stage membranes are cleaned once every thirty six days, the second stage membranes are cleaned once every twelve days, the third stage membranes are cleaned once every four days, and the fifth stage membranes are cleaned once every two days.

T-400 is a 500 gallon storage tank which will hold the membrane cleaning solution. The membranes are cleaned using a solution of HCl and water, where HCl makes up 0.2% of the solution by mass. T-400 will be constructed using fiberglass-reenforced plastic, which will be able to withstand the acidic cleaning conditions. When dirty membranes are inserted into the cleaning process, the P-400 pump drives low pressure, low volume flow through the five membranes. P-400 is designed in order to impart 85 ft of head on 10 gpm of liquid flow. This flow will dissolve any salt sediment or cake which has accumulated on the surface of the membrane, and which may block water transfer through the membrane. The permeate stream and the retentate stream from each membrane is recycled back into the cleaning tank. This low flow operation will continue for one hour, after which point the pump will be turned off and the membranes will be allowed to soak in the solution for 20 hours. After this soak, the pump will be operated for another hour, at which point the cleaning solution will be disposed of and the

membranes will be flushed of cleaning solution by operating the pump with clean water in the T-400 tank. After this, the membranes will be switched with the next series of five membranes from the preconcentration process, and HCl will be added to the clean water from the flushing operation in order to create the new cleaning solution.

10.2.4 Plasma Reactor



Figure 10.1. Top-down view of one of eight units of the R-1 plasma reactor.



Figure 10.2: Side profile of one of eight units of the R-1 plasma reactor. Each unit is 0.8 m long by 20.1 m wide by 0.2 m in depth.

Stream S-320 flows at a rate of 1560 liters per minute from holding tank T-103 into the plasma reactor, R-1. There are eight identical reactors, arranged in parallel, as sized in Figures 10.1 and 10.2. Water flow into R-1 passes through a horizontal distribution manifold before entering R-1 in order to allow for an even distribution of water throughout each channel. Within R-1, the water flows over a weir sized at 29 mm in order to achieve a bed height of 17 mm, as calculated from the following equation (Engineering ToolBox, 2004; Al Shaikhli and Al-Taee, 2018).

$$q = \frac{2}{3}c_d b(2g)^{1/2} h^{3/2}$$

where

$$q(m^{3}/s) = flow rate$$

 $h(m) = elevation head on the weir$
 $b(m) = width of the weir$
 $g(m^{2}/s) = gravitational constant = 9.81 m^{2}/s$
 $c_{d} = discharge constant for the weir$

Each of the eight reactors within R-1 is composed of molded Delrin® FG100 thermoplastic resin, a DuPont acetal homopolymer that is NSF/ANSI 61 certified for potable water contact (Appendix C). Each reactor is 0.8 m long by 20.1 m wide by 0.2 m in depth, with 2230 channels. Each channel is 63.5 mm wide and surrounded by 10 mm baffles that promote plug flow. At the base of each channel is a Pentair Point Four[™] Micro Bubble Diffuser (model number 1DMBDC600, Appendix D). As argon gas flows through these diffusers, bubbles of diameter approximately 100-500 microns are generated that help to carry the surfactant-like molecules of PFOA and PFOS to the surface.

At the surface of the water, the molecules of PFOA and PFOS become exposed to nonthermal plasma generated by electrodes that reach 20 mm above the surface of the water. Because of the novel nature of the degradation reaction, the chemistry of the degradation process is complex and not yet fully characterized. However, at least four distinct reaction mechanisms have been proposed: (1) high energy electrons in the plasma can reach temperatures of 10,000 -100,000 K, which is sufficient to initiate the thermal decomposition reaction of PFAS molecules that typically occurs at around 1,000 K, (2) high energy electrons can collide with vaporized water molecules, generating highly reactive OH• species that can oxidize the PFAS molecules, (3) aqueous electrons formed as a result of the solvation of electrons that escape the plasma zone to the bulk solution have a sufficiently low reductive potential and can promote reductive degradation of PFAS, and (4) the difference in the ionization energy of argon gas (15.7 eV) and PFOA (~11 eV) can fragment PFOA upon charge transfer from Ar^+ to PFOA (Palma et al., 2022; Stratton et al., 2017). Regardless of the reaction mechanism, the breakdown products are well understood - PFOA and PFOS will fragment into shorter and shorter chain compounds, eventually completely mineralizing into CO₂ and F⁻ (Singh et al., 2019).

Each channel has a series of forty-five 2% thoriated tungsten electrodes (Appendix D), linearly spaced 1.36 cm apart from each other. This inter-electrode spacing distance matches that of reactor setup used within the Nau-Hix et al. (2021) field demonstration. A 24 nF capacitor is charged to -30 kV, which discharges to the tungsten electrodes at a rate of 60 Hz during operation of the plasma reactor. The electric energy required to degrade PFAS molecules by an order of magnitude in a unit volume of water (EE/O) is similarly assumed to be 16 kWh/m³ (Nau-Hix et al., 2021).

The plasma reactor is assumed to operate under ideal plug flow conditions with a first order reaction rate. As such, it will obey the following rate law:

$$kt = ln\left(\frac{C_i}{C_f}\right)$$

where

 $k (min^{-1}) = reaction rate constant = .05 min^{-1}$ t (min) = residence time $C_i = reactor influent concentration$ $C_i = reactor effluent concentration$

Stream S-320 has a PFOA concentration of 294 ug/L and a PFOS concentration of 1540 ug/L on the very first cycle before any treatment. The time for a single fluid element to pass through the entire reactor is 1.06 minutes. In order to achieve final effluent concentrations of 25.9 ug/L for PFOA and 13.4 ug/L in stream S-324B, the total residence time required is 36.8 minutes for PFOA and 110.9 minutes for PFOS, as calculated from the rate law above. Therefore, although only 35 passes through R-1 are needed to bring the concentration of PFOA to the desired outlet concentration, a minimum of 105 passes are required for PFOS. As such, the reactor effluent stream is diverted through valve V-302 to be recycled as stream S-324A for 23.8 hours.

10.2.5 Argon Gas Recycling/Compressor

Argon gas is bubbled through each gas diffuser at a rate of 2.5 liters per minute as specified by Nau-Hix et al. (2021) and at a manufacturer recommended pressure of 30 psig. The argon gas is collected from reactor R-1 pumped through compressor C-300 for recycling. Assuming a compressor efficiency of 55%, the minimum power of compressor C-300 is 46.9 horsepower. For such a low power and low efficiency compressor, a screw type compressor with cast iron material construction was chosen as a realistic and relatively low-cost option.

R-1 will also generate a small amount of CO_2 as a result of the mineralization of PFOS and PFOA. In order to avoid the accumulation of product, which could eventually pressurize the system and pose a safety risk, a small amount of gas is purged within the gas recycle system through the V-320 purge valve. Given the 99.0% conversion rate of PFOS and PFOA, 0.16 moles of CO_2 are generated per day. Assuming ideal gas conditions, the volumetric purge flow rate is .0027 liters per minute, or 3.9 liters per day. The argon gas storage vessel, T-311, is an industrial size 300 gas cylinder. Given the purge flow rate and the relatively large size of T-311, it will take nearly 5 years to deplete T-311 of argon.

10.2.6 Heat Exchanger

The purpose of the HX-1 heat exchanger is to prevent the bulk vaporization of the water within R-1. As such, after each pass through R-1, stream S-321 passes through the tube side of HX-1 as the hot stream at a temperature of 40.4 °C. S-302, the permeate from the nanofiltration membrane separation, passes through the shell side of HX-1 as the cold stream at a temperature of 15 °C. The ASPEN Plus EDR system was used to iteratively and optimally size HX-1 (Appendix B). HX-1 is a 1-1 fixed head shell and tube heat exchanger constructed out of corrosion resistant SS304 stainless steel. It has a heat duty of 7.36 MMBtu/hour and a total area of 1300 ft². The cold side outlet leaves as S-303 for mixing in M-1. The hot side outlet leaves as S-322, which is pumped through P-302 and typically recycled as S-324A back to T-303 so that it can be passed through the plasma reactor again. Upon sufficient plasma treatment, the hot side outlet will instead pass through V-302 as S-324B, where it will be held in the temporary holding tank, T-304.

10.2.7 Inline Mixing and Discharge

Stream S-303, the low concentration permeate from the nanofiltration operation, has a PFOS concentration of .00722 ug/L and a PFOA concentration of .0377 ug/L. Stream S-325 is pumped through P-303 at a rate of 21,400 kg/day and at a PFOS concentration of 13.4 and a PFOA concentration of 25.9 ug/L. This stream is subsequently drip fed into unit M-1, a Sulzer CompaX[™] inline mixer of de minimis cost, which is used to induce turbulent flow within S-304 (Appendix D). Upon mixing, the concentration of both PFOS and PFOA will both reach the EPA designated health advisory level of 70 parts per trillion, equivalent to 0.07 ug/L. S-304 is then discharged to post-treatment post treatment operations handled by the municipality, such as disinfection, prior to sale to the consumer.

10.2.8 Schedule of Operations

The plasma reactor system operates on a four day cycle. Starting from day one, assuming a cold-start, the membrane permeate (S-301) proceeds to post-treatment as normal. The membrane retentate (S-300), on the other hand, accumulates in tank T-300. At the end of the first day, valve V-300 is switched, T-301 begins to fill, while T-300 finishes settling. Eleven hours and fifteen minutes are allowed for the salt to precipitate, at which point the solution will reach a solid-liquid slurry, where the salt concentration in the liquid phase is lower than or equal to the saturation concentration. After these precipitation hours have elapsed, the slurry (S-312) is treated by the rotary drum vacuum filter (F-1). The filter takes 12 hours and 35 minutes to treat a full day's worth of slurry. After the filter has finished treating the water, and T-302 is full, and T-300 is empty, T-302 drains into T-303 over the course of 10 minutes. On the third day, the liquid is looped through the reactor continuously for 23 hours and 40 minutes. After this point, the V-302 valve will be switched from recycle to outlet, signaling the final cycle through the

plasma reactor. This will cause T-303 to empty, prior to being filled by T-302. The reactor outlet stream (S-324B) fills up the final holding tank, T-304, between 23:40 and 23:50. During the final, fourth day, the reactor effluent is continuously and gradually reintroduced to the permeate. Figure 10.3 gives a visualization of this schedule, and shows the way that the process enters a steady holding pattern after four days. The purple represents the retentate generated on the first day, the blue the retentate generated on the second day, the red the retentate generated on the third day, and the green the retentate generated on the fourth day. It can be seen that, as the purple retentate is sent to in-line mixing, it will be mixed with the green permeate. This means that when operations are halted, for any reason, the plant's holding tanks will contain one day's worth of untreated retentate, one day's worth of partially-treated retentate, and one day's worth of treated but undiluted retentate.



Figure 10.3: Tracing movement of retentate throughout the plasma process, where each color represents the retentate generated on a different day.

The schedule for membrane cleaning involves cycling through which membranes are cleaned. The cleaning process takes 22 hours, so if cleaning starts at 0:00, operators will have two hours in which to move the membranes between the cleaning process and the nanofiltration process. Beginning from day one, membranes NF-2.1.1, 2.2.1, 2.3.1, 2.4.1, and 2.5.1 will be in cleaning. At 22:00, they will have been cleaned, and they will be brought back to the nanofiltration process and inserted into their housings. Using the valves which precede the

membranes, flow will be switched on for these membranes, and flow will be switched off for NF-2.1.2, 2.2.2, 2.3.2, 2.4.2, and 2.5.2. These membranes will be brought to the cleaning station and inserted into their housings, and at 0:00, the cleaning process will begin again. This will continue, such that each membrane, having been cleaned, is replaced in cleaning by the membrane beneath it. When operators reach the bottom of the stage(this will happen once every thirty six days for stage one, once every twelve days for stage two, once every eleven days for stage three, once every four days for stage four, and once every two days for stage two), they will cycle back to the top of the stage. This means that the membranes will cycle back to absolute start (the top membrane of each stage is in cleaning) once every 396 days, although this completed loop is not particularly meaningful. Each membrane must be replaced once every six months, and these replacements should be staggered so that plant shutdown is not necessary.

11. Energy Balance and Utility Requirements

Equipment Type	Unit Number	Power (kW)	Annual Consumption (kWh)	Annual Cost (\$)
Pump	P-100	75.9	665,000	49,300
Pumps	All the NF pumps	1200	10,500,000	779,000
Rotary Filter	F-1	104	915,000	67,700
Pump	P-300	0.0990	797	59.00
Pump	P-301	285	2,500,000	185,000
Pump	P-302	0.141	1240	91.80
Pump	P-303	0.5	4380	324
Reactor	R-1	29.4	258,000	19,100
Compressor*	C-300	-	-	-
Pump*	P-302	-	-	-

Table 11.1. Energy balances for every major unit operation.

*Electricity and financial costs of gas and liquid pumps for the plasma reactor are embedded within the cost of R-1.

11.1 GAC

While the activation of granular activated carbon and thermal regeneration of spent GAC is an energy-intensive process, this project does not include those factors in the scope. Therefore, the only aspect of this design of the GAC process that requires energy is the pump that is taking the pre-treated water into the reaction vessels. The first row of table 11.1 shows the energy required for the pump. The calculations for the pump were completed using the equation for energy required by a hydraulic pump:

$$E = Q \times \Delta P$$

where

E = the energy required to operate the pump Q = the volumetric flow rate of the water ΔP = the pressure difference observed

11.2 NF

In the nanofiltration process, energy is required to raise the pressure of the water prior to filtration. A high pressure inlet to the membrane is required in order to get a high liquid recovery in each stage. The nanofiltration process aims to raise liquid water to a pressure of 15 bar as it enters each membrane stage. However, there is a pressure drop of 15 psi associated with each membrane (Lenntech, 2020; The Dow Chemical Company, 2015), and strong pumps are required to bring the pressure back up to 15 bar, despite the relatively small pressure drop. Using information taken from a manufacturer(G.R. Pumps, 2022), an energy requirement and a pump efficiency was calculated for each pump. The following equation was used in order to calculate the actual energy requirements for each pump:

$$W_{actual} = W_{predicted} \times (1/\eta)$$

where

 \dot{W}_{actual} = the actual energy requirement for the pump $\dot{W}_{predicted}$ = the predicted, theoretical energy requirement for the pump η = the efficiency of the pump

11.3 Plasma Reactor

Using the following formula for electric energy per order (EE/O) which represents the energy needed to degrade a contaminant by an order of magnitude in a unit volume of water,

$$EE/O = \frac{E \times 1000}{V \times log\left(\frac{C_i}{C_f}\right)}$$

where

E (kWh) = energy consumed by plasma generation, gas compressors, and liquid pumps
 V (liters) = treatment volume of water

 C_i , $C_f(ug/L) = initial and final concentration of PFAS,$

and given that the EE/O of the process is 16 kWh/m³ (Nau-Hix et al., 2021), 21400 liters of water are treated in R-1 per day, and the concentration of PFOS decreases from 1540 ug/L to 13.4 ug/L, the energy consumed is calculated to be 706 kWh/day. At the industrial 5-year average cost of 7.42 cents per kWh for electricity in Delaware (EIA, 2022), the cost of electricity to run the R-1, C-300, and P-302 is \$52 per day.

The primary assumption made when calculating the energy balance around R-1 is that all the energy discharged from the plasma reactor is absorbed by the water as heat. Since the water is also being agitated by the argon gas bubbles, this project has also made the assumption that the water is reasonably well mixed and that there is no significant temperature gradient within the water. Given these assumptions, the bulk temperature of the water is expected to increase by 28.4 °C after one passes through the reactor.

12. Equipment List and Unit Descriptions

12.1 GAC

V-100/V-101

The Model 12-40 system of GAC vessels is designed for holding the GAC, which will remove various kinds of organic substances from liquid matter. The system includes two M-12-40 vessels that can each hold 40,000 pounds of the granular activated carbon of choice. The M12-40 single is typically offered as a stand-alone unit. Typically multiple single units are bought, as opposed to a system, for situations in which units will be operating in parallel, such as this project's application. This vessel is also designed with in-bed sample assemblies that facilitate regular monitoring of the quality of water and adsorption. Based on cost estimates from Calgon Carbon Corporation, each M12-40 vessel is priced at around \$547,000 (Appendix D).

P-100

This hydrological pump is used to move the water that has been through pre-treatment to the splitter S-101, which sends two streams at 800 gpm each to the GAC reaction vessels for treatment. The water comes in at 29.4 psia and is released into the tank at a pressure of 140 psia. This pressure was calculated based on the greatest pressure difference that would potentially be observed, as the discharge pressure rating for each M12-40 vessel is 125 psig. The estimate for the cost of this pump was based on the EPA's Work-Breakdown Structure Model, and was priced at around \$27,300 (Appendix B).

12.2 Plasma

T-300/T-301

These identical holding tanks are used to make the transition between the continuous operation of the membrane separation section and the semi-batch operation of the plasma reactor. These two fiberglass tanks are 2200 liters (581 gallons) each, in order to hold an entire day's worth of retentate. These two parallel tanks operate in syncopation, such that if T-300 is filling with retentate, T-301 spends 11 hours and 15 minutes allowing the liquid to sit, and then 12 hours and 35 minutes draining through the filter into the next tank. Using calculations done in Appendix B, these tanks were found to have a bare module cost of \$52,600 each.

P-300

This reciprocating plunger pump pulls precipitated retentate through V-301 and sends it through F-1. In order to match the flow rate specifications of F-1, P-300 must spend 12 hours and 35 minutes each day pumping water at a rate of 7.5gpm. A pressure head of 50ft is applied to the water by the pump, in order to make sure that all liquid is drained from the holding tank. Based on calculations done in Appendix B, this pump will be constructed with ductile iron, and operate at an efficiency of 0.9. This will mean an energy cost of 0.122hp, provided by an electric motor, and a bare module cost of \$7,470.

F-1

This rotary drum vacuum filter is used to remove precipitated salt particulate from retentate flow, and therefore will be designed with a scraper for solid discharge. An RDF from Seaside Aquatics (Play It Koi, 2022) meets design specifications, and as such was used as a model for the rotary drum vacuum filter to be used in this process. The filter can treat 7.5 gpm of water, and draws

140 hp, most of which goes towards creating the vacuum used to remove the solid particulate. The filter will have a base cost of \$4,000, and based on calculations done in Appendix B, it will have a bare module cost of \$6,920

T-302

This holding tank accumulates filtered retentate over the course of 12 hours and 35 minutes, then drains rapidly into the next tank over the course of 10 minutes. The tank will be large enough to hold 2200 liters, and based on calculations done in Appendix B, it will be constructed from fiberglass and have a bare module cost of \$52,600.

P-302

This pump is used to recycle reactor effluent during reactor operation, and to send reactor effluent to the next pump during the filling and draining period. In order to match the flow rate necessitated by the plasma reactor, this pump needs to operate at a flow rate of 412gpm, with a head of 150ft assumed in order to recycle the water. Assuming an efficiency of 0.5, the tank will draw 10.4hp, and based on calculations done in Appendix B, it will have a bare module cost of \$27,200.

T-304

This holding tank is used to accumulate reactor effluent so that it can be reintroduced to the membrane permeate at the desired rate. It will be large enough to hold 2200 liters, and based on calculations done in Appendix B, it ought to be constructed from fiberglass, and have a bare module cost of \$52,600.

P-303

This reciprocating plunger pump is designed to control the rate at which reactor effluent is reintroduced to the permeate flow, and to make sure that the reactor effluent reaches a high enough pressure to enter the permeate flow at in-line mixing. It must accommodate a flow rate of 4gpm, and a pressure head of 150ft. Based on calculations done in Appendix B, this pump will be constructed from ductile iron, and have an efficiency of 0.9. It will draw 0.188hp to be powered by an electric motor, and it will have a bare module cost of \$9,960.

P-301

This centrifugal pump is used to bring the membrane permeate to the in-line mixer. It will accommodate a continuous flow rate of 1620gpm, and impart a pressure head of 150ft. It will be constructed from cast iron, and an efficiency of 0.5 is assumed. Based on calculations done in Appendix B, it will draw 380hp, and have a bare module cost of \$99,500.

12.2.1 Nanofiltration Equipment

P-200

This centrifugal pump is used to raise inlet water pressure to 15 bar, in order to effectively operate the first stage of membranes. It must accommodate 1600gpm of flow, and provide a head of 500ft. Based on a pump manufacturer (G.R. Pumps, 2022), it will draw 906 hp and be constructed with cast steel. Based on calculations done in Appendix B, it will have a bare module cost of \$145,000

P-201

This block consists of four identical centrifugal pumps operating in parallel. Each pump will accommodate 125gpm, and impart a head of 500ft. This is necessary to raise the pressure back up to the necessary operating pressure of 15 bar after the loss of pressure caused by passing through the first membrane stage. Based on a pump manufacturer (G.R. Pumps, 2022), they will draw 145hp each(580hp total), and be constructed from cast steel. Based on calculations done in Appendix B, they will have a bare module cost of \$39,800 (\$159,200 total).

P-202

This centrifugal pump will apply a 500ft head to 146gpm of water. Based on a pump manufacturer (G.R. Pumps, 2022), it will be built with cast steel and draw 132 hp. Based on calculations done in Appendix B, it will have a bare module cost of \$54,991.

P-203

This reciprocating plunger pump will apply a 540ft head to 44gpm of water. This higher head is necessary to account for growing osmotic pressure in successive membrane stages. Based on a pump manufacturer (G.R. Pumps, 2022), it will be constructed from ductile iron and draw 4hp. Based on calculations done in Appendix B, it will have a bare module cost of \$27,650.

P-204

This reciprocating plunger pump will apply a 540ft head to 13.2gpm of water. Based on a pump manufacturer (G.R. Pumps, 2022), it will draw 1.5hp and be constructed from ductile iron. Based on calculations done in Appendix B, it will have a bare module cost of \$16,200.

NF-200

The first nanofiltration stage features 36 NF90:400 membranes from Dow Filmtec(The Dow Chemical Company, 2015) arranged in parallel. At any given time, 35 of the membranes are operating in parallel, while one is shut down for cleaning. Each membrane will treat 46.2gpm of water at 15 bar, which will lead to a recovery rate of 70%, a PFAS rejection rate of 0.998 and a salt rejection rate of 0.93. The purchase cost for each membrane is \$856, and based on calculations done in Appendix B, this means a bare module cost of \$1,990. For this stage, that means a total purchase cost of \$30,820 and a total bare module cost of \$71,640.

NF-201

The second nanofiltration stage features 12 NF90:400 membranes from Dow Filmtec (The Dow Chemical Company, 2015) arranged in parallel. At any given time, 11 of the membranes are operating in parallel, while one is shut down for cleaning. Each membrane will treat 44.1gpm of water at 15 bar, which will lead to a recovery rate of 70%, a PFAS rejection rate of 0.998 and a salt rejection rate of 0.93. The purchase cost for each membrane is \$856, and based on calculations done in Appendix B, it has a bare module cost of \$1,990. For this stage, that means a total purchase cost of \$10,270 and a total bare module cost of \$23,800.

NF-210

The third nanofiltration stage features 11 NF90:4040 membranes from Lenntech(Lenntech Water Solutions, 2020) arranged in parallel. At any given time, 10 of the membranes are operating in parallel, while one is shut down for cleaning. Each membrane will treat 14.6gpm of water at 15 bar, which will lead to a recovery rate of 70%, a PFAS rejection rate of 0.998 and a salt rejection rate of 0.93. The purchase cost for each membrane is \$595, and based on calculations done in Appendix B, each membrane has a bare module cost of \$1,380. The total purchase cost for this stage is \$6,550, and the total bare module cost is \$15,180.

NF-211

The fourth nanofiltration stage features 4 NF90:4040 membranes from Lenntech(Lenntech Water Solutions, 2020), arranged in parallel. At any given time, 3 of the membranes are operating in parallel, while one is shut down for cleaning. Each membrane will treat 14.6gpm of water at 17 bar, which will lead to a recovery rate of 70%, a PFAS rejection rate of 0.998 and a salt rejection rate of 0.93. The purchase cost for each membrane is \$595, and based on calculations done in Appendix B, each membrane has a bare module cost of \$1,380. The total purchase cost of the stage is \$2,380 and the total bare module cost is \$5,520.

NF-212

The fifth and final nanofiltration stage features 2 NF90:4040 membranes from Lenntech (Lenntech Water Solutions, 2020), arranged in parallel. At any given time, one membrane operates while the other is shut down for cleaning. Each membrane will treat 13.1gpm of water at 17 bar, which will lead to a recovery rate of 70%, a PFAS rejection rate of 0.998 and a salt rejection rate of 0.93. The purchase cost for each membrane is \$595, and based on calculations

done in Appendix B, each membrane has a bare module cost of \$1,380. The total purchase cost of the stage is \$1,190.

12.2.2 Membrane Cleaning Equipment

P-400

This reciprocating plunger pump pushes the cleaning solution through the membranes during the cleaning process. During the low-flow phase of cleaning, the pump will impart a head of 85ft on a flow rate of 10gpm. During the high-flow phase of cleaning, the pump will operate at an increased flow rate of 40gpm. During the soaking phase of cleaning, the pump will be shut down. Based on a report on using pumps on corrosive material(Scantlebury, 2019), the pump will be constructed from Hastelloy C, a material which will resist corrosion caused by the acidic cleaning solution. Calculations done in Appendix B indicate that the pump will draw 1 hp and have a bare module cost of \$84,800.

T-400

This storage tank will hold the cleaning fluid which is pumped through the membranes. The cleaning solution is acidic, but high enough in pH that a fiberglass-re enforced plastic may be used. The tank will be 500 gallons, and based on calculations done in Appendix B, it will have a bare module cost of \$36,260.

NF-400/NF-401

These two membrane systems are designed to house NF90:400 membranes during cleaning. The permeate and retentate flows are both recycled to the cleaning tank. The NF90:400 membranes

are manufactured by Dow Filmtec(The Dow Chemical Company, 2015) and have a unit cost of \$856. Based on calculations done in Appendix B, they will have a bare module cost of \$1,990 each.

NF-402/NF-403/NF-404

These three membrane systems are designed to house NF90:4040 membranes during cleaning. The permeate and retentate flows are both recycled to the cleaning tank. The NF90:4040 membranes are manufactured by Lenntech (Lenntech Water Solutions, 2020) and have a unit cost of \$595. Based on calculations done in Appendix B, they will have a bare module cost of \$1,380 each.

12.2.3 Plasma Reaction Equipment

R-1

R-1 is the plasma reaction unit operation, composed of 8 identical reactors in parallel that degrade PFOS and PFOA from the nanofiltration concentrate stream. The reactor has been upscaled using the same reactor design as Nau-Hix et al. (2021), with the singular exception that the reactor has been widened in the dimension perpendicular to the flow path, ensuring that similar reaction kinetics are maintained. The body of the reactor is made of molded Delrin FG100 thermoplastic, Pentair Point Four Micro Bubble Diffusers, and 2% thoriated tungsten electrodes. The total purchase cost of these construction materials, including the cost of all associated clamps, fittings, and molding is \$974,000. The gas diffusers are the most expensive component of the reactors, comprising 65% of the purchase cost. Applying a bare module factor of 3.05, the total bare module cost of R-1 is \$2,970,000.

C-300

C-300 is the gas compressor used to drive the argon gas recycle streams (S-330, S-331, S-332). It is a 46.3 hp, cast iron screw compressor that pumps 2.5 liters per second of argon gas through each diffuser at 30 psig. It has a purchase cost of \$87,100 and a total bare module cost of \$187,000.

T-311

T-311 is the argon gas storage tank. It is an industrial size 300 gas cylinder, which contains approximately 7000 liters of argon at atmospheric pressure. It has a purchase cost of \$125 and needs to be replaced every 5 years.

HX-1

HX-1 is a 1-1 shell and tube heat exchanger constructed from corrosion resistant SS304 stainless steel. The goal of HX-1 is to prevent the water in R-1 from vaporizing upon recycling. HX-1 accepts the R-1 reactor effluent as its tube side hot stream after each pass through R-1, and it uses the relatively cool permeate from the nanofiltration process as the shell side cold stream. It has an area of 1300 ft², a log mean temperature difference of 10.4 °C, and a tube length of 18 ft. It has a purchase cost of \$108,000, and a bare module cost of \$343,000.

13. Specification Sheets

13.1 GAC Specification Sheets

Adsorption Vessel			
Item: Vessel			
Item No.: V-100, V-101			
No. Required: 2			
Function: Hold the GAC, which will remove the PFA	S from water via adsorp	otion	
Operation: Continuous			
Streams:	S-04/05	S-06/07	
Inlet/Outlet:	IN	OUT	
Temperature(°C)	12	12	
Pressure (bar)	140	140	
Total Mass Flow(kg/day)	4.41E06	4.41E06	
Individual Mass Flows(kg/day)			
H_2O	4.41E06	4.41E06	
PFOA	1.27E-03	4.94E-05	
PFOS	1.67E-02	2.59E-04	
Design Data			
Energy Requirements: None			
Construction Material: Carbon Steel ASME			
Volume: 105,000 L			
Utilities: None			
Comments: None			

GAC Holding Tank			
Item: Tank			
Item No.: T-101			
No. Required: 1			
Function: Hold spent GAC for collection and thermal	l regeneration by Calgon Ca	arbon	
Corporation			
Operation: Continuous			
Streams:	S-08/09	N/A	
Inlet/Outlet:	IN	OUT	
Temperature(°C)	12.0	N/A	
Pressure (bar)	140	N/A	
Total Mass Flow(kg/day)	N/A	N/A	
Individual Mass Flows(kg/day)			
GAC	N/A	N/A	
Design Data			
Energy Requirements: None			
Construction Material: Fiberglass			
Volume: 84.300 L			
· · · · · · · · · · · · · · · · · · ·			

GAC Inlet Pump		
Item: Pump		
Item No.: P-100		
No. Required: 1		
Function: This will pump water from the inlet stream	n to the GAC vessel.	
Operation: Continuous		
Streams:	S-02	S-03
Inlet/Outlet:	IN	OUT
Temperature(°C)	12	12
Pressure (bar)	29.4	140
Total Mass Flow(kg/day)	8.82E06	8.82E06
Individual Mass Flows(kg/day)		
H_2O	8.82E06	8.82E06
PFOA	2.54E-03	2.54E-03
PFOS	3.33E-02	3.33E-02
Design Data		
Energy Requirements: None		
Construction Material: Ductile Iron		
Pressure Head: 30 feet		
Utilities: None		
Comments: None		

13.2 Plasma Reactor Specification Sheets

13.2.1 Plasma Setup

Precipitation Tank

Precipitation Tank Item: Tank Item No.: T-300, T-301 No. Required: 2 Function: Allow solid salt to precipitate out of retentate **Operation:** Batch Streams: S-310A/B Inlet/Outlet: IN Temperature(°C) 15 **Pressure (bar)** 15 **Total Mass Flow(kg/day)** 21,400 Indivi Η

an Data		
F	89.9	171
SO_4	104	189
Ca	441	841
PFOS	0.0329	0.0627
PFOA	0.00629	0.0120
H_2O	21,400	40,800
vidual Mass Flows(kg/day)		

S-311A/B

OUT

15

1

40,800

Design Data

Energy Requirements: None

Construction Material: Fiberglass-reenforced plastic(FRP)

Volume: 2200L

Utilities: None

Comments: None

Filter Feed Pump

Filter Feed Pump

Item: Reciprocating Plunger Pump

Item No.: P-300

No. Required: 1

Function: Send retentate from precipitation tanks to solid filter

Operation: Batch

Streams:	S-311A/B	S-312
Inlet/Outlet:	IN	OUT
Temperature(°C)	15	15
Pressure (bar)	1	2.51
Total Mass Flow(kg/day)	40,800	40,800
Individual Mass Flows(kg/day)		
H ₂ O	40,800	40,800
PFOA	0.0120	0.0120
PFOS	0.0627	0.0627
Ca	841	841
SO_4	189	189
F	171	171
Design Data		
Energy Requirements: 0.122 hp		
Construction Material: Ductile iron		
Pressure Head(ft): 50		

Utilities: Electricity(0.122hp)

Comments: efficiency = 0.9

Rotary Drum Vacuum Filter

Rotary Drum Vacuum Filter			
Item: Filter			
Item No.: F-1			
No. Required: 1			
Function: Remove solid salt particulate from PFAS con	centrate		
Operation: Batch			
Streams:	S-312	S-314,	S-313
Inlet/Outlet:	IN	OUT	
Temperature(°C)	15	15	15
Pressure (bar)	2.51	N/A	2.51
Total Mass Flow(kg/day)	42,000	172	41,400
Individual Mass Flows(kg/day)			
H_2O	40,800	0	40,800
PFOA	0.0120	0	0.0120
PFOS	0.0627	0	0.0627
Са	841	107	734
SO_4	198	196	1.91
F	171	24.0	147
Design Data			
Energy Requirements: 140 hp			
Utilities: Electricity(140 hp), solid removal Comments: Scraper for solid discharge to remove salt			

Pre-Plasma Holding Tank		
Item: Tank		
Item No.: T-302		
No. Required: 1		
Function: Hold filtered retentate while waiting for p	lasma reactor cycle to fin	ish
Operation: Batch		
Streams:	S-313	S-315
Inlet/Outlet:	IN	OUT
Temperature(°C)	15	15
Pressure (bar)	1	1
Total Mass Flow(kg/day)	41,400	3,150,000
Individual Mass Flows(kg/day)		
H ₂ O	40,800	3,080,000
PFOA	0.0120	0.906
PFOS	0.0627	4.74
Ca	734	55,400
SO_4	1.91	145
F	147	11,000
Design Data		
Energy Requirements: None		
Construction Material: Fiberglass-reenforced pl	astic(FRP)	
Volume: 2200 liters		
Utilities: None		
Comments: None		

Plasma Recycle Pump				
Item: Centrifugal Pump				
Item No.: P-302				
No. Required: 1				
Function: Recycle reactor effluent from HX-1 back to T-303				
Operation: Continuous				
Streams:	S-322	S-323		
Inlet/Outlet:	IN	OUT		
Temperature(°C)	21.4	21.4		
Pressure (bar)	1	5.55		
Total Mass Flow(kg/day)	2,320,000	2,320,000		
Individual Mass Flows(kg/day)				
H ₂ O	2,240,000	2,240,000		
PFOA	variable	variable		
PFOS	3.45	3.45		
Са	40,400	40,400		
SO_4	105	105		
F	81,200	81,200		
Design Data				
Energy Requirements: 10.4 hp				
Construction Material: Ductile iron				
Pressure Head(ft): 50				
Utilities: Electricity(10.4 hp)				
Comments: efficiency = 0.5				

Pre-Mixing Holding Tank			
Item: Tank			
Item No.: T-304			
No. Required: 1			
Function: Store plasma reactor effluent as it is re	eintroduced to membrane perr	neate	
Operation: Batch			
Streams:	S-324B	S-325	
Inlet/Outlet:	IN	OUT	
Temperature(°C)	20	20	
Pressure (bar)	5.55	1	
Total Mass Flow(kg/day)	2,320,000	21,500	
Individual Mass Flows(kg/day)			
H ₂ O	2,240,000	21,400	
PFOA	0.0580	5.53x10 ⁻⁴	
PFOS	0.0299	2.85x10 ⁻⁴	
Ca	40,400	38.5	
SO_4	105	1	
F	81,200	77.3	
Design Data			
Energy Requirements: none			
Construction Material: Fiberglass-reenforced	d plastic		
Utilities: none			
Comments: none			
In-Line Mixing Pump			
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Item: Reciprocating Plunger Pump			
Item No.: P-303			
No. Required: 1			
Function: Raise plasma reactor effluent to the sam	e pressure as the membrane	permeate	
Operation: Continuous			
Streams:	S-325	S-326	
Inlet/Outlet:	IN	OUT	
Temperature(°C)	20	20	
Pressure (bar)	1	5.55	
Total Mass Flow(kg/day)	21,500	21,500	
Individual Mass Flows(kg/day)			
H ₂ O	2,1400	21,400	
PFOA	5.53x10 ⁻⁴	5.53x10 ⁻⁴	
PFOS	2.85x10 ⁻⁴	2.85x10 ⁻⁴	
Са	38.5	38.5	
SO_4	1	1	
F	77.3	77.3	
Design Data			
Energy Requirements: 0.188 hp			
Construction Material: ductile iron			
Utilities: Electricity(0.188 hp) Comments: efficiency = 0.9			

Permeate Driving Pump		
Item: Centrifugal Pump		
Item No.: P-301		
No. Required: 1		
Function: Push membrane permeate through to in-li	ne mixing	
Operation: Continuous		
Streams:	S-301	S-302
Inlet/Outlet:	IN	OUT
Temperature(°C)	15	15
Pressure (bar)	1	5.55
Total Mass Flow(kg/day)	8,770,000	8,770,000
Individual Mass Flows(kg/day)		
H ₂ O	8,770,000	8,770,000
PFOA	6.81x10 ⁻⁵	6.81x10 ⁻⁵
PFOS	3.41x10 ⁻⁴	3.41x10 ⁻⁴
Са	193	193
SO_4	45.5	45.5
F	39.3	39.3
Design Data		
Energy Requirements: 380 hp		
Construction Material: ductile iron		
Utilities: Electricity(380 hp)		
Comments: efficiency = 0.5		

Nanofiltration Pump One

Nanofiltration Pump One		
Item: Centrifugal Pump		
Item No.: P-200		
No. Required: 1		
Function: Raise the water pressure prior to the firs	t stage of nanofiltration	
Operation: Continuous		
Streams:	S-001	S-001
Inlet/Outlet:	IN	OUT
Temperature(°C)	15	15
Pressure (bar)	1	15
Total Mass Flow(kg/day)	8,790,000	8,790,000
Individual Mass Flows(kg/day)		
H ₂ O	8,790,000	8,790,000
PFOA	0.00636	0.00636
PFOS	0.0332	0.0332
Ca	634	634
SO_4	149	149
F	129	129
Design Data		
Energy Requirements: 906 hp		
Construction Material: Cast steel		
Pressure Head(ft): 500ft		
Utilities: Electricity(906 hp) Comments: none		

Nanofiltration Pump Two		
Item: Centrifugal Pump		
Item No.: P-201		
No. Required: 4		
Function: Raise the water pressure prior to the second	stage of nanofiltration	
Operation: Continuous		
Streams:	S-212(sum)	S-214
Inlet/Outlet:	IN	OUT
Temperature(°C)	15	15
Pressure (bar)	14	15
Total Mass Flow(kg/day)	660,000	660,000
Individual Mass Flows(kg/day)		
H ₂ O	660,000	660,000
PFOA	0.00159	0.00159
PFOS	0.0083	0.0083
Ca	146	146
SO_4	34.8	34.8
F	30.0	30.0
Design Data		
Energy Requirements: 145 hp		
Construction Material: Cast steel		
Pressure Head(ft): 500ft		
Utilities: Electricity(145 hp) Comments: Pumps are operated in parallel		

Nanofiltration Pump Three		
Item: Centrifugal Pump		
Item No.: P-202		
No. Required: 1		
Function: Raise the water pressure prior to the third	stage of nanofiltration	
Operation: Continuous		
Streams:	S-222(sum)	S-224
Inlet/Outlet:	IN	OUT
Temperature(°C)	15	15
Pressure (bar)	14	15
Total Mass Flow(kg/day)	791,000	791,000
Individual Mass Flows(kg/day)		
H ₂ O	791,000	791,000
PFOA	0.00636	0.00636
PFOS	0.0332	0.0332
Ca	634	634
SO_4	149	149
F	129	129
Design Data		
Energy Requirements: 906 hp		
Construction Material: Cast steel		
Pressure Head(ft): 500ft		
Utilities: Electricity(906 hp)		

Nanofiltration Pump Four		
Item: Reciprocating Plunger Pump		
Item No.: P-203		
No. Required: 1		
Function: Raise the water pressure prior to the fourth	stage of nanofiltration	
Operation: Continuous		
Streams:	S-232(sum)	S-234
Inlet/Outlet:	IN	OUT
Temperature(°C)	15	15
Pressure (bar)	14	16
Total Mass Flow(kg/day)	238,000	238,000
Individual Mass Flows(kg/day)		
H ₂ O	237,000	237,000
PFOA	0.00632	0.00632
PFOS	0.0330	0.0330
Ca	505	505
SO_4	120	120
F	104	104
Design Data		
Energy Requirements: 4 hp		
Construction Material: Cast steel		
Pressure Head(ft): 540ft		
Utilities: Electricity(4 hp)		
Comments: none		

Nanofiltration Pump Five		
Item: Reciprocating Plunger Pump		
Item No.: P-203		
No. Required: 1		
Function: Raise the water pressure prior to the fifth st	tage of nanofiltration	
Operation: Continuous		
Streams:	S-242(sum)	S-244
Inlet/Outlet:	IN	OUT
Temperature(°C)	15	15
Pressure (bar)	15	16
Total Mass Flow(kg/day)	71,200	71,200
Individual Mass Flows(kg/day)		
H ₂ O	71,200	71,200
PFOA	0.00631	0.00631
PFOS	0.0330	0.0330
Ca	469	469
SO_4	112	112
F	96.7	96.7
Design Data		
Energy Requirements: 1.5 hp		
Construction Material: Cast steel		
Pressure Head(ft): 540ft		
Utilities: Electricity(1.5 hp)		
Comments: none		

Stage One Nanofiltrati	on Membrane		
Item: Filter			
Item No.: NF-200			
No. Required: 36			
Function: Cause the first stage of memb	orane separation to produce PF	AS concentr	ate
Operation: Continuous			
Streams:	S-210	S-211,	S-212
Inlet/Outlet:	IN	OUT	
Temperature(°C)	15	15	15
Pressure (bar)	15	14	14
Total Mass Flow(kg/day)	251,000	75,100	176,000
Individual Mass Flows(kg/day)			
H ₂ O	251,800	75,100	176,000
PFOA	1.82x10 ⁻⁴	1.81x10 ⁻⁴	3.63x10 ⁻⁷
PFOS	9.50x10 ⁻⁴	9.48x10 ⁻⁴	1.90x10 ⁻⁶
Ca	18.1	16.0	2.10
SO_4	4.27	3.97	0.299
F	3.69	3.49	0.259
Design Data			
Membrane Type: NF90:400, Opera	ting Pressure: 15 bar		
Salt Rejection: 0.93, PFAS Rejection	on: 0.998		
Overall Recovery: 70%			
Utilities: none			
Comments: Membrane housing must be	e constructed for quick remove	l and replaci	ng of

membranes

Stage Two Nanofiltration Membrane

Item: Filter

Item No.: NF-201

No. Required: 12

Function: Cause the second stage of membrane separation to produce PFAS concentrate **Operation:** Continuous

Streams:	S-220	S-221,	S-222
Inlet/Outlet:	IN	OUT	
Temperature(°C)	15	15	15
Pressure (bar)	15	14	14
Total Mass Flow(kg/day)	241,000	72,000	168,000
Individual Mass Flows(kg/day)			
H ₂ O	240,000	72,000	176,000
PFOA	5.77x10 ⁻⁴	5.76x10 ⁻⁴	1.15x10 ⁻⁶
PFOS	3.02x10 ⁻³	3.01x10 ⁻³	6.03x10 ⁻⁶
Ca	53	49.3	3.71
SO_4	12.6	11.8	0.885
F	10.9	10.2	0.765

Design Data

Membrane Type: NF90:400, Operating Pressure: 15 bar

Salt Rejection: 0.93, PFAS Rejection: 0.998

Overall Recovery: 70%

Utilities: none

Comments: Membrane housing must be constructed for quick removal and replacing of membranes

Stage Three Nanofiltration Membrane

Item: Filter

Item No.: NF-210

No. Required: 11

Function: Cause the third stage of membrane separation to produce PFAS concentrate **Operation:** Continuous

Streams:	S-230	S-231,	S-232
Inlet/Outlet:	IN	OUT	
Temperature(°C)	15	15	15
Pressure (bar)	15	14	14
Total Mass Flow(kg/day)	79,200	23,800	55,400
Individual Mass Flows(kg/day)			
H ₂ O	79,100	23,700	55,400
PFOA	6.33x10 ⁻⁴	6.32x10 ⁻⁴	1.27x10 ⁻⁶
PFOS	3.31x10 ⁻³	3.30x10 ⁻³	6.62x10 ⁻⁶
Ca	54.3	50.5	3.80
SO_4	12.9	12.0	0.905
F	11.2	10.4	0.783

Design Data

Membrane Type: NF90:400, Operating Pressure: 15 bar

Salt Rejection: 0.93, PFAS Rejection: 0.998

Overall Recovery: 70%

Utilities: none

Comments: Membrane housing must be constructed for quick removal and replacing of membranes

Stage Four Nanofiltration Me	mbrane		
Item: Filter			
Item No.: NF-211			
No. Required: 4			
Function: Cause the four stage of membrane separat	ion to produce PI	FAS concentr	ate
Operation: Continuous			
Streams:	S-240	S-241,	S-242
Inlet/Outlet:	IN	OUT	
Temperature(°C)	15	15	15
Pressure (bar)	16	15	15
Total Mass Flow(kg/day)	79,300	23,900	55,400
Individual Mass Flows(kg/day)			
H ₂ O	79,100	23,700	55,400
PFOA	2.11x10 ⁻³	2.10x10 ⁻³	4.21x10 ⁻⁶
PFOS	1.10x10 ⁻²	1.10x10 ⁻²	2.22x10 ⁻⁴
Са	168	156	11.8
SO_4	40.1	37.3	2.81
F	34.7	32.2	2.43
Design Data			

Membrane Type: NF90:4040, Operating Pressure: 16 bar

Salt Rejection: 0.93, PFAS Rejection: 0.998

Overall Recovery: 70%

Utilities: none

Comments: Membrane housing must be constructed for quick removal and replacing of membranes. Pressure is raised to 16 bar to account for osmotic pressure.

Stage Five Nanofiltration Membrane

Item: Filter

Item No.: NF-212

No. Required: 1

Function: Cause the fifth stage of membrane separation to produce PFAS concentrate **Operation:** Continuous

Streams:	S-250	S-251,	S-252
Inlet/Outlet:	IN	OUT	
Temperature(°C)	15	15	15
Pressure (bar)	16	15	15
Total Mass Flow(kg/day)	71,200	21,400	49,900
Individual Mass Flows(kg/day)			
H ₂ O	71,200	21,400	49,900
PFOA	6.31x10 ⁻³	6.29x10 ⁻³	1.26x10 ⁻⁵
PFOS	3.30x10 ⁻²	3.29x10 ⁻²	6.60x10 ⁻⁵
Ca	469	436	32.8
SO_4	112	104	7.83
F	96.7	89.9	6.77

Design Data

Membrane Type: NF90:4040, Operating Pressure: 16 bar

Salt Rejection: 0.93, PFAS Rejection: 0.998

Overall Recovery: 70%

Utilities: none

Comments: Membrane housing must be constructed for quick removal and replacing of membranes. Pressure is raised to 16 bar to account for osmotic pressure.

Membrane Cleaning Pump

Membrane Cleaning Pump		
Item: Reciprocating Plunger Pump		
Item No.: P-400		
No. Required: 1		
Function: Push cleaning fluid through membranes du	uring flow cleaning	
Operation: Batch		
Streams:	N/A	N/A
Inlet/Outlet:	IN	OUT
Temperature(°C)	20	20
Pressure (bar)	1	3.53
Total Mass Flow(kg/day)	54,500	54,500
Individual Mass Flows(kg/day)		
H ₂ O	54,400	54,400
HCl	108	108
Design Data		
Energy Requirements: 1 hp		
Construction Material: Hastelloy C		
Utilities: Electricity(1 hp)		
Comments: This unit operates on corrosive material maintenance or inspection	and should be treated care	fully during

Cleaning Fluid Holding Tank			
Item: Tank			
Item No.: T-400			
No. Required: 1			
Function: Store and mix HCl solution during the clea	aning process		
Operation: Batch			
Streams:	N/A	N/A	
Inlet/Outlet:	IN	OUT	
Temperature(°C)	20	20	
Pressure (bar)	2.53	1	
Total Mass Flow(kg/day)	54,500	54,500	
Individual Mass Flows(kg/day)			
H ₂ O	54,400	54,400	
HC1	108	108	
Design Data			
Energy Requirements: none			
Construction Material: Fiberglass-reenforced pla	astic		
Size: 1890 liters			
Utilities: HCl(18.7 liters concentrate/day)			
Comments: This unit operates on corrosive material	and should be treated care	fully during	
maintenance or inspection			

Large Membrane Housing		
Item: Filter		
Item No.: NF-400, NF-401		
No. Required: 2		
Function: House large(NF90:400) membranes during cleaning		
Operation: Batch		
Streams:	N/A	N/A
Inlet/Outlet:	IN	OUT
Temperature(°C)	20	20
Pressure (bar)	3.53	2.53
Total Mass Flow(kg/day)	18,500	18,500
Individual Mass Flows(kg/day)		
H ₂ O	18,500	18,500
HCl	37	37
Design Data		
Energy Requirements: none		
Membrane Model: NF90:400		
Utilities: None		
Comments: This unit operates on corrosive material and should	be treated care	efully during
maintenance or inspection. Permeate and retentate flows reunite	on return to T-	400

Large Membrane Housing		
Item: Filter		
Item No.: NF-402, NF-403, NF-404		
No. Required: 3		
Function: House large(NF90:400) membranes during cleaning		
Operation: Batch		
Streams:	N/A	N/A
Inlet/Outlet:	IN	OUT
Temperature(°C)	20	20
Pressure (bar)	3.53	2.53
Total Mass Flow(kg/day)	5,840	5,840
Individual Mass Flows(kg/day)		
H ₂ O	5,830	5,830
HCl	11.7	11.7
Design Data		
Energy Requirements: none		
Membrane Model: NF90:4040		
Utilities: None		
Comments: This unit operates on corrosive material and should	be treated care	fully during
maintenance or inspection. Permeate and retentate flows reunite	on return to T-4	100

13.2.4 Plasma Reaction Specification Sheets

Plasma Reactor

Plasma Reactor				
Item No.: R-1				
No. Required: 8				
Function: Decrease concentration of PFOA	and PFOS in	water		
Operation: Batch				
Streams:	S-320	S-330	S-321	S-331
Inlet/Outlet:	IN	IN	OUT	OUT
Temperature(°C)	20.0	40.0	40.4	20.0
Pressure (bar)	1.0	2.0	1.0	1.0
Total Mass Flow (tonnes/day)	2360	7.42 (g/day)	2360	7.42 (g/day)
Individual Mass Flows				
H2O (tonnes/day)	2240	0	2240	0
PFOA (g/day)	variable	0	variable	0
PFOS (g/day)	variable	0	variable	0
Ca (kg/day)	40400	0	40400	0
SO4 (kg/day)	105	0	105	0
F (kg/day)	8120	0	8120	0
Ar (g/day)	0	7.29	0	7.29
CO2 (g/day)	0	0.13	0	0.13

Design Data

Energy Requirements: 706 kWh/day

Materials: Pentair Point Four Micro Bubble Diffuser (Model no. 1DMBDC600), Pentair pinch clamps and fittings, 2% thoriated tungsten electrodes, Delrin FG100 resin

Utilities: Electricity

Comments: none

Gas Compressor

Gas Compressor		
Item: Compressor		
Item No.: C-300		
No. Required: 1		
Function: Drive flow of argon recycle system		
Operation: Continuous		
Streams:	S-331	S-332
Inlet/Outlet:	IN	OUT
Temperature(°C)	20	40
Pressure (bar)	1.00	2.00
Total Mass Flow (g/day)	7.42	7.42
Individual Mass Flows		
Ar (g/day)	7.29	7.29
CO2 (g/day)	0.13	0.13
Design Data		
Power Requirements: 46.9 hp		
Screw type compressor with cast iron material construct	ction	
Utilities: electricity		
Comments: A pressure of 2 bar (30 psig) is recommended b	by Pentair to drive flo	w through
gas diffusers.		

Argon Gas Tank					
Item: Tank					
Item No.: T-311					
No. Required: 1					
Function: Store reservoir of argon gas for losses f	rom purge stream				
Operation: n/a					
Streams:	S-332	S-330			
Inlet/Outlet:	IN	OUT			
Temperature(°C)	40	40			
Pressure (bar)	2.00	2.00			
Total Mass Flow (g/day)	7.42	7.42			
Individual Mass Flows					
Ar (g/day)	7.29	7.29			
CO2 (g/day)	0.13	0.13			
Design Data					
Energy Requirements: none					
Standard industrial size 300 gas cyclinder					
Utilities: None					
Comments: This unit will need to be replaced eve	ery 5 years once the argon is dep	oleted.			

Heat Exchanger

Item: 1,1-Shell and Tube Heat Exchanger

Item No.: HX-1

No. Required: 1

Function: Transfers heat from reactor effluent to nanofiltration permeate to prevent

vaporization of water in reactor upon recycle.

Operation: Batch

Streams:	S-302	S-321	S-303	S-322
Inlet/Outlet:	IN	IN	OUT	OUT
Temperature(°C)	15.0	40.4	19.9	21.4
Pressure (bar)	5.55	1.0	5.55	1.0
Total Mass Flow (tonnes/day)				
Individual Mass Flows				
H2O (tonnes/day)	8770	2360	8770	2360
PFOA (g/day)	.0681	variable	.0681	variable
PFOS (g/day)	.341	variable	.341	variable
Ca (kg/day)	193	40400	193	40400
SO4 (kg/day)	46	105	46	105
F (kg/day)	39	81200	39	81200
Design Data				
Energy Requirements: none				
Membrane Model: NF90:4040				
Utilities: Electricity				
Comments: None				

14. Equipment Cost Summary

Unit Type	Unit Number	Purchase Cost (\$)	Bare Module Factor	Bare Module Cost (\$)	Calculation Source
Pump	P-100	n/a	n/a	27,300	Appendix B
Adsorption Tower	V-100	n/a	n/a	547,000	Appendix D
Adsorption Tower	V-101	n/a	n/a	547,000	Appendix D
Holding Tank	T-101	n/a	n/a	25,500	Appendix B
Holding Tank	Т300	13,200	4.00	52,600	Appendix B
Holding Tank	T301	13,200	4.00	52,600	Appendix B
Pump	P-300	2,260	3.30	7,470	Appendix B
Filter	F-1	4,000	1.73	6,920	Appendix D
Holding Tank	T-302	13,200	4.00	52,600	Appendix B
Pump	P-302	8,240	3.30	27,200	Appendix B
Holding Tank	T-304	13,200	4.00	52,600	Appendix B
Pump	P-303	3,020	3.30	9,960	Appendix B
Pump	P-301	30,200	3.30	99,500	Appendix B
Pump	P-200	43,900	3.30	145,000	Appendix D
Pump	P-201	48,200	3.30	159,200	Appendix D
Pump	P-202	16,700	3.30	54,991	Appendix D
Pump	P-203	4,910	3.30	16,200	Appendix D
Filter	NF-200	30,800	2.32	71,640	Appendix D
Filter	NF-201	10,300	2.32	23,800	Appendix D
Filter	NF-210	6,550	2.32	15,180	Appendix D
Filter	NF-211	2,380	2.32	5,520	Appendix D

Filter	NF-212	1,190	2.32	2,760	Appendix D
Pump	P-400	1,190	3.30	84,800	Appendix B
Holding Tank	T-400	9,065	4.00	36,260	Appendix B
Filter	NF-400	856	2.32	1,990	Appendix D
Filter	NF-401	856	2.32	1,990	Appendix D
Filter	NF-402	595	2.32	1,380	Appendix D
Filter	NF-403	595	2.32	1,380	Appendix D
Filter	NF-404	595	2.32	1,380	Appendix D
Compressor	C-300	87,100	2.15	187,000	Appendix B
Heat Exchanger	HX-1	108,000	3.17	343,000	Appendix B
Plasma Reactor	R-1	974,000	3.05	2,970,000	Section 12.2.4

15. Fixed Capital Investment Summary

The fixed capital investment for each plant design are listed below. The total capital investment includes the costs of equipment, cost of site preparation and service facilities, allocated costs for electric utilities, contingencies and contractor's fees, the cost of land, royalties, and startup, as well as working capital.

15.1 GAC

Line Item	Unit Cost	Cost	
Bare Module Costs of GAC Vessels	see section 14	\$	1,093,000
Bare Module Costs of Other GAC Equipment	see Appendix B	\$	2,381,000
Total Bare Module Investme	nt	\$	3,474,000
	15% of Total Bare Module		
Cost of Site Preparation and Service Facilities	Investment	\$	3,474,000
	\$2900000*S^0.83, where		
Allocated Costs for Electric Utilities	S = 0.05 MW	\$	241,000
T otal Direct Permanent Investment			4,237,000
	18% of Direct Permanent		
Cost of Contingencies and Contractor's Fees	Investment	\$	763,000
Total Depreciable Capital			5,000,000
	2% of Total Depreciable		
Cost of Land	Capital	\$	100,000
	2% of Total Depreciable		
Cost of Royalties	Capital	\$	100,000
	10% of Total Depreciable		
Cost of Startup	Capital	\$	500,000
Total Permanent Investment			5,700,000
	18% of Total Permanent		
Working Capital	Investment	\$	1,026,000
Total Capital Investment		\$	6,726,000

15.2 Plasma

Line Item	Unit Cost	Cost	t
Bare Module Costs of NF System	see section 14	\$	1,638,000
Bare Module Costs of Plasma Reactor	see section 14	\$	2,676,000
Total Bare Module Invest	ment	\$	4,314,000
	15% of Total Bare Module		
Cost of Site Preparation and Service Facilities	Investment	\$	647,000
	\$2900000*S^0.83, where		
Allocated Costs for Electric Utilities	S = 1.62 MW	\$	4,331,000
Total Direct Permanent Invo	estment	\$	9,292,000
	18% of Direct Permanent		
Cost of Contingencies and Contractor's Fees	Investment	\$	1,673,000
Total Depreciable Capital			10,965,000
	2% of Total Depreciable		
Cost of Land	Capital	\$	219,000
	2% of Total Depreciable		
Cost of Royalties	Capital	\$	219,000
	10% of Total Depreciable		
Cost of Startup	Capital	\$	1,097,000
Total Permanent Investment			12,500,000
	18% of Total Permanent		
Working Capital	Investment	\$	2,250,000
Total Capital Investme	nt	\$	14,750,000

16. Operating Cost

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			-	-

Line Item	Unit Cost				
Granular Activated Carbon	\$3.25/lb carbon	\$	1,334,670		
Raw Mat	erials	\$	1,335,000		
Electricity	\$.0742/kWh	\$	37,100		
GAC Transportation (Virgin and Fouled)	\$.26/ton-mile	\$	785,120		
Settled Solids Disposal	\$1384.46/ton	\$	2,000		
RCRA Hazardous Carbon Testing	\$1200/changeout	\$	12,000		
Utiliti	es	\$	836,000		
Direct wages and benefits (DW&B)	\$40/operator-hr	\$	1,664,000		
Direct salaries and benefits	15% of DW&B	\$	249,600		
Operating supplies and services	6% of DW&B	\$	99,840		
Technical assistance to manufacturing	\$60000/(operator/shift)-year	\$	300,000		
Control laboratory	\$65000/(operator/shift)-year	\$	325,000		
Operat	ions	\$	2,638,000		
Wages and benefits (MW&B)	4.5% of Total Depreciable Capital	\$	225,000		
Salaries and benefits	25% of MW&B	\$	56,250		
Materials and services	100% of MW&B	\$	56,250		
Maintenance overhead	5% of MW&B	\$	11,250		
Mainten	\$	349,000			
General plant overhead	7.1% of M&O-SW&B	\$	212,090		
Mechanical department services	2.4% of M&O-SW&B	\$	71,690		
Employee relations department	5.9% of M&O-SW&B	\$	176,240		
Business services	7.4% of M&O-SW&B	\$	221,050		
Operating O	Verhead	\$	681,000		
	8% of (Total Depreciable Capital -				
Direct plant	1.18 Allocated Costs)	\$	380,720		
Property taxes and insurance	2% of Total Depreciable Capital	\$	100,000		
Othe	\$	481,000			
Total Cost of I	\$	6,320,000			

16.2 Plasma

Line Item	Unit Cost	Total	Annual Cost	
Argon	\$.07/day	\$	20	
HCl (for cleaning)	\$18.41/L	\$	58,460	
Membranes	\$870/membrane	\$	101,220	
Raw Ma	\$	160,000		
Electricity	\$.0742/kWh	\$	1,053,990	
Hazardous waste disposal (HCI)	\$.10/lb	\$	310	
Utili	ities	\$	1,054,000	
Direct wages and benefits (DW&B)	\$40/operator-hr	\$	1,664,000	
Direct salaries and benefits	15% of DW&B	\$	249,600	
Operating supplies and services	6% of DW&B	\$	99,840	
Technical assistance to manufacturing	\$60000/(operator/shift)-year	\$	300,000	
Control laboratory	\$65000/(operator/shift)-year	\$	325,000	
Opera	ations	\$	2,638,000	
Wages and benefits (MW&B)	3.5% of Total Depreciable Capital	\$	383,780	
Salaries and benefits	25% of MW&B	\$	95,940	
Materials and services	100% of MW&B	\$	95,940	
Maintenance overhead	5% of MW&B	\$	19,190	
Mainte	\$	595,000		
General plant overhead	7.1% of M&O-SW&B	\$	229,560	
Mechanical department services	2.4% of M&O-SW&B	\$	77,600	
Employee relations department	5.9% of M&O-SW&B	\$	190,760	
Business services	7.4% of M&O-SW&B	\$	239,260	
Operating	Overhead	\$	737,000	
	8% of (Total Depreciable Capital -			
Direct plant	1.18 Allocated Costs)	\$	530,680	
Property taxes and insurance	2% of Total Depreciable Capital	\$	219,300	
Oth	\$	750,000		
Total Cost of	\$	5,934,000		

17. Other Considerations

17.1 Environmental Considerations

The key objective of this report is to determine the financial viability of the construction and operation of a drinking water treatment plant that utilizes plasma for PFAS degradation as opposed to traditional adsorption methods. Investigating such financial viability is of interest because of the fundamental environmental benefit of utilizing a plasma reactor - the plasma is able to permanently destroy PFAS whereas activated carbon sequesters PFAS, generating PFAS-contaminated solid waste in the process. The PFAS-contaminated fouled GAC has three possible disposal outcomes, none of which are particularly risk-free. First, it can be landfilled as hazardous waste. In this case, there is risk of groundwater contamination upon the puncture of the landfill membrane and infiltration of rainwater into the landfill, ultimately leaching PFAS back into the groundwater. Second, the fouled GAC can be incinerated. Duschesne et al. (2020) found that even at temperatures of 900°C, which exceeds the typical temperature of municipal solid waste incinerators, incomplete combustion of PFAS can occur, resulting in the production of additional shorter chain PFAS species that retain carcinogenic properties. Third, thermal regeneration of the GAC can be used to desorb the PFAS. While the extended time and temperature requires for this process typically also completely mineralizes any PFAS in the offgas, thermal regeneration only has about a 90% restoration in the sorptive capacity of the GAC (Baghirzade et al., 2021). Eventually the PFAS-contaminated GAC will no longer be able to be regenerated and will need to be landfilled or incinerated. As such, plasma-based water treatment technology presents a promising alternative that results in high efficiency, permanent PFAS destruction.

However, understanding the operational carbon footprint of these different treatment options is also critical to evaluating the holistic environmental impact of these two different designs over time. In terms of carbon footprint, the state of Delaware had an 2020 USEPA eGRID factor of 755.03 pounds of CO₂ equivalent per MWh used (USEPA, 2022). With the plasma-based treatment plant operating at 1.62 MW and the GAC-based treatment plant operating at .05 MW, the plasma-based treatment plant exceeds the operational carbon emissions of the GAC-based treatment plant by 13,800 pounds of CO₂ equivalent per year. However, this does not account for the carbon footprint of GAC regeneration, which while performed offsite for financial reasons, is still a major embedded environmental burden. According to He (2012), thermal regeneration of GAC has a carbon footprint factor of 0.7 pounds of CO2e per pound of spent carbon. Given that the designed GAC-based treatment plant generates 821,000 pounds of spent GAC per year, this process generates an additional 575,000 pounds of CO2e. In sum, the plasma-based treatment plant is not only environmentally superior from a groundwater contamination perspective but also from an operational carbon footprint perspective.

17.2 Safety Considerations

The safety of plant employees and process operators is subject to a number of concerns. In the GAC process, there is a risk associated with the handling of wet or used GAC. The adsorbed PFAS poses one risk to operators, who should wear protective clothing and respirators while handling the PFAS-laden material. Further, wet GAC adsorbs oxygen from the air, potentially creating low-oxygen environments, and posing a life-threatening risk (WWD, 2021). In situations when wet GAC is being handled, or when operators are entering into the vicinity of wet GAC, approved respirators, or potentially oxygen tanks, ought to be used. To mitigate these risks, wet GAC ought to only be handled in open-air, or well ventilated environments, although these precautions are still necessary in these environments.

The plasma reactor is a high-voltage piece of equipment, where sparks jump openly and large volumes of flowing and conductive water are present. As such, protective equipment, especially insulating gloves and footwear, should be worn while operators are interacting with or near the plasma reactor. Extreme care should be taken in the event that an operator is near the plasma reactor while it is in operation, and in the event of any flooding, spillage, or leaks in the liquid transport system near the plasma reactor, the reactor should be immediately shut down to prevent the danger of a short circuit. The plasma reactor should be disconnected from power during any cleaning or maintenance that may occur.

The concentrated solution of aqueous PFAS should be treated with care, much like the used GAC should. Protective clothing, including eye protection and a respirator, ought to be used while operators are nearby to the PFAS concentrate, and operators who come into contact with the PFAS concentrate ought to wash themselves thoroughly and promptly. Spillage of PFAS concentrate, even on the small scale, ought to be avoided as much as possible.

The membrane cleaning process features the use of an HCl solution. HCl, and other acids, must be handled and stored with care. Concentrated HCl ought to be stored in its original container, and when the HCl cleaning solution is mixed, it ought to be handled by operators in protective clothing, in well ventilated or open air environments. The fiberglass-reenforced plastic holding tank in the cleaning process is capable of resisting corrosion from the HCl, as is the Hastelloy C pump which drives the cleaning process. The piping in the cleaning process ought to be constructed from corrosion-resistant materials such as plastics, since the cleaning process operates at low pressures.

Both processes have been designed with public safety in mind, but concerns still remain which must be monitored and addressed. In the plasma reactor process, the existence of an aqueous PFAS concentrate means that spillage must be a concern. An increased concentration of PFAS near the surface of the ground will eventually return to the water table, but in the short term it may have very negative effects on plant employees, nearby wildlife, and potentially the nearby public, depending on the vicinity and the size of the spill. As such, inspections ought to be done frequently by operators, and maintenance should be enacted quickly. Further, a quick-shutdown of the plant should be planned, in the event of a catastrophic failure.

These processes, the GAC and the plasma reactor, are both meant to remove dangerous chemicals from drinking water, and as such the operation of the plant itself is a safety concern. PFAS concentration in the plant outlet should be tested regularly, and increased PFAS concentration in the plant outlet should be investigated and addressed as quickly as possible to ensure the safety of clean water distributed. Furthermore, plant shutdowns should be avoided, and should be coordinated with the water department in order to occur at times when the decrease in drinking water production can be accommodated by a stored reserve of potable water.

17.3 Global, Cultural, Ethical, and Social Considerations

There are no significant global, cultural, ethical, or social considerations that affect this report. The purification of water for municipal tap water distribution in New Castle County, Delaware is a highly regulated and reasonably equitable process, and it is uncontroversial that consumers should expect clean, carcinogen-free, drinking water.

18. Business Case

Water is a public good, so it is by definition a commodity that is provided without profit to all members of society. As such, the sale price of water to the consumer is dynamically adjusted solely to "break-even" or recoup capital and operating expenses. For this reason, calculations of sales figures, profitability, internal rate of return, and return on investment are omitted from this report.

Table 18.1. Capital and operating cost comparison between GAC and plasma-based treatment designs.

	Capital Cost	Operating Cost (annual)
GAC	\$ 6,726,000	\$ 6,320,000
Plasma	\$ 14,750,000	\$ 5,934,000

Instead, with the expectation that the removal of PFAS from water will be more stringently mandated within the future regulatory environment, municipalities will be required to invest in removal technologies regardless of profitability. To that end, this report provides a cost comparison between two competing treatment plant designs (Table 18.1). While the plasma-based treatment design has a slightly lower annual operating cost, it has a significantly greater capital cost. At these prices, it would take 20.8 years for the annual cost savings from the plasma-based treatment design to break even with the GAC-based treatment design. Given the environmental benefits of the plasma-based treatment design as discussed in Section 17.1, the sensitivity of total capital and operating cost to reductions in two potential input costs to the plasma-based treatment plant are discussed below.

One major assumption of the plasma-based treatment design is that the diffusers are necessary to increase the concentration of PFAS near the surface of the water such that contact

with plasma, and hence PFAS degradation, is enhanced. However, with the implementation of the 99.8% nanofiltration preconcentration operation, the validity of this assumption can be reasonably challenged. It is possible that similar rates of PFAS degradation can be achieved without the argon gas diffusers because the preconcentration step is already increasing the bulk concentration of PFAS in the treatment volume by 500 times. The removal of gas diffusers and argon gas recycle loop would decrease the total capital cost of the plasma-based treatment plant to \$11,400,000. Further research is needed to investigate the PFAS degradation reaction kinetics within plasma reactors at higher concentrations without bubbling.

Another major assumption was that the plasma reactor had an EE/O of 16 kWh/m³, which was the average value reported in Nau-Hix et al. (2021). However, in the same paper, values of EE/O as low as 9.2 kWh/m³ were recorded. Operating at this decreased value of EE/O would result in \$449,000 of operating cost savings from electric utilities reduction and \$2,540,000 in total capital cost savings from the reduction in size of HX-1 and reduced allocated costs for electric utilities. Further research is also needed to determine optimal reactor designs that minimize the value of EE/O.

Table 18.2. Sensitivity analysis of ratio of total capital investment of plasma-based treatment design to the total capital investment of the GAC-based treatment design. For example, a 50% decrease in both electric utility usage and total bare module cost of the plasma-based treatment design would yield a design with 1.16 times the total capital investment of the GAC-based treatment design. The stairstep line delineates combinations of percentage decreases in electric utility usage and total bare module costs necessary for the total capital investment of the plasma-based treatment design to equal that of the GAC-based treatment design.

		Percent Decrease in Plasma Total Bare Module Costs									
		10	20	30	40	50	60	70	80	90	100
Percent Decrease in Electric Utility Usage	10	199%	187%	176%	164%	152%	140%	129%	117%	105%	94%
	20	190%	179%	167%	155%	143%	132%	120%	108%	97%	85%
	30	181%	170%	158%	146%	135%	123%	111%	99%	88%	76%
	40	172%	161%	149%	137%	125%	114%	102%	90%	79%	67%
	50	163%	151%	139%	128%	116%	104%	93%	81%	69%	57%
	60	153%	141%	130%	118%	106%	95%	83%	71%	59%	48%
	70	143%	131%	120%	108%	96%	84%	73%	61%	49%	38%
	80	132%	121%	109%	97%	85%	74%	62%	50%	39%	27%
	90	120%	109%	97%	85%	74%	62%	50%	39%	27%	15%
	100	105%	94%	82%	70%	59%	47%	35%	23%	12%	0%

19. Conclusions and Recommendations

The novel plasma reactor with a preconcentration method was compared against the industry standard granular activated carbon(GAC) method for the removal of PFAS from drinking water. Equipment costs, operational costs, and capital costs were calculated for each process in order to compare them. Both processes were designed to lower the concentration of PFAS in a 2,330,000 gallon/day stream of water from 4,500 ppt to 70 ppt.

These two processes must be compared on three fronts: their capital cost, their operational costs, and their environmental impact.

The capital cost associated with the plasma process was found to be \$14,800,000, which is 2.2 times larger than the capital cost found to be associated with the GAC process, \$6,730,000. This difference can be accounted for by a number of factors. The plasma reactor itself is a large cost, as it is a large, non-standard piece of equipment which would have to be constructed custom for this process. The nanofiltration preconcentration also involves a number of very large, powerful pumps, whose price is quite large compared to the pumps used in the GAC process.

This discrepancy in capital costs is offset by an opposite discrepancy in operational costs. The operational cost of the GAC process is mostly composed of the cost of replacing the GAC, including the handling of dangerous waste, and is, in total, \$6,320,000 per year. This is 107.5% the operational cost of the plasma process, which is \$5,930,000 per year, and which is made up mostly of the price of the electricity used in the process.

Environmental considerations are less easily quantified, but seem to favor the plasma process for multiple reasons. The first is that, while the carbon footprint of the specific process is minimal, the environmental impact of producing and regenerating GAC is very large(He, 2012).

The plasma process does not require the continual purchase and use of carbon products, while the GAC does. The two processes differ in the treatment of the PFAS as well. During thermal regeneration of the GAC, the PFAS breaks down into shorter chain PFAS species, which detach from the GAC as gas or as soot, which is washed off (Baghirzade, 2021). In this way, the shorter chain PFAS species can potentially return to the water system, where they may or may not impact public health, since experts are still unsure of the health effects of these short chain species. The plasma reactor, on the other hand, decreases the PFAS concentration by mineralizing the compounds, and all byproducts of the plasma reaction are environmentally safe at the levels at which they are produced by the reaction(Singh, 2019A).

Many factors which contribute to the cost of these processes are variable. For instance, a 23% reduction in the capital cost of the plasma process may be achieved by removing the argon recycle and diffuser system from the reactor. The plasma process uses argon diffusers in order to raise the concentration of PFAS at the surface of the water, but this may not be necessary, or may even be counterproductive, given the high concentration of PFAS achieved by the nanofiltration(Stratton, 2015). The plasma reactor's operational and capital costs were determined based on the average reactor efficiency across multiple literature sources, however, the operational cost of the plasma process drops by 8% and the capital cost drops by 17% when using the highest reported efficiency in literature. These price fluctuations are all due to the lack of information available on these plasma reactors, and although it cannot be quantified, it can be assumed that construction and operational costs of the plasma reactor will decrease as more research is done on their design and construction.

Altogether, this report found that the plasma process is more environmentally sound than the GAC process, that the plasma process has a lower yearly operational cost, and that the price

of the plasma reactor is more likely to decrease over time than the GAC. These factors must be balanced against the much lower capital cost of the GAC process, but they represent an advantage for the plasma process in the long run.
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22. Appendix

Appendix A: Patents

The following section includes printouts of the following documents, in the order given:

- Patent Number WO 03/045505 A1: Fire Extinguishing or Retarding Material
- Patent Application Number US2020012648: PFAS Treatment Scheme Using Separation and Electrochemical Elimination
- Patent Application Number US202017027386: Plasma Treatment System with Multiple Horizontal Channels
- Patent Number US201916698360: System and Method for Water Treatment Including Granular Activated Carbon Regeneration

(19) World Intellectual Property Organization International Bureau



(43) International Publication Date 5 June 2003 (05.06.2003)



(10) International Publication Number WO 03/045505 A1

- (51) International Patent Classification7: A62D 1/00 (21) International Application Number: PCT/US02/25521 (22) International Filing Date: 9 August 2002 (09.08.2002) (25) Filing Language: English (26) Publication Language: English (30) Priority Data: US 60/336.852 27 November 2001 (27.11.2001) Not furnished 6 August 2002 (06.08.2002) US (71) Applicant (for all designated States except US): CHEM-GUARD INCORPORATED [US/US]; 204 S. 6th Avenue,
- Mansfield, TX 76063 (US).
- (72) Inventor; and
- (75) Inventor/Applicant (for US only): CLARK, Kirtland, P. [US/US]; 2616 Brookwood Drive, Mansfield, TX 76063 (US).
- (74) Agent: BERGEN, Grady, K.; 2626 Cole Ave., Suite 400, Dallas, TX 75204 (US).

(81) Designated States (national): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZM, ZW.

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Published:

with international search report

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: FIRE EXTINGUISHING OR RETARDING MATERIAL

(57) Abstract: A foam concentrate or fire fighting composition for extinguishing and/or retarding fires is provided that meets UL162, Class B performance criteria for at least one of AFFF agents, AR- AFFF agents and fluoroprotein (FP) agents. The concentrate is used to form the fire fighting composition when mixed with water. The concentrate or fire fighting composition includes a high molecular weight fluoropolymer and water and may have a fluorine content wherein less than about 0.008% fluorine by weight of the fire fighting composition is provided from any fluorochemical surfactant. Further, the composition may meet the UL162, Class B performance criteria without forming a stable seal on cyclohexane.

FIRE EXTINGUISHING OR RETARDING MATERIAL

BACKGROUND

The prior art teaches the use of aqueous film forming foam (AFFF) agents for the rapid extinguishment of Class B fires and enhancement of safety by providing flashback or burnback resistance. First described by Francen in U.S. Pat. No. 3,562,156, AFFF agents by definition must have a positive spreading coefficient on cyclohexane. Many US patents describe the composition of AFFF agents which meet the positive spreading coefficient criteria as do US Pat. Nos. 4,420,434; 4,472,286; 4,999,119; 5,085,786; 5,218,021 and 5,616,273.

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All of the prior art has one common element; the requirement of various quantities and types of fluorochemical surfactants to obtain the positive spreading coefficient when combined with various hydrocarbon surfactants. US Pat. No. 5,616,273 describes today's AFFF and alcohol-resistant aqueous film forming foam (AR-AFFF) agents used to generate aqueous film forming foams having fluorine contents ranging from 0.020 to 0.044 percent in premix form. The actual fluorine level has been dependent on the required performance specifications with higher fluorine content providing faster extinguishing performance and greater burn back resistance. The lowest fluorine content product (0.020 %F) would contain about 1.3% by weight fluorochemical surfactant solids in the 3% liquid concentrate since these products contain about 50% by weight fluorine.

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The criterion necessary to attain spontaneous spreading of two immiscible liquids has been taught by Harkins et al, *Journal Of American Chemistry*, 44, 2665 (1922). The measure of the tendency for spontaneous spreading of an aqueous solution over the surface of non-polar solvents such as hydrocarbons is defined by the spreading coefficient (SC) and can be expressed as follows:

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 $SC_{a/b} = \gamma_a - \gamma_b - \gamma_{l,}$

(1)

where,

γь

 $SC_{a/b} = Spreading Coefficient;$

 γ_a = Surface tension of the lower hydrocarbon phase;

= Surface tension of the upper aqueous phase; and

 γ_1 = Interfacial tension between the aqueous upper phase and the lower hydrocarbon phase.

PCT/US02/25521

If the SC is positive, by theory an aqueous solution should spread and film formation on top of the hydrocarbon surface should occur. The more positive the SC, the greater the spreading tendency will be. However, in practice it has been found that no visible film seal occurs on cyclohexane until the SC is greater than about +3.5 to about +4.0, especially if the fluorochemical content is low. It is further known in the art that γ_a is reduced as the temperature of the hydrocarbon is increased, as occurs during the burning of these fuels. This will lower the effective SC during fire extinguishing unless the fire extinguishing solution also has decreasing γ_b on increasing temperature.

Fluorochemical surfactants have recently come under fire by the EPA and environmental groups. In fact, 3M agreed in May 2000 to stop the manufacture of perfluorooctanesulfonate (PFOS) and perfluorooctanoic acid (PFOA) based products including fluorinated surfactants used in AFFF and AR-AFFF agents. The EPA, prior to May 2000, had determined that PFOS posed a long-term threat to the environment after PFOS was found in all animals tested and was determined to be toxic after various long-term feeding studies. The EPA has since initiated a program requiring other perfluorochemical producers to supply information on their products to the EPA. This will allow the EPA to evaluate potential environmental problems from other fluorochemical surfactants already in the marketplace.

It is therefore desirable to have fire extinguishing products which do not contain fluorochemical surfactants, while extinguishing Class B fires as well as AFFF agents, since they should escape most EPA/environmental scrutiny.

The instant invention provides compositions that require little or no use of fluorochemical surfactants, yet the novel fire fighting liquid concentrates still meet or exceed Aqueous Film Forming Foam agent (AFFF) performance criteria on Class B, UL162 fires. If fluorochemical surfactant use is severely curtailed by the EPA, these agents could be important for the future of firefighting.

The commercial AFFF agent market consists most importantly of products which are UL listed such that consumers can be assured of minimum performance characteristics of AFFF agents. The UL 162 Standard for Safety covers Foam Equipment and Liquid Concentrates. Section 3.16, UL162 (Seventh edition, 1997) defines six liquid concentrates recognized by UL as low expansion liquid concentrates. Part a) defines *Aqueous Film Forming (AFFF)* as "a liquid concentrate that has a fluorinated surfactant base plus stabilizing additives." Part b) defines *Protein* as "a liquid concentrate that has a hydrolyzed protein plus stabilizing additives." Part c) defines *Fluoroprotein (FP)* as "a liquid concentrate that is similar to protein, but with one or more fluorinated surfactant additives." Part d) defines *Film Forming Fluoroprotein (FFFP)* as "a

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liquid concentrate that has both a hydrolyzed protein and fluorinated surfactant base plus stabilizing additives." Part e) defines *Synthetic* as "a liquid concentrate that has a base other than fluorinated surfactant or hydrolyzed protein. Finally Part f) defines *Alcohol Resistant* as "a liquid concentrate intended to extinguish both hydrocarbon and polar (water miscible) fuel fires."

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Fire test foam application and duration to burn back ignition is given in UL162 Table 10.1 for Class B fire tests. These minimum performance criteria must be met for liquid concentrates to be "UL listed" as Class B liquid concentrates. Of the six liquid concentrates defined by UL 162, only *protein* and *synthetic* do not contain fluorosurfactant and, of these, only *protein* has UL listed products for use on Class B liquid fires. At this time, *synthetic liquid concentrates* are only UL listed as *wetting agents* and defined by UL as "liquid concentrates which, when added to plain water in proper quantities, materially reduce the surface tension of plain water and increases its penetration and spreading ability… Listed wetting agents solutions or foams improve the efficiency of water in extinguishing fires."

15 DISCLOSURE OF THE INVENTION

The invention provides compositions for use as fire extinguishing concentrates, which meet or exceed Fluoroprotein (FP), AFFF and AR-AFFF performance criteria on Class B, UL162 fires, but without the need of fluorochemical surfactants, as required in the prior art. These compositions include synthetic liquid concentrates stabilized with high molecular weight fluorinated polymers (HMW-FP), which extinguish both non-polar Class B type fires and polar fires. No fluorosurfactants are required to meet the UL162 standard, but may be used to improve extinguishing speed and burnback times, if desired.

The invention further provides a method of extinguishing Class B fires using novel fire fighting compositions having no added fluorochemical surfactant or with very low fluorochemical surfactant content. This method provides fast extinguishment and burn back similar to that provided by FP agents, as well as AFFF agents having high fluorochemical surfactant content.

It has been found that synthetic liquid concentrate can be stabilized to Class B liquid fire performance (UL162) with the addition of various foam stabilizing polymeric additives. The effectual polymeric additive and the effective level necessary for improving the synthetic liquid concentrate may be identified and determined through a laboratory test. Especially effective in stabilizing the synthetic liquid concentrate foam bubble to Class B liquids are high molecular weight polymers (HMW-FPs) containing perfluorinated substituents, including commercial products such as Lodyne 5100 marketed by Ciba Specialty Chemicals Corporation, Basel, Switzerland; Chemguard FP-111 and FP-211, available from Chemguard Incorporated,

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Mansfield, Texas; and Dynax 5011, marketed by Dynax Corporation, Elmsford, New York. All of these products are additives for use in polar type AFFF (AR-AFFF) agents. They are known to act in AR-AFFF formulations by staying in the foam bubble and laying down a thin vapor-impervious film between the polar water-soluble solvent and the foam-water layer as the first bubbles are attacked by the solvent.

The present invention may also provide protein-based fire extinguishing agents without the use of fluorochemical surfactants.

HMW-FP has lower toxicity compared to monomeric fluorochemical surfactants. In fact, it is much easier to list polymers (none reactive) on the TOSCA inventory than low molecular weight materials. Similarly, in Europe, polymers are exempt from the EINICS list. It is widely understood that as polymers increase in MW, their absorption rate through skin decreases. Further, high MW polymers rapidly adsorb to solid surfaces such as dirt, rocks, etc, and are much less available for entering water ways. Therefore, they are in general more environmentally benign than low MW surfactants and chemicals.

The present invention pertains to novel fire extinguishing compositions especially useful for extinguishing UL 162 Class B polar (water soluble) and non-polar (water insoluble) liquid fires by the addition of effectual HMW-FP to various synthetic liquid concentrates at effective levels. The effectual polymer and the effective level may be determined through a laboratory test described under the Experimental Section below.

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The synthetic surfactant liquid compositions may be produced at many strengths including but not limited to 1, 3 and 6% by weight foam concentrates, which are typical commercial concentrations. The concentrates may also be less than 1% by weight to greater than 6% by weight or even 10% by weight, if desired. The lowest numbered strength for the concentrate is actually the most concentrated product. Therefore, one part of 1% concentrate and 99 parts water gives 100 parts of use strength pre-mix, whereas, three parts 3% and 97 parts water gives 100 parts of pre-mix. As used herein, the term "water" may include pure, deionized or distilled water, tap or fresh water, sea water, brine, or an aqueous or water-containing solution or mixture capable of serving as a water component for the fire fighting composition.

For the sake of simplicity only 3% concentrate products are exemplified here, while it will be readily understood by those skilled in the art that many other strength products may be used.
Unless stated otherwise, all percentages presented herein for compositions are based on weight.
A general composition for a 3% liquid concentrate (used at 3 parts concentrate to 97 parts fresh or tap water) may include the following components:

9	Comr	ponent	<u>% by weight (100%)</u>
4	A	High MW fluorinated polymer (HMW-FP)	0.2 - 10
]	В	Amphoteric Hydrocarbon Surfactant	0 – 3
(С	Anionic Hydrocarbon Surfactant	2 – 10
]	D	Nonionic Hydrocarbon surfactant	0 - 5
]	E	Fluorochemical Surfactant	0 - 0.4
]	F	Foam aids including glycol ethers	0 - 15
(G	Freeze protection package	0 - 45
]	H	Sequestering, buffer, corrosion package	0 – 5
]	[Polymeric film formers	0 - 2
	J	Biocides, antimicrobial	0-0.1
]	K	Electrolytes	0 – 3
]	L	Polymeric foam stabilizers and thickeners	0 - 10
]	М	Water	Balance

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The above components would be reduced or increased accordingly relative to the 3% liquid concentrate to prepare 6% and 1% synthetic liquid foam concentrates, or other concentrate levels. Thus, for a 1% concentrate, the above amounts may be increased by a factor of 3, whereas for a 6% concentrate the above amounts may be reduced by half.

20 Most Class A foam concentrates fit within the definition of the base surfactant defined above. Therefore, one may also add an effectual HMW-FP (as may be determined from the laboratory test described) to many Class A foam concentrates. Similarly, an effectual HMW-FP may also be added to 3 or 6% liquid protein concentrate containing no or limited amounts of fluorochemical surfactant.

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The HMW-FPs (Component A) are products prepared from perfluorinated monomers, either mono- or polyfunctional, polymerized with reactive polyfunctional monomers, prepolymers or high MW polymers with appropriate reactive sites. As used herein with respect to the fluoropolymers described, high molecular weight (HMW) is construed to encompass those polymers having an average molecular weight of from about 3000 g/mol or greater, more particularly those having an average molecular weight of from about 5000 g/mol or greater, and still more particularly those having an average molecular weight of from about 5000 g/mol or greater, and still more particularly those having an average molecular weight of from about 10,000 g/mol, 20,000 g/mol, 30,000 g/mol, 50,000 g/mol or greater. A suitable range may include those having an average molecular weight of from about 5,000 g/mol, 10,000 g/mol, 20,000 g/mol or 30,000 g/mol to about 100,000 g/mol, 150,000 g/mol or more. Those soluble polymers having relatively higher molecular weights may be particularly well suited.

Examples of suitable fluoropolymers include, but are not limited to, those described in US Pat. Nos. 6,156,222, 5,750,043 and 4,303,534 and European Patent No. EP 0 765 676 A1, which are herein incorporated by reference. Szonyi and Cambon describe a suitable addition polymer

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between Fluotan B830, a perfluoro alkyl polyamine, and xanthan gum in *Fire Safety Journal*, 16, (1990), pages 353-365, which is incorporated herein by reference. Another suitable perfluorinated polymer is prepared from (hydroxypropyl) cellulose (Hercules Klucel, MW = 60,000) and perfluorooctanyl chloride, as described in Macromolecules, 27, 1994, pages 6988-6990, which is incorporated herein by reference.

One suitable commercially available polymer (Component A) is Lodyne 5100, which is a high MW perfluorinated polyamino acid (anionic) and contains approximately 19% fluorine by weight of solids. Other commercially available polymers include high MW perfluorinated polyols, available as Chemguard FP-111, which is a non-anionic polyol and contains approximately 17% fluorine by weight of solids, and Chemguard FP-211. Chemguard FP-111 has perfluoro-tails from C_6-C_{12} while Chemguard FP-211 has only C_4 perfluoro-tails (CF₃CF₂CF₂CF₂-).

Dynax 5011 is a relatively lower molecular weight (i.e. MW ~ 5000 g/mol) anionic polymer containing about 18% fluorine by weight of solids, did not work well alone, but did when combined with Lodyne 5100 as a 50/50 mixture. Therefore, it has been found that poorer performing polymers can be used effectively if mixed with higher efficiency polymers such as Lodyne 5100 or Chemguard FP-111.

The high molecular weight fluoropolymers may be used in an amount to provide a foam concentrate that may have from about 0.005% or less to about 6% or more fluorine by weight of concentrate, more typically from about 0.01% to about 4.5% fluorine by weight of concentrate. The final fire fighting foam or composition may have a fluorine content of from about 0.0003% to about 0.065% fluorine by weight of solution, with from about 0.0006% to about 0.05% by weight fluorine from the fluoropolymers being typical, and from 0.001% to about 0.035% by weight fluorine being more typical. The amounts of fluorine from the fluoropolymer will vary in the concentrate depending upon the type of concentrate employed. Thus a 3% concentrate may have from about 0.01% by weight fluorine to about 2% by weight fluorine from the HMW-FP, with from about 0.02% to about 1.5% by weight being typical and from about 0.05% to about 1% by weight being more typical. A 1% foam concentrate may have from about 0.03% to about 6% by weight fluorine from the HMW-FP, with from about 0.06% to about 4.5% by weight fluorine being typical, and from about 0.15% to about 3% by weight fluorine being more typical. A 6% concentrate may have from about 0.005% to about 1% by weight fluorine from the HMW-FP. with from about 0.01% to about 0.5% by weight fluorine being typical, and from about 0.025% to about 0.4% by weight fluorine being more typical.

Amphoteric hydrocarbon surfactants (Component B) include, but are not limited to, those which contain in the same molecule, amino and carboxy, sulfonic, sulfuric ester and the like.

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Higher alkyl (C6-C14) betaines and sulfobetaines are included. Commercially available products include Chembetaine CAS and Mirataine CS, both sulfobetaines, and Deriphat 160C, a C12 amino-dicarboxylate. These products are foaming agents and help reduce interfacial tension in water solution.

Anionic hydrocarbon surfactants (Component C) include, but are not limited to, alkyl carboxylates, sulfates, sulfonates, and their ethoxylated derivatives. Alkali metal and ammonium salts are suitable. The C8-C16 hydrocarbon surfactants are suitable, with more narrowly the C8-C12, and still more narrowly the C8-C10 being suitable.

The nonionic hydrocarbon surfactants (Component D) help reduce interfacial tension and solubilize other components, especially in hard water, sea water or brine solutions. In addition, they serve to control foam drainage, foam fluidity, and foam expansion. Suitable nonionic surfactants include, but are limited to, polyoxyethylene derivatives of alkylphenols, linear or branched alcohols, fatty acids, alkylamines, alkylamides, and acetylenic glycols, alkyl glycosides and polyglycosides, as defined in US Patent 5,207,932 (herein incorporated by reference) and others, and block polymers of polyoxyethylene and polyoxypropylene units.

While the use of fluorochemical surfactants (Component E) may be eliminated, they may be useful at certain levels. The fluorochemical surfactants are typically single perfluoro-tail molecules and may have multiple hydrophilic heads. Examples of fluorochemical surfactants can be found in the many of the AFFF-related patents, including, but not limited to, those described in U.S. Pat. Nos. 5,616,273, 5,218,021; 5,085,786; 4,999,119; 4,472,286; 4,420,434; 4,060,489, which are herein incorporated by reference.

Quantities of fluorochemical surfactant may be added to increase extinguishing speed and burnback resistance. The total fluorochemical surfactant content may be less than one-half of the typical workable levels in the absence of the fluorinated polymers to provide UL 162 Class B fire performance. The fluorosurfactant may provide less than about 0.2% or 0.1% fluorine in a 3% concentrate, or less than about 0.006% or 0.003% fluorine, respectively, at the working strength. Fluorine content provided by any fluorosurfactant in the final or working fire fighting composition may be less than 0.002% or even 0.001% fluorine by weight of the working composition. This compares very favorably with data of U.S. Patent No. 5,207,932 leading to a commercial product with low end working fluorine content of 0.013% fluorine (a 55% reduction in fluorine content).

Foam aids (Component F) are used to enhance foam expansion and drain properties, while providing solubilization and anti-freeze action. Useful foam aids are disclosed in U.S. Pat. Nos. 5,616,273, 3,457,172; 3,422,011 and 3,579,446, which are herein incorporated by reference.

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Typical foam aids are alcohols or ethers such as: ethylene glycol monoalkyl ethers, diethylene glycol monoalkyl ethers, propylene glycol monoalkyl ethers, dipropylene glycol monoalkyl ethers, triethylene glycol monoalkyl ethers, 1-butoxyethoxy-2-propanol, glycerine, and hexylene glycol.

The freeze protection package (Component G), include glycerine, ethylene glycol, diethylene glycol, and propylene glycol. Also included are salts and other solids which reduce freeze point such as calcium, potassium, sodium and ammonium chloride and urea. Component H, the sequestering, buffer, and corrosion package, are sequestering and chelating agents exemplified by polyaminopolycarboxylic acids, ethylenediaminetetraacetic acid, citric acid, tartaric acid, nitrilotriacetic acid, hydroxyethylethylenediaminetriacetic acid and salts thereof. Buffers are exemplified by Sorensen's phosphate or McIlvaine's citrate buffers. Corrosion inhibitors are only limited by compatibility with other formula components. These may be exemplified by ortho-phenylphenol, toluyl triazole, and many phosphate ester acids.

Component I is a water soluble polymeric film former and may be used for the 15 formulation of AR-AFFF (alcohol resistant) agents which are used to fight both polar (water soluble) and non-polar solvent and fuel fires. These polymeric film formers, dissolved in AR-AFFF agents, precipitate from solution when the bubbles contact polar solvents and fuel, and form a vapor repelling polymer film at the solvent/foam interface, preventing further foam collapse. Examples of suitable compounds include thixotropic polysaccharide gums as described in U.S. Pat. Nos. 3,957,657; 4,060,132; 4,060,489; 4,306,979; 4,387,032; 4,420,434; 4,424,133; 4,464,267, 5,218,021, and 5,750,043, which are herein incorporated by reference. Suitable commercially available compounds are marketed as Rhodopol, Kelco, Keltrol, Actigum, Cecalgum, Calaxy, and Kalzan.

Gums and resins useful as Component I include acidic gums such as xanthan gum, pectic acid, alginic acid, agar, carrageenan gum, rhamsam gum, welan gum, mannan gum, locust bean gum, galactomannan gum, pectin, starch, bacterial alginic acid, succinoglucan, gum arabic, carboxymethylcellulose, heparin, phosphoric acid polysaccharide gums, dextran sulfate, dermantan sulfate, fucan sulfate, gum karaya, gum tragacanth and sulfated locust bean gum.

Neutral polysaccharides useful as Components I include: cellulose, hydroxyethyl cellulose, dextran and modified dextrans, neutral glucans, hydroxypropyl cellulose, as well, as other cellulose ethers and esters. Modified starches include starch esters, ethers, oxidized starches, and enzymatically digested starches.

Components J, antimicrobials and preservatives, may be used to prevent biological decomposition of natural product based polymers incorporated as Components I. Included are

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Kathon CG/ICP and Givgard G-4-40 manufactured by Rohm & Haas Company and Givaudan, Inc., respectively, and are disclosed in U.S. Pat. No. 5,207,932, which is herein incorporated by reference. Additional preservatives are disclosed in the above-mentioned polar agent patents -U.S. Pat. Nos. 3,957,657; 4,060,132; 4,060,489; 4,306,979; 4,387,032; 4,420,434; 4,424,133; 4,464,267, 5,218,021, and 5,750,043.

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Components K include electrolytes that may be added to AFFF and AR-AFFF agents to balance the performance of such agents when proportioned with water ranging from soft to very hard, including sea water or brine, and to improve agent performance in very soft water. Typical electrolytes are salts of monovalent or polyvalent metals of Groups 1, 2, or 3, or organic bases. The alkali metals particularly useful are sodium, potassium, and lithium, or the alkaline earth metals, especially magnesium, calcium, strontium, and zinc or aluminum. Organic bases might include ammonium, trialkylammonium, bis-ammonium salts or the like. The cations of the electrolyte are not critical, except that halides may not be desirable from the standpoint of metal corrosion. Sulfates, bisulfates, phosphates, nitrates and the like are acceptable. Examples of polyvalent salts include such things as magnesium sulfate and magnesium nitrate.

Components L are polymeric foam stabilizers and thickeners which can be optionally incorporated into AFFF and AR-AFFF agents to enhance the foam stability and foam drainage properties. Examples of polymeric stabilizers and thickeners are partially hydrolyzed protein, starches, polyvinyl resins such as polyvinyl alcohol, polyacrylamides, carboxyvinyl polymers, polypyrrolidine, and poly(oxyethylene) glycol.

Many commercial synthetic surfactant concentrates are marketed worldwide and include those available from Chemguard, Kidde, and Tyco. High MW perfluorinated polymers may be added to these liquid concentrates at an effective concentration. These products include: Class A foams (CLASS A PLUS and SILVEX), excellent for extinguishing forest fires, structural fires, and tire fires; high expansion foams sold under the names HI-EX, EXTRA, C2, and VEE-FOAM; vapor suppressant foam sold by Chemguard as VRC foam; bomb foam, a 6% product sold by Chemguard as AFC-380.

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Synthetic surfactant concentrates listed as "wetting agents" by Underwriters Laboratory may also be included as base surfactant mixtures for use in this invention. Products listed by UL as "wetting agents" are as follows: Fire Strike by Biocenter Inc.; Bio-Fire by Envirorenu Technologies LLC; Enviro-Skin 1% by Environmental Products Inc.; F-500 by Hazard Control Technologies Inc.; Knockdown by National Foam Inc.; Phos-Chek WD881 by Solutia Inc.; Flameout by Summit Environmental Corp. Inc. Micro-Blazeout by Verde Environmental Inc.; Bio-solve by Westford Chemical Corp.

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In the examples below, references are made to specifications or procedures that may be used in the industry to evaluate the efficiency of synthetic surfactant concentrates. More specifically, the examples refer to the following specifications and laboratory test methods:

5 1. Surface Tension and Interfacial Tension: According to ASTM D-1331-56.

Based on laboratory tests, the surface tension of cyclohexane used for calculating the SC was 24.7 dynes/cm. The SC against cyclohexane for the fire fighting compositions described herein may range from about -4 to 4 or more, without forming a film at 23 °C.

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2. Laboratory Film Spreading and Burn back Test: This test can be carried out to determine film speed and film formation of Synthetic surfactant premixes on cyclohexane.

A 100X20 mm pyrex petri dish is placed over a dark, wet surface, so that good visual observation is possible. 50 ml cyclohexane solvent is added to the petri dish. A 0.5 inch (~1.3 cm) long stainless steel wood screw, pointing upwards, is placed in the center of the dish. The timer is started simultaneously 3 ml of premix are added dropwise from a pipette in one-second intervals onto the top of the screw.

When the surface of the solvent is completely covered with the film, the time of seal is recorded. The timer is left running and the screw is removed carefully so as not to disturb the film layer. With a lighter, the surface is tested for completeness of a seal. If the seal is not complete or is broken, the solvent will ignite or flash. The flames are extinguished by smothering and the result is recorded. A stable seal is formed if after two minutes from when the seal is formed the fuel will not ignite when a flame is brought near the surface of the fuel.

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3. Laboratory Foam Expansion and Drain Time Test.

100 ml of a premix to be tested is prepared with either tap or artificial sea-water (as defined by ASTM D1141). 100 ml of premix is poured into a Waring Blender with a glass canister. At mix speed, the premix solution is blended for 20 seconds. The generated foam is poured into a graduated 1000 ml cylinder. The foam height is recorded and the foam expansion ratio is calculated by dividing foam volume (ml) by foam weight (g). The time which passes between the time the blender has stopped and when the drain in the graduated cylinder reaches 25.0 ml is recorded. This time is called the ¹/₄ drain time.

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4. Laboratory Hot Heptane Foam Stability Test.

This test may be carried out to determine which of the many commercial HMW-FPs may be useful and what concentration may be necessary to provide the desired fire extinguishing performance.

The polymer or polymer mixture being evaluated is formulated typically at about 0.3 - 0.5% fluorine content into a 3% synthetic liquid concentrate (Blank A, Table 1). The concentrate is made into a premix and then is foamed using the procedure of Test Method 3, described above.

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Heptane is heated to about 73°C and 150 ml is poured into each of two 1000 ml beakers set into insulating panels to the 150 ml level. When the temperature reaches about 70°C, 150 ml of pre-made foam is poured into each beaker. Begin timing as soon as each heptane layer is fully covered with foam. Note: Water may immediately begins to drain from the foam and passes through the heptane to the bottom of the beaker. As foam continues to drain and break down, vapor bubbles near the heptane surface are broken, such as with a pipette. Finally, the foam layer thins and the heptane layer breaks through to the air. When the heptane layer begins to break such that approximately 1% of heptane surface is open, the timer is stopped. Foam Life is calculated by the equation:

Foam Life (minutes) =
$$FO_t - FC_t$$
 (2)

where,

 FC_t = Foam Cover Time FO_t = Time Foam Opens to 1%

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Foam Life may include the average of two or more runs from foam cover time to foam breakup time. Useful polymers or polymer mixtures may have foam lives equal to or greater than 30 minutes, 40 minutes, 50 minutes, 60 minutes or more. After about 60 minutes, or other allotted time period, the remaining foam is decanted from the beaker and weighed.

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By way of example, the Blank A formula discussed below had a foam life of only 6.7 minutes and all foam was gone by 7.5 minutes.

5. The UL 162 Type III, Class B, topside, fire test (heptane) for AFFF agents.

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This test may be used to test synthetic liquid concentrates as premixes in tap water and synthetic sea water. In the examples presented herein, this test was used for 3% synthetic liquid concentrates. For each fire test, 55 gallons (~250 liters) of heptane is charged to a 50 ft² (~4.645m²) heavy steel UL pan with enough water in the bottom to give at least eight inches of sideboard. A US military type aspirating nozzle adjusted to give a 2.0 gallon (~9.092 liter) per minute flow rate is placed on a stand. The fire is lit, allowed to burn for 60 seconds, and then foam is directed directly onto the surface of the fuel until the fire is about 75% extinguished. Thereafter, the nozzle may be moved to direct the foam stream back and forth across the surface until approximately 90% extinguishment (control time) is obtained, at which time the fire may be fought from two sides of the pan. Times are recorded at 90% control and at extinguishment. Foam application is continued for a total of 3 minutes.

At about 8 minutes, a 1.0 square foot (~0.0929m²) steel stovepipe is placed 1.0 ft (0.3048 m) from each side of the corner last extinguished and all foam inside the pipe is removed. After waiting 9 minutes from foam shut-off, the fuel inside the pipe is lit and allowed to burn for 1 minute. The pipe is then removed and timing of the burnback is started. When the fire increases to 20% of the pan area, the burnback time is recorded.

Foam quality is measured by taking the expansion ratio and drain time from the nozzle after running the fire test.

An AFFF product passes the UL 162 Type III, Class B, topside, fire test by extinguishing before 3 minutes and having a burnback equal to or greater than 5 minutes. Stronger products give shorter extinguishing and longer burnback times.

6. The UL162 Type II, Class B topside isopropanol fire test for AR-AFFF agents.

This test uses the same 50 ft² (~4.645 m²) pan as the above heptane test (5) but now the foam is applied to a backboard instead of directly into the fuel. The application rate is 4.5 gpm (~20.4575 lpm) or 0.09 gal/ft² (~4.40 liters/m²) from a nozzle placed on a stand. No touching or moving of the nozzle is allowed during foam application. 55 gallons (~250 liters) of isopropanol (no water) are placed in the pan, the temperature is taken and the fire is lit. After one minute of preburn, foam application is begun. Foam is applied for five minutes, while Control and Extinguishment times are recorded.

At about 13 minutes from the end of foam application, a 1.0 square foot ($\sim 0.0929m^2$) steel stove pipe is placed 1.0 ft (0.3048 m) from each side of the corner last extinguished and all foam inside the pipe is removed. After waiting 15 minutes from foam shut-off, the fuel inside the pipe

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is lit and allowed to burn for 1 minute. The pipe is then removed and timing of the burnback is started. When the fire increases to 20% of the pan area, the burnback time is recorded.

Foam quality is measured by taking the expansion ratio and drain time from the nozzle after running the fire test.

An AR-AFFF (polar) product passes this fire test by extinguishing before 5 minutes and having a burnback equal to or greater than 5 minutes. Stronger products give shorter extinguishing and longer burnback times.

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The UL 162 Type III, Class B, topside, fire test for Fluoroprotein (FP) agents.

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This test may be used to test liquid concentrates as premixes in tap water and synthetic sea water. In the examples presented herein, this test was used on 3% synthetic concentrates. For each fire test, 55 gallons (~250 liters) of heptane is charged to a 50 ft² (~4.645 m²) heavy steel UL pan with enough water in the bottom to give at least eight inches of sideboard. A US military type aspirating nozzle adjusted to give a 3.0 gallon (13.6383 l) per minute flow rate is placed on a stand. The fire is lit, allowed to burn for 60 seconds, and then foam is directed onto the surface of the fuel until the fire is about 75% extinguished. Thereafter, the nozzle may be moved to direct the foam stream back and forth until approximately 90% extinguishment (control time) is obtained, at which time the fire may be fought from two sides of the pan. Times are recorded at 90% control and at extinguishment. Foam application is continued for a total of 5.0 minutes.

At about 14 minutes, a 1.0 square foot ($\sim 0.0929m^2$) steel stovepipe is placed 1.0 ft (0.3048 m) from each side of the corner last extinguished and all foam inside the pipe is removed. After waiting 15 minutes from foam shut-off, the fuel inside the pipe is lit and allowed to burn for 1 minute. The pipe is then removed and timing of the burnback is started. When the fire increases to 20% of the pan area, the burnback time is recorded.

Foam quality is measured by taking the expansion ratio and drain time from the nozzle after running the fire test.

A FP product passes this fire test by extinguishing before 5.0 minutes and having a burnback equal to or greater than 5 minutes. Stronger products give shorter extinguishing and longer burnback times. It should be noted that FPs when compared with AFFF agents are applied at a rate of 0.06 gal/ft² (~2.94 l/m²) vs 0.04 gal/ ft² (~1.948 l/m²) and for two minutes longer than AFFF agents; a longer burnback of 21 minutes minimum is required for FPs vs 15 minutes for AFFF agents.

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EXAMPLES

Three simple 3% synthetic surfactant concentrates were used for the examples given in this patent application; Blanks A, B, and C are given below.

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Components	Blank A	Blank B	Blank C
	(as 100%)	(as 100%)	(as 100%)
High MW Fluorinated Polymer (HMW-FP)	0	0	0
Fluorinated Surfactant	0	0	0
Chemguard HS-100	0	0.7	0
Cocoamidopropyl hydroxyproyl Betaine	0.8	0.8	0.8
Sodium Decyl Sulfate	4.5	4.5	5.4
Polysaccharide	0	0	0.8
Butyl Carbitol	5.0	5.0	5.0
Magnesium Sulfate	2.0	2.0	2.0
Water	87.7	87.0	86.0

Table	1	
I UDIC	1	

Chemguard HS-100 is a commercially available anionic hydrocarbon surfactant manufactured by Chemguard Inc. at 45% solids in water. The cocoamidopropyl

hydroxyproyl betaine used was that available as Chembetaine CAS, which is a 50% solids

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cocoamidopropyl hydroxypropyl sulfobetane, available from Chemron. The sodium decyl sulfate used was that available as Sulfochem NADS, which is 30% solids sodium decyl sulfate in water, available from Chemron. The polysaccharide was ADM xanthan gum from ADM. Glycol ether DB is butyl carbitol or 2-(2-Butoxyethoxy)ethanol and magnesium sulfate is charged as the heptahydrate.

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Table 2a

3%	Blank A	A1	A2	A3	A4a	A4b	A5
Non-polar							
Agents							
High MW	none	5100	FP-111	FP-211	5011	5011	EMP68
Fluorinated Polymer							
(HMW-FP)							
% Fluorine in conc.	none	0.30	0.30	0.40	0.27	0.45	0.37
Tap water tests							
Surface Tension*	24.6	21.6	20.3	22.1	24.3	24.3	23.0
Interfacial Tension**	0.7	2.3	2.1	2.5	3.4	3.5	2.3
Spreading Coefficient	-0.6	+0.8	+2.3	+0.1	-3.0	-3.1	-0.6
Cyclohexane Seal (%)	<10	<10	<10	<10	<10	<10	<10
Flash Test	Fail	Fail	Fail	Fail	Fail	Fail	Fail

*dynes/cm; ** dynes/cm, against cyclohexane

Table 2b

3% Non-polar Agents Blank A A6 A7 **A8** 5100/FP-111 5100/FP-211 5100/5011 High MW Fluorinated none Polymer (HMW-FP) 0.15/0.15 0.15/0.14 % Fluorine in conc. none 0.15/0.20 Tap water tests Surface Tension* 24.6 20.3 21.6 23.1 Interfacial Tension** 0.7 2.4 2.3 2.7 Spreading Coefficient -1.1 +0.8 -0.6 +2.0Cyclohexane Seal (%) <10 <10 ×10 <10 Flash Test Fail Fail Fail Fail

*dynes/cm; ** dynes/cm, against cyclohexane

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Table 2c

3% Non-polar Agents	Blank B	B1	B2	B3	B4a
High MW Fluorinated Polymer (HMW-FP)	none	5100	FP-111	FP - 211	5011
% Fluorine in conc.	none	0.30	0.30	0.40	0.27
Tap water tests					
Surface Tension*	24.8	22.5	20.4	19.6	24.4
Interfacial Tension**	3.0	2.3	2.3	2.2	2.3
Spreading Coefficient	-3.1	-0.1	+2.0	+2.9	-2.0
Cyclohexane Seal (%)	<10	<10	<10	<10	<10
Flash Test	Fail	Fail	Fail	Fail	Fail

*dynes/cm; ** dynes/cm, against cyclohexane

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Lodyne 5100, is available from Ciba Specialty Chemicals Corporation, and contains 6.5% fluorine as is. Chemguard FP-111 and Chemguard FP-211 by assay had 3.3% fluorine as is, each. Dynax 5011 from Dynax Corporation by assay had 6.3% fluorine as is, while Atofina's Forafac EMP68-II had 6.2% fluorine as is.

Table 3a

Hot Heptane Foam Stability Test

3% Non-polar Agents	Blank A	A1	A2	A3	A4a	A4b	A5
Foam Life (min.)	6.7	>60	>60	>60	7.7	16.2	20.0
Foam Weight (gm)	0	3.6	4.1	2.4	0	0	0

Table 3b

Hot Heptane Foam Stability Test

	A6	A7	. A8
Foam Life (min.)	>60	>60	>60
Foam Weight (gm)	3.5	4.7	3.5

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Table 4a

UL 162 Type III, Class B, Heptane Fire Tests, 3%Tap, 0.04 gal/ ft² (~1.948 l/m²)

3% Non-polar Agents	Blank A	A1	A2	A3	A4a	A4b	A5
Heptane,°F (°C)	86 (30)	81 (27.2)	81(27.2)	82 (27.8)	77 (25)	81(27.2)	79(26.1)
Water, °F (°C)	86 (30)	81 (27.2)	84(28.9)	86 (30)	77 (25)	84 (28.9)	84 (28.9)
Control Time*	2.8	1.7	1.8	1.2	1.5	1.3	1.8
Extinguish. Time*	None	2.8	2.7	2.0	2.4	2.3	3.2
Burnback Time*	N/R	>9.01	8.0	>10.0 ²	0	0	0
Foam Exp.	6.7	6.9	5.6	9.3	9.2	9.1	5.7
Foam ¼ Drain*	4.2	3.4	2.6	3.4	3.7	3.6	3.2

*Time in minutes, ¹15% burnback area at 9.0 min., ²0.1% burnback area at 10 min.

Table 4b

UL 162 7	Гуре III,	Class B, Hept	ane Fire Tests	, 3%Tap,	0.04 gal/	ft² (~1.948 l/m²)
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3% Non-polar Agents	Blank A	A6	A7	A8
Heptane, °F (°C)	86 (30)	82 (27.2)	77(25)	81(27.2)
Water, °F (°C)	86 (30)	84 (28.9)	81(27.2)	82(27.8)
Control Time*	2.8	1.9	1.3	1.3
Extinguish. Time*	None	3.0	2.1	2.3
Burnback Time*	N/R	6.8	7.6	7.3
Foam Exp.	6.7	5.6	8.6	8.0
Foam ¼ Drain*	4.2	3.1	3.4	3.6

*Time in minutes

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Table 5

3% Non-polar Agents	Blank B	B1	B2	B3	B1	B2
Water Type	Тар	Тар	Tap	Тар	Sea	Sea
Heptane, °F °C)	82(27.8)	81(27.2)	80(26.7)	81(27.2)	82(27.8)	75(23.9)
Water, °F (°C)	90(32.2)	86(30)	80(26.7)	86(30)	90(32.2)	79(26.1)
Control Time*	1.3	1.0	1.1	1.3	1.1	1.0
Extinguish. Time*	None	2.0	2.2	2.3	2.0	1.8
Burnback Time*	N/R	>8.01	>9.0 ²	7.0	5.7	>8.0
Foam Exp.	6.1	8.6	7.3	8.3	7.3	6.3
Foam ¼ Drain*	4.0	3.4	5.1	4.3	4.5	3.5

UL	162 Type III,	Class B, Heptane Fire	Tests, 0.04 ga	l/ ft² (~1.948 l/m²)
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*Time in minutes, ¹ Only 6% burning at 8.0 min., ² Only 1% burning at 9.0 min.

Table 6

UL 162 Type III, Class B, Heptane Fire Tests, 3% Tap, 0.04 gal/ft² (~1.948 l/m²)

	Blank C	C1	C6	C8
HMW-FP	None	5100	5100/	5100/
			FP-111	5011
% Fluorine in Conc.	0	0.30	0.15/0.15	0.15/0.14
Heptane, °F (°C)	82(27.8)	81(27.2)	79(26.1)	77(25)
Water, °F (°C)	83(28.4)	78(25.6)	78(25.6)	77(25)
Control Time*	2.8	1.4	1.9	1.2
Extinguish. Time*	None	2.7	3.0	2.4
Burnback Time*	N/R	7.5	5.4	1.7
Foam Exp.	8.6	6.9	5.9	8.8
Foam ¼ Drain*	4.7	8.3	7.4	7.6

*Time in minutes

Table 7

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III 162 Type II Class R	Iconronanol Fire Teste	20% in Tan Water	$0.00 \text{ col}/\Omega^2$ ($1.4.40 \text{ liters/m}^2$)
OL 102 Type II, Class D,	isopropation time resis	s, 570 m rap water,	0.09 gai/it (~4.40 mers/iii)

3X3 Polar Agents	Blank C	C 1	C6	C 7	C8
HMW-FP	None	5100	5100/	5100/	5100/
			FP-111	FP-211	5011
% Fluorine	0	0.30	0.15/0.15	0.15/0.20	0.15/0.14
in Conc.					
IPA, °F (°C)	73(22.8)	82(27.8)	52 (11.1)	58(14.4)	60(15.6)
Control Time*	none ¹	1.7	1.3	1.3	1.4
Extinguish. Time*	Only 2% ¹	3.0	2.5	2.3	2.8
Burnback Time*	N/R	7.2	6.2	9.8	1.8
Foam Exp.	9.5	7.5	6.3	7.4	8.8
Foam	6.5	7.2	6.0	5.7	5.4
1/4 Drain*					

*Time in minutes, ¹ After 3.3 minutes of foam application, only 2% extinguished so stopped test with backup unit.

Table 8a

3% Non-polar	A9	A9	A10	A10	A11
Agents					
Components	A1+	A1+	A2 +	A2 +	A +
-	1157N	1157N	1157N	1157N	1157N
% Fluorine	0.30/0.10	0.30/0.10	0.30/0.10	0.30/0.10	0.10
in conc.					
Water Type	Тар	Sea	Тар	Sea	Тар
Heptane, °F (°C)	75(23.9)	70(21.1)	77(25)	77(25)	72(22.2)
Water, °F (°C)	75(23.9)	72(22.2)	84 (28.9)	77(25)	77(25)
Control Time**	1.2	1.1	1.1	1.1	1.6
Extinguish. Time**	2.3	2.7	2.5	2.2	2.8
Burnback Time**	8.2	8.2	16.5	8.5	2.2
Foam Exp.	7.6	6.8	5.9	5.3	8.3
Foam	2.7	4.0	3.7	3.2	3.0
¹ ⁄4 Drain**					
Surface Tension	21.0		20.2		19.8
Interfacial Tension	2.7		2.6		1.8
Spreading Coeffic.	+1.0		+1.9		+3.1

UL 162 Type III, Class B, Heptane Fire Tests, 0.04 gal/ft² (~1.948 l/m²)

*Dashed line indicates no data available. ** Time in minutes

Table 8b*

UL 162 Type III, Class B, Heptane Fire Tests, 0.04 gal/ft² (~1.948 l/m²)

3% Non-polarAgents	A12	A12	A13	A14
Components	A +	A +	A +	A +
	1157N	1157N	1157N	1157N
% Fluorine in conc.	0.20	0.20	0.30	0.40
Water Type	Тар	Sea	Sea	Sea
Heptane, °F (°C)	77(25)	78(25.6)	78(25.6)	78(25.6)
Water, °F (°C)	83(28.4)	85(29.4)	85(29.4)	88(31.1)
Control Time**	1.3	1.2	1.0	0.9
Extinguish.Time**	2.4	2.0	1.7	1.4
Burnback Time**	6.1	3.4	3.7	7.6
Foam Exp.	8.5	9.1	8.6	8.5
Foam ¹ / ₄ Drain**	3.3	2.7	2.7	2.4
Surface Tension	18.7 ¹		18.5 ¹	18.3 ¹
Interfacial Tension	2.3 ¹		2.3 ¹	2.3 ¹
Spreading Coeffic.	$+3.7^{1}$		+3.9 ¹	$+4.1^{1}$

*Dashed line indicates no data available. ** Time in minutes, ¹ Measured in tap water

Blanks A, B and C

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The compositions of examples Blank A, B, and C are given in Table 1. Blank A is the surfactant concentrate used for evaluation of HMW-FP as in Tables 3a and 3b using the Hot Heptane Foam Stability Test. This is a basic concentrate and not an optimized concentrate. The

HMW-FP, including single products or mixtures, may be evaluated at from about 0.3% to 0.5% fluorine content on "as is" 3% Synthetic Liquid Foam Concentrate.

Blank A (Table 3A) gave only 6.7 minutes of foam life as determined by the Hot Heptane Foam Stability Test (Test 4) and failed the UL162 Class B fire test (Table 4a). At 3.0 minutes, Blank A had only extinguished 95% of the fire and only 98% when the foam ran out at 3.8 minutes, therefore, no burnback test could be run. At 5.0 minutes after stopping foam application, all of the foam had disappeared. This performance is exemplary of Class A and UL wetting type foams on Class B fuels at 2 gpm (~9.092 liter/min) or 0.04 gal/ ft² (~1.948 l/m²). Typically, Class A foams require higher application rates of from 3.0-5.0 gpm (~13.64 – 22.73 l/min) to extinguish the Class B fire within 3.0 minutes. However, even at this higher application rate, Class A foams typically have no foam left on the fuel at the start of burnback time.

In the UL162 Class B fire test, Blank B, which utilized Blank A plus 0.8 % solids Chemguard HS-100, the fire was 99.5 % extinguished at 3.0 minutes, but candles along the edge continued to burn and increased in intensity after 1.0 minutes, therefore, the burnback could not be run.

Blank C (Table 1), which utilized Blank A plus 0.8 % solids polysaccharide and 0.9% Chembetaine CAS, only extinguished 90% of the UL162 Class B fire (Table 6) at 3.0 minutes. Blank C, therefore, failed the UL162 Class B heptane fire test.

$20 \qquad \underline{Samples A1 - A8}$

The compositions of Samples A1-A8 are given in Table 1, 2a, and 2b. All of these concentrates were prepared by the addition of the HMW-FP to Blank A: Lodyne 5100, Chemguard FP-111, Chemguard FP-211, Dynax 5011, Forafac EMP68-II, and mixtures thereof.

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The surface and interfacial tensions measured in tap water against air and cyclohexane, respectively, are given in Tables 2a and 2b. It was noted that Blank A had both the highest surface tension and the lowest interfacial tension and a negative spreading coefficient of -0.6dynes/cm. Of the compositions containing the fluorinated polymers, A1-A8, the highest surface tension was 24.3 dynes/cm (A4a and A4b with Dynax 5011) and the lowest was 20.3 dynes/cm (A2 and A6 with Chemguard FP-111). There was less spread in the interfacial tensions with a high of 3.5 dynes/cm and a low of 2.1 dynes/cm. Therefore, the spreading coefficients were calculated as low as -3.1 dynes/cm to, as great as, +2.3 dynes/cm. However, although 5 of the 10 compositions had positive spreading coefficients, none of the premixes spread more than 10% on heptane and all immediately flashed and burned when a flame approached the cyclohexane surface.

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Those samples that did not contain fluorochemical surfactant, while in some cases having positive spreading coefficients, did not seal on cyclohexane nor prevent vapor flashing and burning. They thus are not AFFF compositions by definition.

The Hot Heptane Foam Stability Test (Test 4) for samples A1-A8 (Tables 3a and 3b) was used to select suitable HMW-FPs. HMW-FP, including single products or mixtures, may be evaluated at from about 0.3% and 0.5% fluorine content on "as is" 3% Synthetic Liquid Foam Concentrate. From Tables 3a and 3b it is seen that six of the ten samples had foam lives exceeding 60 minutes. Samples A4a and A4b, containing Dynax 5011, sample A5, containing Forafac EMP68-II, and Blank A each had a foam life that was under 60 minutes, and even under 30 minutes.

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It was found that a 50/50 mixture of Lodyne 5100/Dynax 5011 (Sample A8), however, did provide a foam life of greater than 60 minutes, as did mixtures of Lodyne 5100/Chemguard FP-111 (Sample A6) and Lodyne 5100/Chemguard FP-211 (A7).

Tables 4a and 4b set forth UL 162 Type III, Class B, fire tests run on 55 gallons of heptane in a 50 square foot (\sim 4.645m²) UL steel, square, pan. The foam application rate was 2.0 gpm (\sim 9.092 liter/min) or 0.04 gal/ft² (\sim 1.948 l/m²). All fires were run on fuel at 77-86 °F (25-30 °C) and lower water layer at 77-86°F (25-30 °C). Blank A and A5 were the only 3% concentrates failing to extinguish the fire within the required 3.0 minute period. Blank A also failed the required burnback test (5.0 min.), as did A4a, A4b, and A5. This was expected based on their poor performance on the hot heptane test with foam lives much less than 60 minutes or even 30 minutes. In effect, compositions which cannot last for 60 minutes or even 30 minutes on the hot heptane test may not have the foam stability necessary to meet the burnback test requirements on UL162, equivalent to 15 minutes hold after stopping foam application.

Exceptional burnback performance was noted with A1, A2 and A3 compositions with Lodyne 5100 and Chemguard FP-111 and FP-211. They had better burnback performance than many AFFF agents containing more than 0.4 % fluorine on solids in the form of fluorochemical surfactants. The foam expansion ratios and drain times were well within values expected for good fire extinguishing agents.

Compositions A1, A2, A3, A6, A7, and A8 met the requirements for the UL162 Class B fire test for AFFF agents at only 0.30 to 0.40% fluorine, although not being classified as such.

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Samples B1-B4a

The compositions of samples B1 – B4a are given in Tables 1 and 2c. All of these concentrates are prepared by the addition of the following HMW-FP to Blank B: Lodyne 5100, Chemguard FP-111, Chemguard FP-211, and Dynax 5011.

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The surface and interfacial tensions measured in tap water against air and cyclohexane, respectively, are given in Table 2c. It should be noted that Blank B had both the highest surface tension and the highest interfacial tension and a negative spreading coefficient of -3.1 dynes/cm. Of the compositions containing the fluorinated polymers, B1-B4a, the highest surface tension was 24.4 dynes/cm (B4a with Dynax 5011) and the lowest was 19.6 dynes/cm (B3 with Chemguard FP-211). There was less spread in the interfacial tensions with a high of 3.0 dynes/cm and a low of 2.2 dynes/cm. Therefore, the spreading coefficients were calculated as low as -3.1 dynes/cm to as great as +2.9 dynes/cm. However, although 2 of the 5 compositions had positive spreading coefficients, none of the premixes spread more than 10% on heptane and all immediately flashed and burned when a flame approached the cyclohexane surface.

The compositions not containing fluorochemical surfactant, while in some cases having positive spreading coefficient, did not seal on cyclohexane nor prevent vapor flashing and burning.

From Table 5, only Blank B failed the UL162 fire test (i.e. extinguishing time <3min, burnback time >5min), while all compositions containing HMW-FP chosen from the hot heptane test (Test 4) of Tables 3a and 3b readily passed . It should be noted that including Chemguard HS-100 in Blank B in general gave faster control times and extinguishing times. Comparing sample A1 with B1 and A2 with B2, extinguishing times were reduced by 0.8 and 0.5 minutes, respectively. Again, burnback performance was exceptional for B1 and B2 made with Lodyne 5100 and Chemguard FP-111.

Table 5 shows sea water performance data for B1 and B2, which fully meet the requirements of the UL162 Class B fire test for AFFF agents.

Samples C1, C6, C7, C8

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Polar type fire extinguishing agents can be readily prepared using the HMW-FPs as described herein. These compositions, known as 3X3 products may be used at 3% dilution rate on both polar and non-polar fires. The compositions of examples C1, C6, C7and C8 are given in Tables 1, 6, and 7. All of these concentrates are prepared by the addition of the following HMW-FPs to Blank C: Lodyne 5100, and mixtures of Lodyne 5100 and Chemguard FP-111, Chemguard FP-211, and Dynax 5011. Blank C is similar to Blank A with the addition of only 0.8% solids of polysaccharide and 0.9% solids of Chembetaine CAS. The polysaccharide content was held low to get a better measure for the strength of the HMW-FPs to form vapor barriers on isopropanol.

Table 6 shows UL162 Type III Class B heptane fire tests with Blank C, C1, C6, and C8; all at 3%. Blank C did not extinguish the fire, therefore no burnback was run. C8 gave good

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extinguishment but failed the burnback test. C1 and C6 passed all UL162 Type III ClassB fire performance requirements although C6 barely passed the extinguishing time. Based on the data from the Chemguard HS-100 formulations, it is expected that the C-formulations could be speeded up (extinguishment) with the addition of this hydrocarbon surfactant.

Table 7 describes UL162 Type II Class B fire tests on isopropanol at 4.5 gpm (~20.4575 lpm) or 0.09 gal/ ft² (~4.40 liters/m²) application density as described above (Test 6); all at 3%. Blank C failed fire performance by not controlling the isopropanol fire. The necessity for extra foam stabilizer as described in the art is demonstrated in this failure. Samples C1, C6, C7 and C8 passed all Class B fire test requirements with good extinguishing and burnback times. Only C8 containing a mixture of Lodyne 5100 and Dynax 5011 failed the test and then only the burnback.

Samples A9 - A14

Tables 8a and 8b contain data showing UL162 Class B heptane fire performance when low levels of Forafac 1157N are added to compositions A1 and A2. Forafac 1157N, manufactured by Atofina, is an amphoteric fluorochemical surfactant used for AFFF and AR-AFFF agents. The lowest fluorine content 3% UL listed AFFF product using only Forafac 1157N is known to contain 0.43% fluorine.

Samples A9 and A10 are equivalent to A1 and A2 with the addition of only 0.10% fluorine from Forafac 1157N to each. Note that fire extinguishing times were reduced, while burnback times were increased. A2 in tap water had a 16.5 minute burnback time. Performance in both sea and tap water were similar. This performance was obtained in spite of no appreciable change in the spreading coefficients for A1 conversion to A9 going from +1.6 to +1.8 dynes/cm. The spreading coefficient for A2 conversion to A10 dropped, going from +3.1 (A2) to +2.7 (A10) dynes/cm.

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It was noted that neither A9 nor A10 spread on cyclohexane and flashing occurred immediately on flame testing. Therefore neither of these compositions, despite the presence of fluorosurfactant at 0.10% fluorine level in the 3% concentrate, can be considered AFFF agents.

Examples A11 through A14 have only fluorosurfactant added to Blank A; no HMW-FP is added. A12 with 0.20% fluorine from Forafac 1157N was the first 3% composition to pass the UL162 Class B fire test, but only in tap water; the sea water fire test with A12 did not pass the burnback specification by failing at 3.4 minutes. A13 at 0.30% fluorine also failed the burnback test in sea water. A pass was not obtained in sea water until A14, when Forafac 1157N was charged at a level of 0.40% fluorine in the 3% concentrate.

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Even at such a high level of fluorosurfactant, A14 still had a poorer burnback than either A9 or A10 with only 0.10% fluorine as fluorosurfactant. Furthermore, A14 would not make an acceptable 3X3 polar agent merely on addition of 0.8% polysaccharide and 0.9% Chembetaine CAS as did Synthetic 3% concentrates A1, A6 and A7 on conversion to C1, C6 and C7 with only 0.30% fluorine as polymer.

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Cyclohexane seal tests were run on A11 through A14 at 3% in tap water to determine AFFF properties. A11 at 0.10% fluorine did not seal and immediately flashed on attempted ignition. A12, at 0.20% fluorine, spread on cyclohexane, but immediately flashed on attempted ignition. A13 (0.30% fluorine) and A14 (0.40% fluorine), both sealed on cyclohexane and passed the ignition test. Therefore, a minimum Forafac 1157N fluorosurfactant level equal to 0.30% fluorine was required to give a true AFFF agent using Blank A. Yet acceptable UL162 burnback performance in sea water was not obtained until the fluorosurfactant was present at 0.40% fluorine. Note that an SC of 3.9-4.1 was required to get AFFF agent performance on the cyclohexane seal test.

15 Samples D1 - D3

	Table 9		
UL 162 Type III, Class B, Hept	ane Fire Tests,	3% tap, 0.06 g	al/ft² (~2.94 l/n
Components	D1	D2	D3
	(as is%)	(as is%)	(as is%)
Chemguard FP-111	2.0	2.0	2.0
Fluorinated Surfactant	0	0	0
Chemguard HS-100	0	0	1.5
Chembetaine CAS	1.6	1.6	0
Glucopon 325N	0	0	2.0
Sulfochem NOS	5.0	5.0	0
Sulfochem NADS	19.5	15.0	15.0
Urea	10.0	10.0	0
Busan 1024	0	0.1	0
Polysaccharide	0	0.6	0
Glycol ether DB	5.0	5.0	5.0
Magnesium Sulfate	2.0	2.0	2.0
Water	54.9	58.7	72.5
Fire Performance, Tap			
Temp. (heptane/water) °F(°C)	65/65	55/55	75/81
	(18.3)/(18.3)	(12.8)/(12.8)	(23.9)/(27.2)
Control Time (min.)	1.1	1.0	2.7
Extinguishment Time (min.)	2.3	2.9	4.3
Burnback Time (min.)	>10.01	SE@0.8 ²	>9.0 ³
Foam Expansion Ratio	6.4	5.2	7.5
Foam ¹ / ₄ Drain Time (min.)	3.8	7.2	2.4

¹ Only 8% burning at 10.0 min.; ² SE = Self Extinguish.; ³ Only 5% burning at 9.0 min.

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The UL162 Type III, Class B fire test recognizes a difference between AFFF and FP type fire extinguishing agents. AFFF agents must extinguish in 3.0 minutes or less at an application density of only 0.04 gal/ft² (~1.948 l/m²), while FP agents only need to extinguish in 5.0 minutes at an application density of 0.06 gal/ft² (~2.94 l/m²). This means 6.0 gallons (~27.3 l) of premix are used for AFFF while 15.0 gallons (~68.2 l) of premix are applied for FP agents. As noted above, however, the burnback requirements for FP agents are more severe than for AFFF agents. FP agents must have a minimum of 21 minutes burnback from time of foam shutoff compared to 15 minutes minimum burnback for AFFF agents.

From the data shown in Table 9, it can be seen that Compositions D1, D2 and D3 meet both the extinguishing and burnback requirements of the UL162 fire test on heptane at 0.06 gal/ ft² application density. D3 was slower to extinguish than D1 or D2, but still had excellent burnback, demonstrating remarkable foam stability on hot heptane. At the start of the burnback test on D3, the heptane still registered 127°F, yet 100% of the heptane was covered with resilient foam which continued to resist burnback to only 5% area involvement after 9 minutes. This is equivalent to greater than 25 minutes burnback versus 21 minutes required.

Only 2% of "as is" Chemguard FP-111 (HMW-FP, 0.067% fluorine) was required for meeting the UL FP agent performance requirement compared with about 0.30% fluorine for a composition to meet AFFF type performance criteria. Fluoroprotein products are expected to work well for subsurface tank injection to extinguish tank fires in a manner similar to commercial FP agents prepared from protein concentrate. The difference being that this product does not contain protein concentrate, zinc, and iron as do most FP agents, and therefore, the formulations of this invention are much more environmentally friendly.

The fire fighting compositions utilizing the high molecular weight fluoropolymers, as described herein, may be applied to liquid hydrocarbons, both polar and non-polar, to extinguish such liquids during burning and that may provide a durable vapor barrier of foam on the surface of such liquids to prevent or reduce the release of combustible vapors therefrom. The composition may be applied both to the surface of such liquids or may be introduced below the surface, such as through injection. The composition may be applied in combination with other fire fighting agents, if necessary, such as the dual-agent application of both foam and a dry chemical or powder fire fighting agents. An example of such a dry chemical or powder agent is that available commercially as Purple K. In such dual application, the fire fighting agents may be applied through the use of adjacent or as generally concentric nozzles. In some instances, the dry or powder agent may be applied alone to initially extinguish any flame, with the foam being applied to prevent reigniting of the fuel.

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While the invention has been shown in some of its forms, it should be apparent to those skilled in the art that it is not so limited, but is susceptible to various changes and modifications without departing from the scope of the invention. Accordingly, it is appropriate that the appended claims should be construed broadly and in a manner to encompass such changes and modifications consistent with the scope of the invention.

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<u>CLAIMS</u>

1. A foam concentrate comprising water and a high molecular weight fluoropolymer, the foam concentrate providing a fire fighting composition when mixed with water so that the fire fighting composition does not form a stable seal on cyclohexane and meets UL 162, Class B performance criteria for at least one of AFFF agents, AR-AFFF agents and fluoroprotein (FP) agents.

2. The foam concentrate of claim 1, further comprising a fluorochemical surfactant.

3. The foam concentrate of claim 2, wherein the concentrate has a fluorine content provided from the fluorochemical surfactant that provides the fire fighting composition with less than about 0.008% fluorine by weight of the fire fighting composition.

4. The foam concentrate of claim 2, wherein the concentrate has a fluorine content provided from the fluorochemical surfactant that provides the fire fighting composition with less than about 0.006% fluorine by weight of the fire fighting composition.

5. The foam concentrate of claim 1, wherein:

the fire fighting composition meets UL 162, Class B performance criteria for at least two of AFFF agents, AR-AFFF agents and FP agents.

6. The foam concentrate of claim 1, wherein:

the fire fighting composition meets UL 162, Class B performance criteria for AFFF agents, AR-AFFF agents and fluoroprotein (FP) agents.

7. The foam concentrate of claim 1, wherein the concentrate has a fluorine content provided from any fluorochemical surfactant that provides the composition with less than about 0.003% fluorine by weight of the composition. 8. The foam concentrate of claim 1, further comprising at least one non-fluorine containing hydrocarbon surfactant.

9. The foam concentrate of claim 1, wherein the concentrate is used in an amount of from 1 to 10 parts concentrate to 90 to 99 parts water to form the composition.

10. The concentrate of claim 1, wherein the high molecular weight fluoropolymer has an average molecular weight of at least 3000 g/mol.

11. The concentrate of claim 1, wherein the fluoropolymer provides a foam life of at least 30 minutes without fluorochemical surfactants.

12. The concentrate of claim 1, wherein the fire fighting composition has a spreading coefficient (SC) against cyclohexane of from about -4 or more.

13. The concentrate of claim 1, further comprising a foaming aid.

14. A foam concentrate for use in a fire fighting composition, the concentrate comprising water and a high molecular weight fluoropolymer, the foam concentrate providing a fire fighting composition when mixed with water so that the fire fighting composition does not form a stable seal on cyclohexane and meets UL 162, Class B performance criteria for at least one of AFFF agents, AR-AFFF agents and fluoroprotein (FP) agents, and wherein the concentrate has a fluorine content provided from any fluorochemical surfactant that provides the fire fighting composition.

15. The concentrate of claim 14, wherein the fluoropolymer is capable of providing a foam life of at least 30 minutes without fluorochemical surfactants.
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16. The foam concentrate of claim 14, wherein the concentrate has a fluorine content from any fluorochemical surfactant that provides the fire fighting composition with less than about 0.006% fluorine by weight of the composition.

17. The foam concentrate of claim 14, wherein:

the fire fighting composition meets UL 162, Class B performance criteria for at least two of AFFF agents, AR-AFFF agents and FP agents.

18. The foam concentrate of claim 14, wherein:

the fire fighting composition meets UL 162, Class B performance criteria for AFFF agents, AR-AFFF agents and fluoroprotein (FP) agents.

19. The foam concentrate of claim 14, wherein:

the high molecular weight fluoropolymer has an average molecular weight of at least 3000 g/mol.

20. The foam concentrate of claim 14, wherein:

the fluoropolymer provides the composition with from about 0.0003% or more fluorine by weight of the composition.

21. The foam concentrate of claim 14, wherein:

the fluoropolymer provides the composition with from about 0.045% or less fluorine by weight of the composition.

22. The foam concentrate of claim 14, wherein:

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the fluoropolymer provides the composition from about 0.0003% to about 0.045% fluorine by weight of the composition.

23. The foam concentrate of claim 14, wherein:

the high molecular weight fluoropolymer has an average molecular weight of at least 5000 g/mol.

24. The foam concentrate of claim 14, wherein:

the high molecular weight fluoropolymer has an average molecular weight of at least 10,000 g/mol.

25. The foam concentrate of claim 14, further comprising a foaming aid.

26. The foam concentrate of claim 14, further comprising at least one non-fluorine containing hydrocarbon surfactant:

27. A foam concentrate for use in a fire fighting composition, the concentrate comprising water and a high molecular weight fluoropolymer, the foam concentrate providing a fire fighting composition when mixed with water so that the fire fighting composition meets UL 162, Class B performance criteria for at least one of AFFF agents, AR-AFFF agents and fluoroprotein (FP) agents, and wherein the concentrate has a fluorine content provided from any fluorochemical surfactant that provides the fire fighting composition with less than about 0.008% fluorine by weight of the fire fighting composition.

28. A fire fighting composition comprising water and a high molecular weight fluoropolymer, and wherein the composition does not form a stable seal on cyclohexane and meets UL 162, Class B performance criteria for at least one of AFFF agents, AR-AFFF agents and fluoroprotein (FP) agents.

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29. The fire fighting composition of claim 28, further comprising a fluorochemical surfactant.

30. The composition of claim 28, wherein the composition contains less than about 0.008% fluorine by weight provided from any fluorochemical surfactant.

31. A method of extinguishing or retarding a fire comprising:

providing a fire fighting composition comprising water and a high molecular fluoropolymer that does not form a stable seal on cyclohexane and that meets UL 162, Class B performance criteria for at least one of AFFF agents, AR-AFFF agents and fluoroprotein (FP) agents; and

applying the composition to an area where extinguishment or retardation of the fire is desired.

32. The method of claim 31, wherein:

the composition contains less than 0.008% by weight fluorine provided by any fluorochemical surfactant.

33. The method of claim 33, further comprising:

applying the composition to the area in combination with a dry fire fighting agent.

INTERNATIONAL SEARCH REPORT

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A. CLASSIFICATION OF SUBJECT MATTER IPC 7 A62D1/00 A62D1/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

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Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT Citation of document, with indication, where appropriate, of the relevant passages Relevant to claim No. Category ° 1,2,5,6, X EP 0 765 676 A (ATOCHEM ELF SA) 2 April 1997 (1997-04-02) 8,9,12, 13,31,33 3,4,7, claim 1; examples 1-22 А 14-30,32 US 4 303 534 A (HISAMOTO IWAO ET AL) 1,2,5,6, X 1 December 1981 (1981-12-01) 8-13,31, 33 3,4,7, claims 1-4; examples 1-6 Α 14-30,32 1,2,5,6, DE 197 10 108 A (ATOCHEM ELF SA) χ 8,9,12, 30 October 1997 (1997-10-30) 13,31 3,4,7, page 6-7; claim 1; example 13 Α 14 - 30, 32Further documents are listed in the continuation of box C. X Patent family members are listed in annex. ° Special categories of cited documents : *T* later document published after the International filing date or priority date and not in conflict with the application but "A" document defining the general state of the art which is not considered to be of particular relevance cited to understand the principle or theory underlying the invention "E" earlier document but published on or after the international *X* document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention citation or other special reason (as specified) cannot be considered to involve an inventive step when the document is combined with one or more other such docu-"O" document referring to an oral disclosure, use, exhibition or ments, such combination being obvious to a person skilled in the art. other means document published prior to the international filing date but later than the priority date claimed *&* document member of the same patent family Date of mailing of the international search report Date of the actual completion of the international search 21 November 2002 03/12/2002 Authorized officer Name and mailing address of the ISA European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Wengeler, H Fax: (+31-70) 340-3016

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(54) Title: PFAS TREATMENT SCHEME USING SEPARATION AND ELECTROCHEMICAL ELIMINATION



(57) Abstract: A system for treating a source of water contaminated with PF AS is disclosed. The system includes a PF AS separation stage having an inlet fluidly connectable to the source of water contaminated with PF AS, a diluate outlet, and a concentrate outlet and a PF AS elimination stage positioned downstream of the PFAS separation stage and having an inlet fluidly connected to an outlet of the PFAS separation stage, the elimination of the PFAS occurring onsite with respect to the source of water contaminated with PF AS, with the system maintaining an elimination rate of PFAS greater than about 99%. A method of treating water contaminated with PF AS is also disclosed.

TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

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PFAS TREATMENT SCHEME USING SEPARATION AND ELECTROCHEMICAL ELIMINATION

CROSS-REFERNCE TO RELATED APPLICATIONS

This application claims priority under 35 U.S.C. § 119(e) to U.S. Provisional Patent Application Serial No. 62/858,401 titled "PFAS Treatment Scheme Using Ion Exchange and Electrochemical Advanced Oxidation" filed June 7, 2019, the entire disclosure of which is hereby incorporated herein by reference in its entirety for all purposes.

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FIELD OF TECHNOLOGY

Aspects and embodiments disclosed herein are generally related to the field of the removal and elimination of perfluoro alkyl substances (PFAS) from water.

BACKGROUND

- 15 There is rising concern about the presence of various contaminants in municipal wastewater, surface water, drinking water, and groundwater. For example, perchlorate ions in water are of concern, as well as PFAS and PFAS precursors, along with a general concern with respect to total organic carbon (TOC).
- PFAS are organic compounds consisting of fluorine, carbon and heteroatoms such as oxygen, nitrogen and sulfur. The hydrophobicity of fluorocarbons and extreme electronegativity of fluorine give these and similar compounds unusual properties. Initially, many of these compounds were used as gases in the fabrication of integrated circuits. The ozone destroying properties of these molecules restricted their use and resulted in methods to prevent their release into the atmosphere. But other PFAS such as fluoro-surfactants have become increasingly
- 25 popular. PFAS are commonly use as surface treatment/coatings in consumer products such as carpets, upholstery, stain resistant apparel, cookware, paper, packaging, and the like, and may also be found in chemicals used for chemical plating, electrolytes, lubricants, and the like, which may eventually end up in the water supply. Further, PFAS have been utilized as key ingredients in aqueous film forming foams (AFFFs). AFFFs have been the product of choice for firefighting
- 30 at military and municipal fire training sites around the world. AFFFs have also been used extensively at oil and gas refineries for both fire training and firefighting exercises. AFFFs work by blanketing spilled oil/fuel, cooling the surface, and preventing re-ignition. PFAS in AFFFs

have contaminated the groundwater at many of these sites and refineries, including more than 100 U.S. Air Force sites.

Although used in relatively small amounts, these compounds are readily released into the environment where their extreme hydrophobicity as well as negligible rates of natural

decomposition results in environmental persistence and bioaccumulation. It appears as if even 5 low levels of bioaccumulation may lead to serious health consequences for contaminated animals such as human beings, the young being especially susceptible. The environmental effects of these compounds on plants and microbes are as yet largely unknown. Nevertheless, serious efforts to limit the environmental release of PFAS are now commencing.

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SUMMARY

In accordance with an aspect, there is provided an onsite system for treating a source of water contaminated with PFAS. The onsite system may comprise a PFAS separation stage 15 having an inlet fluidly connectable to the source of water contaminated with PFAS, a diluate outlet, and a concentrate outlet and a PFAS elimination stage positioned downstream of the PFAS separation stage having an inlet fluidly connected to an outlet of the PFAS separation stage. The elimination of PFAS with the system may occur onsite with respect to the source of water contaminated with PFAS. The system may be configured to maintain an overall elimination rate of PFAS greater than about 99%. 20

In some embodiments, the system maintains a concentration of PFAS in the diluate of the PFAS separation stage below a predetermined threshold. For example, the predetermined threshold may be less than the 70 parts per trillion (ppt) U.S. EPA combined lifetime exposure maximum standard. In particular embodiments, the predetermined threshold is less than 12 ppt.

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In further embodiments, the system comprises a hardness removal stage. In some embodiments, the system includes a control system configured to regulate the feed directed between the PFAS separation stage and the PFAS elimination stage. In some embodiments, the system comprises a PFAS sensor positioned downstream of the diluate outlet of the PFAS separation stage.

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In certain embodiments, the PFAS separation stage comprises one or more ion exchange modules. The ion exchange modules may be regenerated to remove bound PFAS to produce a

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PFAS concentrate. In some embodiments, the regeneration comprises contacting the ion exchange modules with a regeneration solution comprising methanol, water, and NaOH.

In some embodiments, the PFAS separation stage comprises one or more nanofiltration modules. A concentrate comprising PFAS from the one or more nanofiltration modules may

5 have its PFAS concentration increased by passing through one or more nanofiltration diafiltration modules downstream of the one or more nanofiltration modules. In some cases, the one or more nanofiltration diafiltration modules target removal of NaCl and/or KCl.

In some embodiments, the PFAS separation stage involves adsorption onto an electrochemically active substrate. The electrochemically active substrate may comprise

10 granular activated carbon (GAC). The GAC may be incorporated into an electrode in an electrochemical cell. In some embodiments, an electrode in the electrochemical cell comprises platinum, a mixed metal oxide (MMO) coated dimensionally stable anode (DSA) material, graphite, or lead/lead oxide. In further embodiments, the electrochemical cell comprises a sulfate electrolyte. In certain embodiments, the electrochemical cell comprises an ion exchange

15 membrane separator. PFAS that are adsorbed to the electrochemically active substrate may be desorbed by electrical activation of the electrochemical cell.

In some embodiments, the PFAS separation stage involves foam fractionation.

In some embodiments, the PFAS elimination stage comprises an electrochemical PFAS elimination stage. For example, the electrochemical PFAS elimination stage may comprise an electro-advanced oxidation system, such as an electrochemical cell.

In some embodiments, the electrochemical cell involves a boron doped diamond (BDD) electrode.

In particular embodiments, the electrochemical cell involves a Magneli phase titanium oxide electrode, in particular a Ti_nO_{2n-1} (n = 4-10) electrode. An exemplary electrode is Ti_4O_7 .

In some embodiments, an electrode of the electrochemical cell is made of a stainless steel, nickel alloy, titanium, or a DSA material. In some embodiments, the electrochemical cell comprises an electrolyte comprising at least one of hydroxide, sulfate, nitrate, and perchlorate.

In some embodiments, the PFAS elimination stage comprises an advanced oxidation process (AOP) reactor. For example, the AOP may involve a UV-persulfate treatment or a plasma treatment.

In accordance with an aspect, there is provided a method of treating water contaminated with PFAS. The method may comprise introducing contaminated water from a source of water contaminated with a first concentration of PFAS to an inlet of a PFAS separation stage. The method may further comprise treating the contaminated water in the PFAS separation stage to

- 5 produce a product water substantially free of PFAS and a PFAS concentrate having a second PFAS concentration greater than the first PFAS concentration. The method may additionally comprise introducing the PFAS concentrate to an inlet of a PFAS elimination stage and activating the PFAS elimination stage to eliminate the PFAS in the PFAS concentrate. The method may have a PFAS elimination rate greater than about 99%.
- 10 In some embodiments, the elimination of PFAS occurs onsite with respect to the source of contaminated water.

In further embodiments, the method may comprise treating the PFAS concentrate from the PFAS separation stage to produce a concentrate having a third concentration of PFAS. The third PFAS concentration may be greater than the second PFAS concentration. The concentrate having the third concentration of PFAS may be introduced to the inlet of the PFAS elimination stage.

In some embodiments, the method may further comprise monitoring a pressure, temperature, pH, concentration, flow rate, or TOC) level in the source water and/or product water.

20 In certain embodiments, the PFAS separation stage comprises one or more ion exchange modules. In some embodiments, the PFAS separation stage comprises one or more nanofiltration modules. In some embodiments, the PFAS separation stage involves adsorption onto an electrochemically active substrate. In some embodiments, the PFAS separation stage involves foam fractionation.

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In some embodiments, the PFAS elimination stage comprises an electrochemical PFAS elimination stage. For example, the electrochemical PFAS elimination stage may comprise an electro-advanced oxidation system, such as an electrochemical cell.

In some embodiments, the electrochemical cell involves a BDD electrode.

In particular embodiments, the electrochemical cell involves a Magneli phase titanium 30 oxide electrode.

In some embodiments, the electrochemical cell comprises an electrolyte comprising at least one of hydroxide, sulfate, nitrate, and perchlorate.

In some embodiments, the PFAS elimination stage comprises an AOP reactor. For example, the AOP may involve a UV-persulfate treatment or a plasma treatment.

In accordance with another aspect, there is provided a method of retrofitting a water treatment system. The method may comprise providing a PFAS elimination stage and fluidly connecting the PFAS elimination stage downstream of a PFAS separation stage.

In some embodiments, the PFAS elimination stage comprises an electrochemical PFAS elimination stage. For example, the electrochemical PFAS elimination stage may comprise an electro-advanced oxidation system, such as an electrochemical cell.

In some embodiments, the electrochemical cell involves a BDD electrode.

In particular embodiments, the electrochemical cell involves a Magneli phase titanium oxide electrode.

In some embodiments, the PFAS elimination stage comprises an AOP reactor. For example, the AOP may involve a UV-persulfate treatment or a plasma treatment.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings are not intended to be drawn to scale. In the drawings, each identical or nearly identical component that is illustrated in various figures is represented by a

20 like numeral. For purposes of clarity, not every component may be labeled in every drawing. In the drawings:

FIG. 1 is a flow diagram of a PFAS treatment system where recovered water from the elimination of PFAS is collected as treated water. Inset tables provide modeled concentrations of various components of the water stream at specific locations in the system.

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FIG. 2 is a flow diagram of a PFAS treatment system where recovered water from the elimination of PFAS is used as makeup water for the feed to the PFAS separation stage. Inset tables provide modeled concentrations of various components of the water stream at specific locations in the system.

FIG. 3 is a flow diagram of a PFAS treatment system configured to remove higher 30 concentrations of partially oxidized PFAS.

FIG. 4 is a flow diagram of a PFAS treatment system where nanofiltration is used as the PFAS separation stage.

FIG. 5 is a flow diagram of a PFAS treatment system where nanofiltration is used as the PFAS separation stage. Inset tables provide modeled concentrations of various components of the water stream at specific locations in the system.

FIG. 6 is a flow diagram of a method of separating PFAS from a source of water using adsorption onto a GAC electrode and desorption of PFAS from the GAC electrode in an electrochemical cell.

FIG. 7 is a sequence of the reactions taking place at the surface of an electrode duringelectrochemical elimination of PFAS.

FIG. 8 is a scatter plot showing the length of time needed to decrease both the total PFAS concentration and the concentration of the species PFOS without a concentrating separated PFAS from a source of water.

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DETAILED DESCRIPTION

In accordance with one or more embodiments, systems and methods disclosed herein relate to the separation, concentration, and elimination of PFAS from a source of water that is contaminated with PFAS. These man-made chemical compounds are very stable and resilient to breakdown in the environment. They may also be highly water soluble because they carry a negative charge when dissolved. They were developed and widely used as a repellant and protective coating. Though some PFAS compounds have now largely been phased out, elevated levels are still widespread. For example, water contaminated with PFAS may be found in industrial communities where they were manufactured or used, as well as near airfields or military bases where firefighting drills were conducted. PFAS may also be found in remote locations via water or air migration. Many municipal water systems are undergoing aggressive testing and treatment. This invention is not limited to the types of negatively charged and/or

fluorinated compounds being treated.

In some specific non-limiting embodiments, common PFAS such as perfluorooctanoic acid (PFOA) and/or perfluorooctane sulfonic acid (PFOS) may be removed from water. The

30 U.S. Environmental Protection Agency (EPA) developed revised guidelines in May 2016 of a combined lifetime exposure of 70 parts per trillion (ppt) for PFOS and PFOA. Federal, state,

and/or private bodies may also issue relevant regulations. For example, the state of New Hampshire has adopted groundwater Maximum Contaminant Levels (MCLs) of 12 ppt for PFOA, 15 ppt for PFOS, 18 ppt for perfluorohexane sulfonic acid (PFHxS), and 11 ppt for perfluoro nonanoic acid (PFNA). In some cases, the systems described herein can maintain a concentration of PFAS in treated water to be below the regulated levels.

In accordance with one or more embodiments, PFAS may be separated from a process stream in order to provide a concentrated PFAS stream for enhanced PFAS conversion or destruction. Concentration of the PFAS stream reduces the energy consumption necessary to destroy PFAS via known methods, such as electrochemical or photochemical oxidation.

10 A system of the present invention includes a PFAS separation stage having an inlet fluidly connectable to the source of water contaminated with PFAS, a diluate outlet, a concentrate outlet, and a PFAS elimination stage positioned downstream of the PFAS separation stage and having an inlet fluidly connected to an outlet of the PFAS separation stage. During treatment, a source of water contaminated with PFAS is introduced to the inlet of the PFAS

- 15 separation stage. The PFAS are separated from the water, producing a concentrate enriched in PFAS and a diluate that can be discharged for its intended purpose, such as for potable water or irrigation water. Systems of the invention can maintain a concentration of PFAS in the diluate of the PFAS separation stage below a predetermined threshold, such as a Federal, state, or private agency standard. Systems of the present invention are advantageous in that the separation of
- 20 PFAS from the source of contaminated water and the elimination of the separated PFAS occur onsite with respect to the source of water. Typically, separated PFAS are concentrated and then transported to a separate facility for elimination, which is both dangerous and expensive. Further, the elimination of PFAS produces recoverable F⁻ ions and HF, both of which are useful for industrial processes, such as glass etching, metal cleaning, and in electronics manufacturing.
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PFAS Separation

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PFAS, as a class of compounds, are very difficult to treat largely because they are extremely stable compounds which include carbon-fluorine bonds. Carbon-fluorine bonds are the strongest known single bonds in nature and are highly resistant to breakdown. PFAS may be removed from a source of contaminated water by a number of known mechanisms with varying degrees of success. Conventional activated carbon adsorption systems and methods to remove

PFAS from water have shown to be effective on the longer alkyl chain PFAS but have reduced bed lives when treating shorter alkyl chain compounds. Some conventional anion exchange resins have shown to be effective on the longer alkyl chain PFAS but have reduced bed lives when treating shorter alkyl chain compounds.

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Ion Exchange

In some embodiments, separation of PFAS from a source of contaminated water may be achieved using an ion exchange process, such as cation exchange or anion exchange. Conventional anion exchange treatment systems and methods typically utilize anion exchange

- 10 resin where positively charged anion exchange resin beads are disposed in a lead vessel which receives a flow of water contaminated with anionic contaminants, such as PFAS. The negatively charged contaminants are trapped by the positively charged resin beads and clean water flows out of the lead anion exchange vessel into a lag vessel, also containing anion exchange resin beads. A sample tap is frequently used to determine when the majority of the anion exchange
- 15 beads in the lead exchange vessel have become saturated with contaminants. When saturation of the resin anion exchange beads is approached, a level of contaminants will be detected in the effluent tap. When this happens, the lead vessel is taken off-line, and the contaminated water continues flowing to the lag vessel which now becomes the lead vessel. The lead-lag vessel configuration ensures that a high level of treatment is maintained at all times.
- 20 As discussed above, some conventional anion exchange resins can also be used to remove PFAS from water. A number of known methods exist to regenerate the anion exchange beads in the anion exchange vessel. Some known methods rely on flushing the resin with a brine or caustic solution. Other known methods may include the addition of solvents, such as methanol or ethanol, to enhance the removal of the PFAS trapped on the anion exchange beads. Effective 25 resin regeneration has been demonstrated by passing a solvent (such as methanol or ethanol),
- blended with a solution containing sodium chloride, sodium hydroxide, or another salt, through the resin. However, such methods may generate a large amount of toxic regenerant solution which must be disposed of at significant expense. There is also a need to further treat the waste regenerant solution to concentrate the PFAS and reduce the volume of waste. This is a key step,
 because resin regeneration produces a significant volume of toxic waste.

In accordance with one or more embodiments, the PFAS separation stage includes an ion exchange vessel having a selected ion exchange resin, such as an anion exchange resin, to remove PFAS from the water. A source of water contaminated with PFAS is introduced to an inlet of the PFAS separation stage with ion exchange such that the PFAS binds to the selected

- 5 anion exchange resin and are removed from the water. A regeneration solution is periodically used to remove the PFAS from the anion exchange resin, thereby regenerating the anion exchange resin and generating a spent regeneration solution comprised of the removed PFAS and a regeneration solution. The PFAS concentration of the regeneration solution may be increased by removing liquid volume from the regeneration solution to allow partial reuse of the
- 10 regeneration solution. The remaining solution, having an enriched concentration of PFAS, may be further treated for PFAS elimination using a PFAS elimination stage.

Regeneration solutions comprising a salt solution and an alcohol have been demonstrated to be effective in regenerating the anion exchange resin. The anion systems used in these regeneration chemistries can be chosen from, for example, Cl^- , OH^- , SO_4^{2-} , and NO_3^- , among

- 15 others. While all of these ions effective in regenerating an ion exchange resin, there is a difference in efficiency of removal. To balance this efficiency of removal, there is also a knockon effect of anion choice on the PFAS elimination stage. For example, chloride ion solutions are frequently used for ion exchange regeneration, but have implications for an electrochemical PFAS elimination system, as the chloride ion would be preferentially be driven to hypochlorite
- 20 or chlorate in an electrochemical cell, causing a significant increase in energy consumption and inefficiency for the oxidation of the PFAS. Further, some chloride will be oxidized to perchlorate, which is an environmentally persistent anion requiring further treatment. Sulfate ion solutions at the concentrations effective for regenerating the anion exchange resin have a depressing effect on the oxidation of the PFAS. Nitrate and hydroxide ion solutions are both
- suitable, however, comparing the MCL values, nitrate has a primary MCL of 10 ppm and hydroxide would have a potential problem with the overall solution pH. Hydroxide solutions may be neutralized with sulfuric acid after oxidation, as the sulfate ion has a secondary MCL of 250 ppm. To make the regeneration effective for PFAS, a water-miscible solvent will be needed in the regeneration solution. As noted herein, alcohols are an example of useful solvents for this purpose, with methanol being an exemplary alcohol.

The chloride and sulfate concentrations in the regeneration solution may be substantially reduced by first stripping the regeneration solution with NaOH without methanol. It may be possible to get rid of greater than at least 95% of the other anions by first stripping the resin with NaOH. The spent NaOH fraction can then be neutralized and reused as makeup water for the source of contaminated water. Subsequent stripping with methanol and NaOH would remove the PFAS without other anions. In some cases, a second regeneration may be run using a lower NaOH concentration as the first regeneration stripped a substantial fraction of anions from the regeneration solution. The preparation of the PFAS concentrate solution without the burden of the associated anions will make subsequent treatment of the PFAS concentrate solution more

10 efficient and effective.

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Irrespective of the choice of anion system, the alcohol will need to be removed prior to the oxidation and to further concentrate the PFAS in the concentrate. Removal of the methanol from the PFAS concentrate is typically achieved thermally, such as with distillation. In accordance with some embodiments, removal of the methanol to concentrate the PFAS in solution may be achieved with solvent-resistant nanofiltration, diafiltration, or pervaporation.

15 solution may be achieved with solvent-resistant nanofiltration, diafiltration, or pervaporation Other techniques for recovering the parts of a regeneration solution and increasing the concentration of PFAS dissolved therein are known in the art.

Systems for treating water using ion exchange to remove PFAS from water, regeneration solutions for desorbing the PFAS from the ion exchange resin and removing a portion of the
regeneration solution to increase the concentration of PFAS in the remaining regeneration solution are shown in FIGS. 1-3.

Filtration

In some embodiments, separation of PFAS from a source of contaminated water may be achieved using a physical separation process, such as filtration with a membrane. In such cases, the membranes comprise pores of a diameter sufficient to allow water to pass through but for the PFAS to be retained and collected. In accordance with one or more embodiments, the PFAS separation stage includes one or more solvent-resistant nanofiltration stages. The number of nanofiltration stages and the types of nanofiltration membranes utilized in a PFAS separation

30 stage of the invention will depend on the matrix of the source of contaminated water. As an example, nanofiltration membranes are sensitive to high concentrations of total suspended solids

(TSS), free chlorine, and certain heavy metals (such as Al, Mn, Fe, and Zn) in solution; thus, if the source of water contaminated with PFAS is also high in TSS, free chlorine and/or heavy metals, the excess TSS, chlorine, and/or heavy metals should be removed using a one or more pre-treatments prior to PFAS separation.

The permeate of the one or more stages of nanofiltration is substantially free of PFAS; the concentrate of the nanofiltration stages has an enriched concentration of PFAS. As described herein, the PFAS in the concentrate may have the concentration further enriched to reduce the energy consumption and increase the effectiveness of a later PFAS elimination stage. In some embodiments, the concentrate from the nanofiltration PFAS separation stage may be introduced to the inlet of a separate nanofiltration diafiltration stage to remove excess salts, such as NaCl or 10 KCl, from the concentrate and further concentrate the PFAS in the concentrate solution that results from this step. The diluate from this step, made up with water from an external source of water having a low TSS content, may be used as make up water for the source of contaminated water.

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In accordance with certain embodiments of a nanofiltration-based PFAS separation stage, systems of the present invention incorporating said nanofiltration may include a stage for hardness removal, such as by chemical precipitation. The inclusion of a hardness removal stage may be necessary if there is a concern for potential scaling or fouling of membranes or other downstream process equipment introduced by insoluble alkaline earth metal salts, such as

calcium or magnesium sulfates, phosphates, and carbonates. The optional hardness removal 20 stage may be configured to accept the PFAS enriched concentrate from the one or more nanofiltration PFAS separation stages.

Systems for treating water using one or more nanofiltration stages to remove PFAS from water, removing hardness from the PFAS enriched concentrate from the nanofiltration stages, and using an additional stage of nanofiltration diafiltration to increase the concentration of PFAS in the remaining solution are shown in FIGS. 4 and 5.

Adsorption

In some embodiments, separation of PFAS from a source of contaminated water may be 30 achieved using an adsorption process, where the PFAS are physically captured in the pores of a porous material (i.e., physisorption) or have favorable chemical interactions with functionalities

on a filtration medium (i.e., chemisorption). In accordance with one or more embodiments, the PFAS separation stage may include adsorption onto an electrochemically active substrate. An example of an electrochemically active substrate that can be used to adsorb PFAS is granular activated carbon (GAC). Adsorption onto GAC, compared to other PFAS separation methods, is

- 5 a low-cost solution to remove PFAS from water that can potentially avoid known issues with other removal methods, such as the generation of large quantities of hazardous regeneration solutions of ion exchange vessels and the lower recovery rate and higher energy consumption of membrane-based separation methods such as nanofiltration and reverse osmosis (RO). Akin to ion exchange, GAC removes PFAS from a source of contaminated water by adsorption.
- 10 However, employing GAC for a PFAS elimination stage is achievable by incineration at temperature higher than 600°C, which is highly energy and cost intensive

In some embodiments, the GAC used for adsorption removal of PFAS may be modified to enhance its ability to remove negatively charged species from water, such as deprotonated PFAS. For example, the GAC may be coated in a positively charged surfactant that

15 preferentially interacts with the negatively charged PFAS in solution. The positively charged surfactant may be a quaternary ammonium-based surfactant, such as cetyltrimethylammonium chloride (CTAC). Activated carbons useful for the present invention and modifications that may be performed on said activated carbons are described in U.S. Patent No. 8,932,984, U.S. Patent No. 9,914,110, and PCT/US2019/046540, all to Evoqua Water Technologies LLC, each of which hereby being incorporated herein by reference in its entirety for all purposes.

In the present invention, the adsorptive properties of GAC are advantageous for use as a component of an electrode in an electrochemical cell. The GAC electrode comprises GAC, conductors (such as graphite or carbon black), and suitable binders (e.g., polytetrafluoroethylene (PTFE) or polyvinylidene fluoride (PVDF)). When a GAC electrode is used in an

- 25 electrochemical cell, the other electrode may be a chemically and electrochemically stable electrode, for example platinum, MMO-coated DSA material, graphite, Pb/PbO₂, among others known in the art. In particular embodiments, both the cathode and the anode of the electrochemical cell may be GAC electrodes if a cation exchange membrane is embedded in between both GAC electrodes.
- 30 A general process of using a GAC electrode to reversibly adsorb and desorb PFAS from a source of contaminated water is shown in FIG. 6 and can broadly be described as a three-step

process. In step 1, a source of water contaminated with PFAS is allowed to circulate around a GAC electrode, leaving PFAS adsorbed on the surface of the electrode. Step 1 may be run in a batch mode if the level of PFAS contamination in the source of water is high; alternatively, step 1 may be performed in a single pass if the level of PFAS contamination in the source of water is

- 5 low. In step 2, a prepared synthetic water would be circulated through the electrochemical cell in which the cathode is the GAC electrode, and an ion exchange membrane may be embedded in between the electrodes. Activating the electrochemical cell, such as applying a voltage or reversing an applied current, allows the adsorbed PFAS on the GAC cathode to desorb and concentrate the synthetic water circulating in the electrochemical cell. A preferred mode of
- 10 operation for step 2 is batch mode, and the concentrated PFAS aqueous solution will be collected for further elimination treatments. To reduce energy consumption, a salt (such as Na₂SO₄) may be added into the synthetic water circulating in the electrochemical cell to increase water conductivity. The amount of salt added to the synthetic water is dependent on the subsequent elimination step and discharge regulations as discussed herein. Step 3 is a potential balance step
- 15 to zero charge of the GAC electrode to prevent any drop in PFAS removal efficiency due to double layer adsorption of cations on the GAC electrode. This step ensures that the GAC electrode recovered after PFAS desorption is both charge neutral and free of adsorbed salts. The desorbed PFAS from the GAC electrode may be further concentrated using methods described herein or introduced to a PFAS elimination stage.
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Foam Fractionation

In some embodiments, separation of PFAS from a source of contaminated water may be achieved using foam fractionation, where foam produced in a source of contaminated water rises and removes hydrophobic molecules from the water. Foam fractionation has typically been utilized in aquatic settings, such as aquariums, to remove dissolved proteins from the water. During foam fractionation, gas bubbles rise through a vessel of contaminated water, forming a foam that has a large surface area air-water interface with a high electrical charge. The charged

groups on PFAS molecules adsorb to the bubbles of the foam and form a surface layer enriched

in PFAS that can subsequently be removed. The bubbles may be formed using any suitable gas,such as compressed air or nitrogen. In some embodiments, the bubbles for form the foam are

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formed from an oxidizing gas, such as ozone. Foam fractionation system useful for the invention are known in the art.

PFAS Elimination

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Various techniques for treating the concentrated stream to effect PFAS conversion or destruction may be implemented. The elimination of PFAS from concentrated streams using the PFAS elimination methods described herein produces H^+ and F^- ions in solution.

Electrochemical

In accordance with one or more embodiments, a PFAS elimination stage may include an electrochemical PFAS elimination stage comprising an electro-advanced oxidation system. The electro-advanced oxidation system may comprise an electrochemical cell used to degrade PFAS in water. The electrochemical cell may generally include two electrodes, i.e., a cathode and an anode. A reference electrode may also be used, for example, in proximity to the anode.

In accordance with one or more embodiments, the cathode may be constructed of various materials. Environmental conditions, e.g., pH level, and specific process requirements, e.g., those pertaining to cleaning or maintenance, may impact cathode selection. In some non-limiting embodiments, the cathode may be made of stainless steel, nickel alloy, titanium, or a DSA material. DSA materials may be uncoated or may be coated with noble metals or metal oxides, such as Pt or IrO₂, among others.

In accordance with one or more embodiments, the anode may be constructed of a material characterized by a high oxygen evolution overpotential. Overpotential may generally relate to the potential difference (voltage) between a half-reaction's thermodynamically determined reduction potential and the potential at which a redox event is experimentally observed. The term may be directly related to an electrochemical cell's voltage efficiency.

observed. The term may be directly related to an electrochemical cell's voltage efficiency. In accordance with one or more embodiments, the anode may exhibit a preference for a surface reaction in water. Based on various physical characteristics and/or the chemical composition of the anode, water molecules may be repelled from the surface while non-polar organic pollutants may be easily absorbed. This may promote a direct oxidation reaction on the surface which may, for example, be particularly beneficial for the treatment of PFAS.

In accordance with one or more embodiments, the anode may be constructed of a Magnéli phase titanium oxide of the general formula Ti_nO_{2n-1} , where n = 4-10 inclusive. Magnéli phase titanium oxide anodes may have superior performance for inhibiting oxygen evolution compared to other anode materials. This may allow for the direct oxidation of PFAS on its surface. Additionally, in comparison to other electrodes with similar overpotential characteristics, Magnéli phase titanium oxide is less expensive than boron doped diamond (BDD), more robust than Ti/SnO₂, and more environmentally friendly than Pb/PbO₂. Magnéli phase electrodes and electrochemical cells comprising said electrodes for PFAS elimination are described in PCT/US2019/047922, the disclosure of which is herein incorporated by reference in its entirety for all purposes. In accordance with one or more embodiments, the anode may be

constructed of BDD.

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In accordance with one or more embodiments, the Magnéli phase titanium oxide anode or BDD anode may be used in an electrochemical cell. The anode may be formed in a variety of shapes, for example, planar or circular. In at least some preferred embodiments, the anode may be characterized by a mesh or foam structure, which may be associated with a higher active surface area, pore structure, and/or pore distribution.

The supporting electrolyte chosen for the electrochemical PFAS elimination may be chosen to minimize energy consumption for removing PFAS from the contaminated water. As shown in Table 1, electrolytes may include any of Cl⁻, SO₄²⁻, NO₃⁻, ClO₄⁻ and OH⁻ ions. The
energy consumption data of Table 1 is presented as a range to show the spread of efficiency by employing different electrolytes in the source water based on the treatment of PFAS, in particular PFOA. Among the electrolytes of Table 1, both NO₃⁻ and ClO₄⁻ are effective for PFAS elimination but have significant environmental impact for disposal. Reduction of PFOA is possible by adopting a dilute concentration Cl⁻ solution as the supporting electrolyte; however, in practice, chlorination and oxygen evolution are the dominant reactions occurring on the electrode surfaces. These electrode surface reactions produce free chlorine, chlorate ions, and perchlorate ions in solution, which pose concerns as sources of secondary contamination. SO₄²⁻ electrolytes

effective at low concentrations (less than 20 mM, preferably about 5mM of SO4²⁻); this
concentration range is insufficient for the ion exchange regeneration process. This result is also in agreement with literature which suggests that SO4²⁻ electrolytes do not promote the electro-

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are effective at PFAS elimination and have low environmental impact; however, sulfates are only

oxidative generation of OH• due to strong adsorption at the surfaces of the electrodes. NaOH represents a balanced choice among the common electrolytes even though the PFAS elimination efficiency of NaOH electrolytes is inversely dependent on the NaOH concentration.

5 Table 1. Effect of Electrolyte on Energy Consumption for PFOA Removal from Contaminated Water Containing 10 ppm PFOA

Electrolyte	Energy Consumption per ppm PFOA removal (kWh/m ³ /ppm)
10 mM NaCl	10-100
5000 ppm NaCl	> 3000
5 mM Na ₂ SO ₄	1-10
100 mM Na ₂ SO ₄	> 1000
10 mM NaClO ₄	<1
10 mM NaOH	1-10
5000 ppm NaOH	10-100
5000 ppm NaNO ₃	1-10

In operation, a process stream containing an elevated PFAS level may be introduced to an electrochemical cell for treatment. The electrochemical cell may include a Magnéli phase

- 10 titanium oxide anode or a BDD anode as described herein. The anode material may have a porosity of at least about 25%. The anode material may have a mean pore size ranging from about 100 µm to about 2 mm. The electrochemical cell may include an electrolyte as described herein and a voltage may be applied to the anode as described herein to provide a desired level of treatment. Various pre-treatment and/or post-treatment unit operations may also be integrated.
- 15 A product stream may be directed to a further unit operation for additional treatment, sent to a point of use, or otherwise discharged. Polarity of the electrochemical cell may be reversed periodically if desired such as to facilitate maintenance.

In accordance with one or more embodiments, Equations 1 through 5 shown in FIG. 7 may represent the underlying mechanism for electrochemical PFAS removal with a BDD or

20 Magnéli phase titanium oxide (Ti_nO_{2n-1}) anode. The reaction may generally be characterized as a Kolbe-type oxidation. The reaction initiates from direct oxidation of carboxylate ions to carboxylate radicals (Eq. 1) on a the electrode surface by applying a sufficient positive voltage.

The carboxylate radicals are subsequently decarboxylated to perfluoroalkyl radicals (Eq. 2). By coupling with hydroxyl free radicals which are anodically generated on the electrode surface, the perfluoroalkyl radicals are converted to perfluoro alcohols (Eq. 3) which further defluorinate to perfluoro carbonyl fluoride (Eq. 4) and finally hydrolyzed to a perfluorocarboxylic as a

5 byproduct by losing one carbon in the chain (Eq. 5). Reactions 1 to 5 may generally be repeated until all carbon from PFAS are eventually stripped off to inorganic CO₂, H⁺, and F⁻.

Photochemical

In accordance with one or more embodiments, a PFAS elimination stage may include photochemical treatment of the PFAS. For example, ultraviolet (UV) treatment has shown to be effective in the destruction of PFAS. UV treatment generally utilizes UV activation of an oxidizing salt for the elimination of various organic species. Any strong oxidant may be used. In some non-limiting embodiments, a persulfate compound may be used. In at least some embodiments, ammonium persulfate, sodium persulfate, and/or potassium persulfate may be

15 used. Other strong oxidants, e.g., ozone or hydrogen peroxide, may also be used. The source of contaminated water may be dosed with the oxidant.

In accordance with one or more embodiments, the source of contaminated water dosed with an oxidant may be exposed to a source of UV light. For instance, the systems and methods disclosed herein may include the use of one or more UV lamps, each emitting light at a desired 20 wavelength in the UV range of the electromagnetic spectrum. For instance, according to some embodiments, the UV lamp may have a wavelength ranging from about 180 to about 280 nm, and in some embodiments, may have a wavelength ranging from about 185 nm to about 254 nm. According to various aspects, the combination of persulfate with UV light is more effective than using either component on its own.

UV treatments to remove organic compounds are commonly known, including the VANOX[®] AOP system commercially available from Evoqua Water Technologies LLC (Pittsburgh, PA), which may be implemented. Some related patents and patent application publications are hereby incorporated herein by reference in their entireties for all purposes include: U.S. Patent Nos. 8,591,730; 8,652,336; 8,961,798; US 2016/02077813; US
2018/0273412; and PCT/US2019/051861, all to Evoqua Water Technologies LLC.

Plasma

In accordance with one or more embodiments, a PFAS elimination stage may include a plasma treatment. Plasmas are typically produced using a low- or ambient pressure high voltage discharge in the presence of a gas or mixture of gases, to produce free electrons, partially ionized

5 gas ions, and fully ionized gas ions. The free electrons and ionic species, in an aquatic environment may cause the degradation of PFAS and other organic matter in a sample of contaminated water. Destruction of PFAS by plasma has been demonstrated and evidenced in the literature. Reports have shown electrons produced by plasma may be primarily responsible for degrading PFAS while the secondary oxidative species generated by plasma, such as

10 hydroxyl radicals, play an insignificant role in initiating the reaction.

In accordance with one or more embodiments, one or more sensors may measure a level of PFAS upstream and/or downstream of the PFAS elimination stage. A controller may receive input from the sensor(s) in order to monitor PFAS levels, intermittently or continuously. Monitoring may be in real-time or with lag, either onsite or remotely. A detected PFAS level

- 15 may be compared to a threshold level that may be considered unacceptable, such as may be dictated by a controlling regulatory body. Additional properties such as pH, flow rate, voltage, temperature, and other concentrations may be monitored by various interconnected or interrelational sensors throughout the system. The controller may send one or more control signals to adjust various operational parameters, i.e., applied voltage, in response to sensor input.
- 20 In accordance with another aspect, there is provided a method of treating water contaminated with PFAS. The method may comprise introducing contaminated water from a source of water contaminated with a first concentration of PFAS to an inlet of a PFAS separation stage and treating the contaminated water in the PFAS separation stage to produce a product water substantially free of PFAS and a PFAS concentrate having a second PFAS concentration
- 25 greater than the first PFAS concentration. The method may further comprise introducing the PFAS concentrate to an inlet of a PFAS elimination stage and activating the PFAS elimination stage to eliminate the PFAS in the PFAS concentrate. The elimination rate of PFAS may be greater than about 99%. The elimination of PFAS occurs onsite with respect to the source of contaminated water.
- 30 In some embodiments, the method of treating water contaminated with PFAS may include treating the PFAS concentrate from the PFAS separation stage to produce a concentrate

having a third concentration of PFAS, the third PFAS concentration greater than the second PFAS concentration. The method of treating water contaminated with PFAS may further include introducing the concentrate having the third concentration of PFAS to the inlet of the PFAS elimination stage. In some cases, process conditions, such as pressure, temperature, pH,

5 concentration, flow rate, or TOC level in the source water and/or product water are monitored during treatment.

In accordance with another aspect, there is provided a method of method of retrofitting a water treatment system as described herein. The method may comprise providing a PFAS elimination module and fluidly connecting the PFAS elimination module downstream of a PFAS

10 separation stage. The PFAS separation stage and/or the PFAS elimination stage may be the PFAS separation stage and/or the PFAS elimination stage as described herein, for example, a PFAS separation stage comprising ion exchange, nanofiltration, or adsorption onto electrochemically active substrates and/or a PFAS elimination stage comprising an electrochemical cell, UV-persulfate treatment, or plasma treatment.

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EXAMPLES

The function and advantages of these and other embodiments can be better understood from the following examples. These examples are intended to be illustrative in nature and are not considered to be limiting the scope of the invention.

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Example 1

In this example, the benefits of non-direct electrochemical treatment for PFAS elimination, rather than directly electrochemically treating the PFAS contaminated water as it enters a water treatment system, are discussed. A first reason for non-direct electrochemical treatment for PFAS elimination is reducing the energy expenditure needed to drive the reactions. Generally, organic species removal by electrochemical oxidation at low concentration (usually

less than 100 ppm) follows an exponential relationship with energy input. In this region, reactions on anode surfaces are limited by mass transport of species to the reaction site rather

than being dependent on anodic current. Therefore, the EEO (Energy Expense per Order) isusually applied to describe energy efficiency of an electrochemical PFAS elimination system

As shown in FIG. 8, generated from the LC/MS/MS measured PFAS concentrations shown in Table 2 below, the time necessary to decrease the concentration of PFAS, in particular PFOS, by an order of magnitude has a non-linear dependence. Specifically referring to the data of FIG. 8, to reduce PFOS or total PFAS from water by one order, 2.77 or 5.17 hours of

- 5 treatment shall be applied, respectively, on a well-determined BDD module and process flow, noting that the time to reduce PFOS or total PFAS from water varies with different module designs, process flow conditions, water matrix, and the volume of effluent to treat, among other factors.
- 10 Table 2. Elapsed Time for PFAS Elimination Using an Electrochemical PFAS Elimination Stage with a BDD Electrode

	Treatme													
	nt Time													Total PFAS
Sample Name	(hours)	PF4A	PF5A	PF6A	PF7A	PFOA	PF4S	PFSS	PF6S	PF7S	PF8S	PF9S	PF10S	remaining
	0										10000			10000.00
BDD -PFOS	5	125.4	115.6	111.6	100	48.4	0	14.06	250	65,4	216	0	0	1047.46
from 10000 ppb	7	85.4	70.2	58.8	39.6	10.62	0	5.68	61.8	7.7	17.06	0	0	356.86
	9	66	49.1	34.5	16.4	5.03	0	2.65	17.4	1.71	7.54	0	0	200.33

Consider source water of a volume Q m³ containing C ppb PFAS for treatment: in order to reduce total PFAS to the U.S. EPA's guideline of 70 ppt, PFAS removal on the order of $(\log C+1.155)$ is required.

Energy consumption for total PFAS removal directly by electrochemical PFAS elimination in the same process configuration of FIG. 8 shall be described as below:

 $E(source PFAS \ destruct.) = a \times I \times V \times 5.17 \times (\log C + 1.155) \times Q$ (1) where a is a process constant, I is current, and V is cell voltage.

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However, if a combined process is applied together with electrochemical PFAS elimination to concentrate the PFAS by 10^b time the original PFAS concentration via ion exchange or other technologies as described herein, the energy consumption for total PFAS removal will be:

 $E(conc. PFAS \ destruct.) = a \times I \times V \times 5.17 \times [(\log(C \times 10^b) + 1.155] \times Q/10^b \quad (2)$ 25 Combining (1) and (2) above:

 $E(source PFAS \ destruct.) = E(conc. PFAS \ destruct.) \frac{(logC+1.155)10^{b}}{Log\ C+1.155+b} (3)$

Consider a raw water of 1000 ppt PFAS and a desired PFAS concentration enhancement of 10⁴:

 $E(source PFAS \ destruct.) = E(conc. PFAS \ destruct.) \times 2241$ (4)

It is worth noting that the estimation above does not consider energy expense in the 5 process of concentrating PFAS by various technologies (defined as E(concentration)thereafter); however, the energy necessary to achieve this is significantly lower than direct electrochemical oxidation from raw water. A very conservative ratio between $E(source PFAS \ destruct.)$ and $E(conc. PFAS \ destruct.)$ is 10 when 1000 ppt PFAS in source water was treated.

10 Therefore, the total energy expense for a process combing concentrating PFAS and elimination by BDD to treat 1000 ppt PFAS from (4) shall be modified to be:

$$E(conc. PFAS \ destruct.) =$$

$$\frac{B(source PFAS \ destruct.)}{2241} + \frac{E(source PFAS \ destruct.)}{10} \approx \frac{E(source PFAS \ destruct.)}{10}$$
(5)

In addition, significant extra capital cost will be a concern for direct oxidation treatment on raw water since treatment by a constrained period is usually required in industrial applications while the capacity of BDD is still limited by the technology. Comparison of module input is shown in (6):

 $BDD (modules, by source PFAS destruct.) = \frac{\log C + 1.155}{\log C + b + 1.155} \times 10^{b} BDD (modules, by conc. PFAS destruct.)$ (6)

- 20 Therefore, for the same raw water having 1000 ppt PFAS and a 10⁴ concentration enhancement, the number of BDD modules required to treat the source water directly would be 2241 times that of the number of BDD modules in a constrained fixed time of period. This cost would be very concerning, as commercial BDD modules may be cost-prohibitive.
- A second reason is to control by-products resulting from the oxidation of chloride ions in the matrix of the source of contaminated water. Source water for direct electrochemical oxidation will inevitably produce chlorine, chlorate, and even perchlorate on BDD anodes. Even though organic chlorine disinfection by-products (e.g., trihalomethanes (THMs)) would tend to be eliminated by inert anodes, inorganic chlorine compounds including chlorine, chlorate and perchlorate would remain and keep accumulating during the treatment in the batch process.
- 30 However, in a process combining PFAS concentrating procedures and BDD elimination as

described herein, the source water matrix is well-controlled, and the production of chloride byproducts is substantially mitigated.

Table 3 shows collected data for free chlorine, chlorate, and perchlorate concentrations of a source water containing 500 ppm NaCl and 500 ppb PFOA after treatment by BDD anodes.

- 5 The reaction was manually stopped, and chlorine species were analyzed when 500 ppb PFOA was decreased to 20 ppb as detected by ion chromatography coupled with a PROTOSIL HPLC column where a solution of 10 mM boric acid and 10% acetonitrile (adjusted to pH 8) was employed as the mobile phase. Measurement of free chlorine was achieved by an iodometric titration method while chlorate and perchlorate were measured by ion chromatography
- 10 employing a METROSEP A Supp 5 anion exchange column where a solution of carbonate and bicarbonate was used as the mobile phase.

Table 3. Inorganic chlorine contaminants present after electrochemical PFAS elimination using aBDD electrode.

Chlorine Species	Concentration (ppm)					
Free chlorine (as NaClO)	58					
Chlorate (ClO ₃ ⁻)	115					
Perchlorate (ClO ₄ ⁻)	2.3					

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Example 2

FIG. 1 provides a schematic of a water treatment system including one or more anion exchange vessels for the removal of PFAS from a source of contaminated water and electrochemical elimination of the separated PFAS. The source of contaminated water has a

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PFAS concentration of 0.1-100 ppb that is directed to the inlet of one of the one or more anion
exchange vessels to allow the PFAS in the water to adsorb onto the anion exchange resin. The
treated water exiting the one or more anion exchange vessels does not have a detectable
concentration of PFAS. After a predetermined period of time, the adsorbed PFAS are removed
from the anion exchange resin by flushing the anion exchange vessel with a regeneration solution

25 consisting of 50-70% methanol, 30-50% water, and 0.5-1.0% NaOH. The PFAS-loaded regeneration solution exits the anion exchange vessel and has a PFAS concentration of 0.05-50 mg/L.

To facilitate electrochemical PFAS elimination and recover methanol from the regeneration solution for reuse, the methanol is thermally removed from the PFAS-loaded regeneration solution, removing 50-70% of the total volume of the regeneration solution and leaving behind water and 1-2% NaOH. The collected methanol is fed back to the anion

- 5 exchange regeneration solution as makeup flow during the anion exchange regeneration process. After the methanol has been removed from the PFAS-loaded regeneration solution, the PFAS concentration in the now-concentrated regeneration solution is 0.1-100 mg/L. The PFASenriched regeneration solution is introduced into an electrochemical PFAS elimination stage, where the PFAS are electrochemically oxidized until none remain. The treated water from the
- 10 electrochemical PFAS elimination has the remaining 1-2% NaOH neutralized, and the resulting neutralized water is discharged as treated water with no detectable PFAS concentration. The water treatment system of this example is effective if the PFAS compounds in the source of contaminated water were oxidized to near completion.

15 Example 3

FIG. 2 provides a schematic of a water treatment system including one or more anion exchange vessels for the removal of PFAS from a source of contaminated water and electrochemical elimination of the separated PFAS. The source of contaminated water has a PFAS concentration of 0.1-100 ppb that is directed to the inlet of the one or more anion

- 20 exchange vessels to allow the PFAS in the water to adsorb onto the anion exchange resin. The treated water exiting the one or more anion exchange vessels does not have a detectable concentration of PFAS. After a predetermined period of time, the adsorbed PFAS are removed from the anion exchange resin by flushing the anion exchange vessel with a regeneration solution consisting of 50-70% methanol, 30-50% water, and 0.5-1.0% NaOH. The PFAS-loaded
 25 regeneration solution exits the one or more anion exchange vessels having a PFAS concentration
- of 0.05-50 mg/L.

To facilitate electrochemical PFAS elimination and recover methanol from the regeneration solution for reuse, the methanol is thermally removed from the PFAS-loaded regeneration solution, removing 50-70% of the total volume of the regeneration solution and

30 leaving behind water and 1-2% NaOH. The collected methanol is fed back to the anion exchange regeneration solution as makeup flow during the anion exchange regeneration process.

After the methanol has been removed from the PFAS-loaded regeneration solution, the PFAS concentration in the now-concentrated regeneration solution is 0.1-100 mg/L. The PFAS-enriched regeneration solution is introduced into an electrochemical PFAS elimination stage, where the PFAS are electrochemically oxidized to reduce the concentration of PFAS in the

6 enriched PFAS-loaded regeneration solution. In this example, the electrochemical PFAS elimination did not fully eliminate all PFAS from the enriched PFAS-loaded regeneration solution; the PFAS concentration after electrochemical PFAS elimination is 0.005-5 mg/L. The resulting solution from the incomplete electrochemical PFAS elimination has the 1-2% NaOH remaining neutralized and is fed back into the inlet of one of the one or more anion exchange
 10 vessels of the PFAS separation stage to continue the PFAS separation process.

Example 4

FIG. 3 provides a schematic of a water treatment system including one or more anion exchange vessels for the removal of PFAS from a source of contaminated water and
electrochemical elimination of the separated PFAS. The source of contaminated water has a PFAS concentration of 0.1-100 ppb that is directed to the inlet of one of the one or more anion exchange vessels to allow the PFAS in the water to adsorb onto the anion exchange resin. The treated water exiting the anion exchange vessel does not have a detectable concentration of PFAS. After a predetermined period of time, the adsorbed PFAS are removed from the anion
exchange resin by flushing the anion exchange vessel with a regeneration solution consisting of 50-70% methanol, 30-50% water, and 0.5-1.0% NaOH. The PFAS-loaded regeneration solution exits the anion exchange vessel and has a PFAS concentration of 0.05-50 mg/L.

To facilitate electrochemical PFAS elimination and recover methanol from the regeneration solution for reuse, the methanol is thermally removed from the PFAS-loaded 25 regeneration solution, removing 50-70% of the total volume of the regeneration solution and leaving behind water and 1-2% NaOH. The collected methanol is fed back to the anion exchange regeneration solution as makeup flow during the anion exchange regeneration process. After the methanol has been removed from the PFAS-loaded regeneration solution, the PFAS concentration in the now-concentrated regeneration solution is 0.1-100 mg/L. The PFAS-

30 enriched regeneration solution is introduced into an electrochemical PFAS elimination stage, where the PFAS are electrochemically oxidized to reduce the concentration of PFAS in the

enriched PFAS-loaded regeneration solution. In this example, it was found that the electrochemical elimination of PFAS did not oxidize the PFAS to near completion, indicating that short chain PFAS remain in the solution after a first pass of electrochemical elimination. This solution may have the remaining short chain PFAS concentrated using a membrane

5 concentrator, such as a nanofiltration stage, to produce a concentrate solution enriched in the remaining short chain PFAS. This enriched solution is fed back into the electrochemical PFAS elimination stage, thus facilitating the complete oxidation of the remaining short chain PFAS. Alternatively, if the electrochemical elimination of the PFAS was close to complete, the resulting solution from the electrochemical PFAS elimination has the 1-2% NaOH remaining neutralized and is fed back into the inlet of one of the one or more anion exchange vessels of the PFAS

separation stage to continue the PFAS separation process.

Example 5

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FIG. 4 provides a schematic of a water treatment system including a nanofiltration PFAS separation stage. The nanofiltration PFAS separation stage can include one or more nanofiltration units, and the number and type of nanofiltration units will depend of the water matrix of the source of water contaminated with PFAS. The water contaminated with PFAS is directed to the inlet of the one or more nanofiltration units. The permeate from the one or more nanofiltration units is discharged as treated water substantially free of PFAS. The concentrate from the one or more nanofiltration units is enriched in PFAS.

- 20 is optionally directed to the inlet of a hardness removal unit should a concern exist that the concentrate has an enriched concentration in ions that may foul any additional membranes in the water treatment system or may cause scale formation on downstream process equipment. Either after passing through the hardness removal stage or coming direct from the concentrate outlet of the nanofiltration PFAS separation stage, the PFAS enriched concentrate is directed to the inlet
- 25 of a nanofiltration diafiltration stage to further concentrate the PFAS from the original enriched PFAS concentrate and remove chloride salts from the permeate solution. The nanofiltration diafiltration concentration step requires the use of a water supply that has low TSS, such as the diluate from a RO or electrodialysis (ED) unit, as makeup water to ensure that salts are washed out and PFAS are enriched in the resulting concentrate. The further PFAS-enriched concentrate
- 30 is introduced into an electrochemical PFAS elimination stage, where the PFAS are electrochemically oxidized until none remain. The treated water from the electrochemical PFAS

elimination is directed back to the first PFAS separation stage and is combined with the treated water from said first PFAS separation stage and discharged as treated water.

Example 6

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FIG. 5 provides a schematic of a water treatment system including one or more nanofiltration units for the removal of PFAS from a source of contaminated water and electrochemical elimination of the separated PFAS. The source of contaminated water has a PFAS concentration of 0.1-100 ppb and a NaCl concentration of 100-300 ppm; this feed is directed to the inlet of a TSS removal stage configured to reduce clogging and fouling on the membranes of the one or more nanofiltration units. The diluate from the TSS removal stage is

directed to one of the one or more nanofiltration units to allow the PFAS in the water to be trapped by the membranes and collected as the concentrate from the one or more nanofiltration units. The treated water exiting the one or more nanofiltration units has a concentration of PFAS less that the current U.S. EPA lifetime exposure limit of 70 ppt. The concentrate from the one or more nanofiltration units has a PFAS concentration of 0.01-10 ppm, a Ca/Mg ion concentration on the order to >100 ppm, and a NaCl concentration of > 1000 ppm.

To facilitate electrochemical PFAS elimination, the concentrate from the one or more nanofiltration units is directed to the inlet of a hardness removal stage to decrease the concentration of Ca/Mg ions from the concentrate by chemical precipitation. The resulting

- 20 PFAS-enriched concentrate, now having a Ca/Mg concentration of < 10 ppm, is directed from the outlet of the hardness removal stage to a storage tank, where it is used as the feed water of a nanofiltration diafiltration stage to further concentrate the PFAS from the original enriched PFAS concentrate and remove chloride salts from the permeate solution. To dilute the concentration of salts prior to nanofiltration diafiltration, water that originates from a source of
- 25 water with a low TSS concentration, such as from a RO or ED unit, is added to the storage tank holding the PFAS-enriched concentrate. The diluate that results from the nanofiltration diafiltration stage is added to the discharge from the PFAS separation stage as discharge. After reducing the chloride salt concentration to about < 100 ppm and increasing the PFAS concentration to 1-1000 ppm, the further PFAS-enriched concentrate is introduced into an
- 30 electrochemical PFAS elimination stage, where the PFAS are electrochemically oxidized until less than 10 ppb PFAS remain. The treated water from the electrochemical PFAS elimination is

directed back to the first PFAS separation stage and is blended with the treated water from said first PFAS separation stage and discharged as treated water, where the discharged water has a PFAS concentration of < 70 ppt and a chloride salt content of 100-300 ppm.

5 **Example 7**

A GAC electrode (1.7 g electrode material in total including 80% by weight GAC, 10% by weight graphite as the conductor and 10% by weight high molecular weight polyethylene (PE) as the binder) was used to adsorb PFOA of 1 ppm in 1 liter of water. 65% of the initial 1 ppm PFOA was adsorbed onto the GAC as measured by ion chromatography coupled with a PROTOSIL HPLC column using a solution of 10 mM boric acid and 10% acetonitrile (adjusted to pH 8) as the mobile phase. The GAC electrode was then regenerated in 25 mL of a Na₂SO₄ salted deionized (DI) solution when 20 mA DC current was applied in an electrochemical cell with a platinum coated titanium electrode employed as the anode. After 1 hour of electrochemical separation, 0.68 ppm PFOA was detected in the concentrate solution,

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corresponding to 2.6% recovery rate.

The phraseology and terminology used herein is for the purpose of description and should not be regarded as limiting. As used herein, the term "plurality" refers to two or more items or components. The terms "comprising," "including," "carrying," "having," "containing," and "involving," whether in the written description or the claims and the like, are open-ended terms,

- i.e., to mean "including but not limited to." Thus, the use of such terms is meant to encompass 20 the items listed thereafter, and equivalents thereof, as well as additional items. Only the transitional phrases "consisting of" and "consisting essentially of," are closed or semi-closed transitional phrases, respectively, with respect to the claims. Use of ordinal terms such as "first," "second," "third," and the like in the claims to modify a claim element does not by itself connote
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any priority, precedence, or order of one claim element over another or the temporal order in which acts of a method are performed, but are used merely as labels to distinguish one claim element having a certain name from another element having a same name (but for use of the ordinal term) to distinguish the claim elements.

Having thus described several aspects of at least one embodiment, it is to be appreciated 30 various alterations, modifications, and improvements will readily occur to those skilled in the art. Any feature described in any embodiment may be included in or substituted for any feature of

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any other embodiment. Such alterations, modifications, and improvements are intended to be part of this disclosure and are intended to be within the scope of the invention. Accordingly, the foregoing description and drawings are by way of example only.

Those skilled in the art should appreciate that the parameters and configurations
described herein are exemplary and that actual parameters and/or configurations will depend on the specific application in which the disclosed methods and materials are used. Those skilled in the art should also recognize or be able to ascertain, using no more than routine experimentation, equivalents to the specific embodiments disclosed.

What is claimed is:

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CLAIMS

1. An onsite system for treating a source of water contaminated with perfluoro alkyl substances (PFAS), comprising:

a PFAS separation stage having an inlet fluidly connectable to the source of water contaminated with PFAS, a diluate outlet, and a concentrate outlet; and

a PFAS elimination stage positioned downstream of the PFAS separation stage and having an inlet fluidly connected to an outlet of the PFAS separation stage, the elimination of the PFAS occurring onsite with respect to the source of water contaminated with PFAS, the system

10 being configured to maintain an overall elimination rate of PFAS greater than about 99%.

2. The system of claim 1, wherein the system maintains a concentration of PFAS in the diluate of the PFAS separation stage below a predetermined threshold.

15 3. The system of claim 2, wherein the predetermined threshold is less than 70 parts per trillion (ppt).

4. The system of claim 3, wherein the predetermined threshold is less than 12 ppt.

20 5. The system of claim 1, further comprising a hardness removal stage.

6. The system of claim 1, further comprising a control system configured to regulate the feed directed between the PFAS separation stage and the PFAS elimination stage.

25 7. The system of claim 6, further comprising a PFAS sensor positioned downstream of the diluate outlet of the PFAS separation stage.

8. The system of claim 1, wherein the PFAS separation stage comprises one or more ion exchange modules.
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9. The system of claim 8, further comprising regeneration of the ion exchange modules to remove bound PFAS to produce a PFAS concentrate.

10. The system of claim 9, wherein the regeneration comprises contacting the ion exchange modules with a regeneration solution comprising methanol, water, and NaOH.

11. The system of claim 1, wherein the PFAS separation stage comprises one or more nanofiltration modules.

10 12. The system of claim 11, wherein a concentrate comprising PFAS from the one or more nanofiltration modules has its PFAS concentration increased by passing through one or more nanofiltration diafiltration modules downstream of the one or more nanofiltration modules.

13. The system of claim 12, wherein the one or more nanofiltration diafiltration modules targetremoval of NaCl and/or KCl.

14. The system of claim 1, wherein the PFAS separation stage involves adsorption onto an electrochemically active substrate.

20 15. The system of claim 14, wherein the electrochemically active substrate comprises granular activated carbon (GAC).

16. The system of claim 15, wherein the GAC comprises an electrode in an electrochemical cell.

25 17. The system of claim 16, wherein an electrode in the electrochemical cell comprises platinum, a mixed metal oxide (MMO) coated dimensionally stable anode (DSA) material, graphite, or lead/lead oxide.

18. The system of claim 16, wherein the electrochemical cell further comprises a sulfateelectrolyte.

19. The system of claim 16, further comprising an ion exchange membrane separator.

20. The system of claim 16, wherein the adsorbed PFAS are desorbed from the electrochemically active substrate by electrical activation of the electrochemical cell.

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21. The system of claim 1, wherein the PFAS separation stage involves foam fractionation.

22. The system of claim 1, wherein the PFAS elimination stage comprises an electrochemical PFAS elimination stage.

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23. The system of claim 22, wherein the electrochemical PFAS elimination stage comprises an electro-advanced oxidation system.

24. The system of claim 23, wherein the electro-advanced oxidation system comprises anelectrochemical cell.

25. The system of claim 24, wherein the electrochemical cell involves a boron doped diamond (BDD) electrode.

20 26. The system of claim 24, wherein the electrochemical cell involves a Magneli phase titanium oxide electrode.

27. The system of claim 26, wherein the Magneli phase titanium oxide electrode comprises Ti_nO_{2n-1} with n = 4-10.

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28. The system of claim 24, wherein an electrode of the electrochemical cell is made of a stainless steel, nickel alloy, titanium, or a DSA material.

29. The system of claim 24, wherein the electrochemical cell comprises an electrolytecomprising at least one of hydroxide, sulfate, nitrate, and perchlorate.

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30. The system of claim 1, wherein the PFAS elimination stage comprises an advanced oxidation process (AOP) reactor.

31. The system of claim 30, wherein the AOP involves UV-persulfate treatment.

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32. The system of claim 30, wherein the AOP involves plasma treatment.

33. A method of treating water contaminated with PFAS, the method comprising the steps of: introducing contaminated water from a source of water contaminated with a first

10 concentration of PFAS to an inlet of a PFAS separation stage;

treating the contaminated water in the PFAS separation stage to produce a product water substantially free of PFAS and a PFAS concentrate having a second PFAS concentration greater than the first PFAS concentration;

introducing the PFAS concentrate to an inlet of a PFAS elimination stage; and

15 activating the PFAS elimination stage to eliminate the PFAS in the PFAS concentrate, the elimination rate of PFAS is greater than about 99%.

34. The method of claim 33, wherein the elimination of PFAS occurs onsite with respect to the source of contaminated water.

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35. The method of claim 33, further comprising treating the PFAS concentrate from the PFAS separation stage to produce a concentrate having a third concentration of PFAS, the third PFAS concentration greater than the second PFAS concentration.

25 36. The method of claim 35, comprising introducing the concentrate having the third concentration of PFAS to the inlet of the PFAS elimination stage.

37. The method of claim 33, further comprising monitoring a pressure, temperature, pH, concentration, flow rate, or total organic carbon (TOC) level in the source water and/or product water.

38. The method of claim 33, wherein the PFAS separation stage comprises one or more ion exchange modules.

39. The method of claim 33, wherein the PFAS separation stage comprises one or morenanofiltration modules.

40. The method of claim 33, wherein the PFAS separation stage involves adsorption onto an electrochemically active substrate.

10 41. The method of claim 33, wherein the PFAS separation stage foam fractionation.

42. The method of claim 34, wherein the PFAS elimination stage comprises electro-advanced oxidation method.

15 43. The method of claim 42, wherein the electro-advanced oxidation method comprises an electrochemical cell.

44. The method of claim 43, wherein the electrochemical cell involves a BDD electrode.

20 45. The method of claim 43, wherein the electrochemical cell involves a Magneli phase titanium oxide electrode.

46. The method of claim 43, wherein the wherein the electrochemical cell comprises an electrolyte comprising at least one of hydroxide, sulfate, nitrate, and perchlorate.

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47. The method of claim 33, wherein the PFAS elimination stage comprises an AOP reactor.

48. The method of claim 47, wherein the AOP involves UV-persulfate treatment.

30 49. The method of claim 47, wherein the AOP involves plasma treatment.

- 50. A method of retrofitting a water treatment system, comprising: providing a PFAS elimination stage; and fluidly connecting the PFAS elimination stage downstream of a PFAS separation stage.
- 5 51. The method of claim 50, wherein the PFAS elimination stage comprises an electro-advanced oxidation method.

52. The method of claim 51, wherein the electro-advanced oxidation method comprises an electrochemical cell.

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53. The method of claim 52, wherein the electrochemical cell involves a BDD electrode.

54. The method of claim 52, wherein the electrochemical cell involves a Magneli phase titanium oxide electrode.

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56. The method of claim 55, wherein the AOP involves UV-persulfate treatment.

20 57. The method of claim 55, wherein the AOP involves plasma treatment.

^{55.} The method of claim 50, wherein the PFAS elimination stage comprises an AOP reactor.



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Feed water information



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FIG. 6

$C_7F_{15}COO^{-} \longrightarrow C_7F_{15}COO^{+} e^{-}$ (One electron loss as direct oxidation)	(1)
$C_7F_{15}COO \cdot \longrightarrow C_7F_{15} \cdot + CO_2$ (decarboxylation)	(2)
C_7F_{15} + HO · C_7F_{15}OH (hydroxylation)	(3)
$C_7F_{15}OH \longrightarrow C_6F_{13}COF + H^+ + F^-$ (Intramolecular rearrangement for defluorination)	(4)
$C_6F_{13}COF + H_2O \longrightarrow C_6F_{13}COO^- + 2H^+ + F^-$ (hydrolysis for defluorination)	(5)

FIG. 7

SUBSTITUTE SHEET (RULE 26)



FIG. 8

INTERNATIONAL SEARCH REPORT

International application No. PCT/US 20/12648

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)
This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:
1. Claims Nos.: because they relate to subject matter not required to be searched by this Authority namely:
 Claims Nos.: because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
3. Claims Nos.: because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).
Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)
This International Searching Authority found multiple inventions in this international application, as follows:
See Extra Sheet
 As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims. As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees. As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
 4. No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.: 1-32 Remark on Protest The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee. The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
fee was not paid within the time limit specified in the invitation. No protest accompanied the payment of additional search fees.

Form PCT/ISA/210 (continuation of first sheet (2)) (July 2019)

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 20/12648

A. CLA	A. CLASSIFICATION OF SUBJECT MATTER IPC - C02F 1/32; C02F 1/36; C02F 1/78 (2020.01)				
CPC - C02F 1/325; C02F 1/36; C02F 1/78; C02F 2201/3221; C02F 2201/3228					
B FIFI	D International Patent Classification (IPC) or to both	national classification and IPC			
Minimum de					
See Search	Minimum documentation searched (classification system followed by classification symbols) See Search History document				
Documentati See Search I	Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched See Search History document				
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) See Search History document					
C. DOCUN	MENTS CONSIDERED TO BE RELEVANT				
Category*	Citation of document, with indication, where app	propriate, of the relevant passages	Relevant to claim No.		
Y 	US 10,259,730 B2 (Oxytec LLC) 16 April 2019 (16.04 Abstract. col 1 in 47-50; col 3 in 39-43; col 4 in 34-35	2019) Entire document, especially	1-9, 11-15, 21-25, 28-31		
A	8, 30-32; col 10 ln 64-67; col 11 ln 1-2	, col 0 in 5-0, 55, 45-47, 65-67, col 7 in 6-	10, 16-20, 26-27, 32		
Y 	US 2017/0036171 A1 (Massachusetts Institute of Teo Petroleum and Minerals) 9 February 2017 (09.02.201	chnology and King Fahd University of 7) Entire document, especially Abstract	1-9, 11-15, 21-25, 28-31		
A	para [0006]; [0024]; [0030]		10, 16-20, 26-27, 32		
Y	US 8,894,834 B2 (Freydina et al.) 25 November 2014 Abstract, col 6 In 59-66; col 7 In 21-25; col 10 In 50-56	(25.11.2014) Entire document, especially 3; col 11 In 3-7, 22-28, 35-36	5-7		
Y	US 8,337,686 B2 (Rath et al.) 25 December 2012 (25 Abstract, col 3 In 48-52; col 4 In 48-54; col 6 In 51-55	.12.2012) Entire document, especially	8-9		
Y	US 2008/0116136 A1 (Wilkins et al.) 22 May 2008 (22 Abstract, para [0054]	2.05.2008) Entire document, especially	14-15		
Y	US 6,171,480 B1 (Lee et al.) 9 January 2001 (09.01.2 col 1 In 24-33, 45-46; col 6 In 36-39; col 13 in 4-11	2001) Entire document, especially Abstract,	21		
Y	US 8,999,173 B2 (Schwartzel et al.) 7 April 2015 (07.) Abstract, col 8 ln 30-35, 44-46, 52-56; col 10 ln 26-29	04.2015) Entire document, especially ; col 17 ln 3-5	22-25, 28-29		
Further documents are listed in the continuation of Box C. See patent family annex					
 Special categories of cited documents: "A" document defining the general state of the art which is not considered to be of particular relevance "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention 					
"E" earlier ar filing dat	"D" document cited by the applicant in the international application "E" application or patent but published on or after the international filing date "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone				
"L" documer is cited t special re	"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "Y" document of particular relevance; the claimed invention canno combined with one or more other such documents. such combinatio				
"O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than "&" document member of the same patent family the priority date claimed					
Date of the ac	Date of the actual completion of the international search Date of mailing of the international search report				
4 March 2020 2 0 MAY 2020					
Name and ma	Vame and mailing address of the ISA/US Authorized officer				
P.O. Box 1450, Alexandria, Virginia 22313-1450		Lee Young			
Facsimile No	Facsimile No. 571-273-8300 Telephone No. PCT Helpdesk: 571-272-4300				
orm PC1/ISA/210 (second sheet) (July 2019)					

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 20/12648

C (Continua	ation). DOCUMENTS CONSIDERED TO BE RELEVANT	
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 8,652,336 B2 (Sitkiewitz et al.) 18 February 2014 (18.02.2014) Entire document, especially Abstract, col 1 In 9-10, 42-46; col 2 In 4-5; col 4 In 55-59	30-31
A	US 6,398,876 B1 (Starcevic et al.) 4 June 2002 (04.06.2002) Entire document, especially col 2 In 66-67	29

Form PCT/ISA/210 (continuation of second sheet) (July 2019)

International application No.

PCT/US 20/12648

This application contains the following inventions or groups of inventions which are not so linked as to form a single general inventive concept under PCT Rule 13.1. In order for all inventions to be searched, the appropriate additional search fees must be paid.

Group I: Claims 1-32, directed to an onsite system for treating a source of water contaminated with perfluoro alkyl substances (PFAS), comprising: a PFAS separation stage having an inlet fluidly connectable to the source of water contaminated with PFAS, a diluate outlet, and a concentrate outlet; and a PFAS elimination stage positioned downstream of the PFAS separation stage and having an inlet fluidly connected to an outlet of the PFAS separation stage, the elimination of the PFAS occurring onsite with respect to the source of water contaminated with PFAS, the system being configured to maintain an overall elimination rate of PFAS greater than about 99%.

Group II: Claims 33-57, directed to a method of treating water contaminated with PFAS, the method comprising the steps of: introducing contaminated water from a source of water contaminated with a first concentration of PFAS to an inlet of a PFAS separation stage; treating the contaminated water in the PFAS separation stage to produce a product water substantially free of PFAS and a PFAS concentrate having a second PFAS concentration greater than the first PFAS concentration; introducing the PFAS concentrate to an inlet of a PFAS elimination stage; and activating the PFAS elimination stage to eliminate the PFAS in the PFAS concentrate, the elimination rate of PFAS is greater than about 99%.

The inventions listed as Groups I and II do not relate to a single general inventive concept under PCT Rule 13.1 because, under PCT Rule 13.2, they lack the same or corresponding special technical features for the following reasons:

Special Technical Features:

Group I requires an onsite system for treating a source of water contaminated with perfluoro alkyl substances (PFAS), comprising: a PFAS separation stage having an inlet fluidly connectable to the source of water contaminated with PFAS, a diluate outlet, and a concentrate outlet; and a PFAS elimination stage positioned downstream of the PFAS separation stage and having an inlet fluidly connected to an outlet of the PFAS separation stage, the elimination of the PFAS occurring onsite with respect to the source of water contaminated with PFAS, to esparate to the source of water specifically required by Group II.

Group II requires a method of treating water contaminated with PFAS, the method comprising the steps of: introducing contaminated water from a source of water contaminated with a first concentration of PFAS to an inlet of a PFAS separation stage; treating the contaminated water in the PFAS separation stage to produce a product water substantially free of PFAS and a PFAS concentrate having a second PFAS concentration greater than the first PFAS concentration; introducing the PFAS concentrate to an inlet of a PFAS elimination stage; and activating the PFAS elimination stage to eliminate the PFAS in the PFAS concentrate, the elimination rate of PFAS is greater than about 99%, not specifically required by Group I.

Common Technical Features:

Groups I and II share the technical feature of a PFAS elimination stage, a PFAS separation stage connected to the source of water contaminated with PFAS; and an overall elimination rate of PFAS greater than about 99%.

However, these shared technical features do not represent a contribution over prior art, because the shared technical feature is being anticipated by US 10,259,730 B2 to Oxytec LLC (hereinafter 'Oxytec'). Oxytec discloses a PFAS elimination stage (col 6 In 43-47 - '...In some particular embodiments, a gas infusion tank reactor may be used for various ex-situ treatment processes . Any suitable design may be used to implement a gas infusion tank reactor as described herein...'; In 63-67 - '...Ozone gas at a pressure of 1, 2, or 3 atmospheres may optionally be introduced above the water level in the reactor to contact the PFAA containing foam and/or aerosol in the gas phase to remove, de-fluorinate, or otherwise reduce its concentration...'), a PFAS separation stage connected to the source of water contaminated with PFAS (col 4 In 34-35 - '...method of controlling the rate of foam or aerosol formation to the rate of chemical oxidation...'; col 6 In 5-6 - '...Specifically, FIG. 1 shows an in-situ reactive zone or flushing zone treatment...'; col 7 In 6-8 - '...Before or after ex-situ treatment, the extracted groundwater may, in some cases, be further treated...'; Note: a foam comprising PFAAs would be formed during the process, that will later be removed in the elimination stage; see instant claim 21); and an overall elimination rate of PFAS that may be greater than about 99% (col 10 In 64-col 11 In 2 - '...In some embodiments, methods disclosed herein can destroy, or break down... greater than 99%, or greater than 99.% of the perfluorinated materials that are present in a sample as water, soil, waste water, waste streams or solvent systems...').

As the shared technical features were known in the art at the time of the invention, they cannot be considered common technical features that would otherwise unify the groups. Therefore, Groups I and II lack unity under PCT Rule 13.

Form PCT/ISA/210 (extra sheet) (July 2019)

Title of the Invention

Plasma treatment system with multiple horizontal channels

Field of the Invention

The invention relates generally to plasma treatment system for destruction of contaminants in liquid, and more particularly to a plasma treatment system with multiple, horizontal, parallel treatment channels.

Background of the Invention

This section is intended to provide information relating to the field and background of the invention and thus any approach/functionality described
below should not be assumed to be qualified as prior art merely by its inclusion in this section.

There is significant interest in using plasma to treat contaminants in water and wastewater that are highly resistant to destruction by other means. Consequently, plasma is the subject of ongoing research in university and private sector laboratories. While the technology shows progress, scientists and engineers are still working to identify superior system configurations and address economical scale-up for those systems.

Synthetic organic compounds as a major group of contaminants in wastewater are of concern worldwide due to their severe problems for the environment and human health. Thus, in the cases of unavoidable contaminant emissions, these emerging compounds must be treated to satisfy the stringent water quality regulations before discharging into aquatic ecosystem. As wastewater remediation becomes a global concern, the development of innovative advanced processes for wastewater treatment is still a major challenge. With regard to its fast reaction rate and environmental compatibility, electrical plasma generation for contaminant removal from liquids is utilized.

Poly- and perfluoroalkyl substances (PFAS) are a group of fluorinated organic anthropogenic chemicals that are resistant to chemical destruction. Per- and polyfluorinated substances (PFAS) are a class of xenobiotic compounds that have contaminated the environment through human activity and production. PFAS are found in wastewater, drinking water, and groundwater, and are not substantially removed by traditional water treatment technologies. Poly- and perfluoroalkyl substances (PFAS) are a class of organofluorine compounds that are persistent in the environment, bioaccumulative, and can be soluble in aqueous matrices PFAS are thermally stable, lipid and water repelling, and have been deemed "forever chemicals".

PFAS have been liberally used over the past 60 years in aqueous film forming foam (AFFF), household products such as carpets, paper, and non-stick 15 cookware, and even coated cardboard takeout containers. Extensive groundwater and surface water contamination of PFAS originates from a variety of sources, including industrial and commercial manufacturing plants that produce or use PFAS, contaminated biosolids application, contaminated landfill leachate, wastewater and water treatment plants discharges, and AFFF training facilities. Drinking water supplies for millions of U.S. residents 20 have been contaminated with various PFAS, with both perfluorooctanesulfonic acid (PFOS) and perfluorooctanoic acid (PFOA) often surpassing the US EPA's lifetime health advisory (70 ng/L). Since this advisory was set for these two compounds, most research done to date focuses on PFOS and PFOA, but a growing number of studies are 25 investigating a wider range of PFAS, including perfluorocarboxylic acids (PFCA), perfluorosulfonic acids (PFSA), fluorotelomer sulfonates (FtS), and a number of unknown precursor PFAS compounds that are also present in the contaminated water.

One example of prior art is known. The Plasma Research Group at Clarkson University, led by Dr. Selma Mededovic Thagard, has developed two 5 prototypes of an Enhanced Contact Electrical Discharge Plasma (EDP) system, which they have been testing for destruction of per- and polyfluoroalkyl substances (PFAS) compounds. The shallow, rectangular prototype version (subsequently referred to as the Clarkson prototype) is considered prior art for the current invention. A description of Clarkson prototype is given in Chemical & Engineering News, Vol. 97, No.12, p. 10 magazine/97/09712 (March 25, 2019) and US Publication No. 2018/0339921 laid open on November 29, 2018, for example. The disclosure of US Publication No. 2018/0339921 is incorporated herein by reference as background of invention. However, Clarkson's pipe-based prototype is not relevant to the current invention and will not be considered further. For the 15 purposes of this discussion, target contaminant(s) will refer to PFAS or generic target compounds.

The Clarkson prototype is a flow-through system consisting of a reservoir with a diffuser for argon gas, at the bottom. A cathode grid is located above the water surface and anodic plates are located below the water surface. The system is closed at the top, with argon gas in the headspace. As water is pumped through the system, argon gas is bubbled through the diffuser, conveying the PFAS to the gas/water interface. The plasma generated by the electrodes destroys the PFAS by breaking the hydrophobic, hydrocarbon

chains above the gas/liquid interface. For the purposes of this discussion, process gas will refer to argon or other gases (or gas mixtures) suitable for plasma generation.

The need for a gas headspace makes it difficult to scale up this type of EDP system. In fact, DMaxPlasma, a spinoff company started by Dr. Thagard and Dr. Holsen of Clarkson University, indicate on their web site (as of August 22, 2019), "The plasma reactor is modular (reactor dimensions are: L×W×H=30"×20"×0.25"), meaning it can be scaled for a specific treatment

rate and/or multiple reactors can be used side-by-side. The reactors are mobile, easy to bring to a contaminated site and place in line with other treatment operations, can readily be moved within a site to operate at different locations at different times, and can be operated either continuously or pulsed on demand." The description of multiple units placed side by side

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- suggests that the team is currently not able to stack these units in a common process tank. It should be noted that the height given for the unit does not appear to be correct. From the information available, the height is greater than 0.25 inches. That apparent error does not affect the present invention.
- 15 Another example of prior art is known. The Nanjing Gongcheng Energy Saving New Materials Research Institute has carried out "Water treatment method based on plasma", which was led by Liu Dong, Sun Junjie, Lu Jun, and Ye Tianbao. A description of Nanjing Gongcheng Energy Saving New Materials Research Institute on water plasma treatment method is given in
- 20 Chinese Application No. CN110844975A laid open on February 28, 2020. Water treatment method based on plasma includes sewage storage reactor, a high-voltage power supply and a high-voltage electrode, wherein the highvoltage electrode contains a positive electrode and a grounding electrode, the positive electrode and the grounding electrode are respectively fixed at the
- ²⁵ upper part and the lower part of the sewage storage reactor, and the two electrodes are connected with a high-voltage power supply through wires. A baffle is provided at a side of the effluent storage reactor near the effluent outlet, wherein the baffle plate is loaded with a first catalyst on the left side.

This application is an example of water plasma treatment, but it performs operation with catalyst for preventing harmful byproducts and does not utilize gas diffuser and gas hood for contaminant(s) removal.

The other example of prior art is known. The University of Michigan has carried out "Plasma water purifier having packed bed discharges with water dielectric barriers", which was led by Foster John E and Mujovic Selman. A description of University of Michigan on plasma water purifier with water dielectric barriers is given in US Patent No. US10662086B2 laid open on May 26, 2020. System for water purification having a water inlet being distributed

- 10 into a plurality of streams defining extended dielectric barrier layers with high surface area to volume ratios and a plasma disposed between at least a pair of the plurality of water streams forming a surface plasma attachment producing radicals that treat the water via diffusion. Plasma system having a powered electrode and a ground electrode disposed within the chamber
- 15 responsive to an applied voltage, the plasma system configured to receive the gas from the gas inlet and output a plasma within the interstitial spaces between each of the plurality of water streams, at the surface of each of the plurality of water streams, and within each of the plurality of water streams via propagation forming at least a surface plasma attachment producing reactive
- 20 species that purify the water. Therefore mentioned system utilizes plasma (ionized gas) for the purpose of water purification; plasma produces radicals that oxidize organic contaminant(s) and it removes them on oxidation principle instead of diffusion mechanism.

Another example of prior art is known. The Wuhu Hualu Environmental Protection Technology Co Ltd has carried out "Apparatus and method for treating medical wastewater by low temperature plasma", which was led by Huang Qing, Zhang Qifu, Wei Xing, Zhang Hong and Ke Zhigang. A description of Wuhu Hualu Environmental Protection Technology Co Ltd on

medical wastewater treatment by low temperature plasma is given in Chinese Application No. CN108640228A laid open on October 12, 2018. The apparatus includes a low temperature plasma power supply, a plasma discharge reactor, a water collecting tank and a gas supply system, wherein the low temperature plasma power supply is connected with the plasma 5 discharge reactor, and the plasma discharge reactor is arranged in a gascollecting hood of the gas supply system, high-voltage electrodes of the plasma discharge reactor perform plasma discharge on oxygen in the gascollecting hood to generate ozone, and finally, the ozone is used to treat the 10 medical wastewater in the water collecting tank. According to the apparatus and method, a dielectric barrier discharge technology is adopted to generate the low temperature plasma, high energy electrons, ultraviolet light, ozone, etc. generated by the low temperature plasma discharge are used to degrade the medical wastewater. This patent is an example of wastewater treatment by using plasma, but it does not contain channel arrangement for contaminant 15 removal.

The other example of prior art is known. The Korea Basic Science Institute has carried out "Recalcitrant Organic Matter Treatment Apparatus and Method Using Plasma Underwater Discharge Method", which was led by Ryu Seung Min and Park Jun Seuk. A description of Korea Basic Science Institute on method using plasma underwater discharge is given in Korean Patent No.

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- KR101660712B1 laid open on September 29, 2016. Device for treating a non-biodegradable organic material by using a plasma underwater discharge method includes a non-biodegradable organic material supplying unit; a
 reaction unit for converting a non-biodegradable organic material into a
- decomposable organic material by performing plasma underwater discharge treatment using a plasma dual electrode on a material supplied from the nonbiodegradable organic material supplying unit; and a microorganism reaction

unit for biologically treating the decomposable organic material treated from the reaction unit. The plasma dual electrode has an inner side made of a ceramic material, and an outer side made of a metal material, wherein discharge is performed only in the outside of a capillary tube of the ceramic material. The above mentioned system and method is example of plasma treatment of decomposable organic material from water, but it does not

involve horizontal channels for operation.

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It would be desirable to have an effective method to scale up the EDP system by stacking multiple EDP channels in a common process tank, each EDP

10 channel having a gas headspace and corresponding local water surface (i.e., gas/liquid interface).

It would further be desirable to be able to operate such a system in either continuous flow or batch modes.

It would further be desirable to be able to treat either water or wastewater, or a stream resulting from pretreatment of a water or wastewater stream to concentrate the target contaminant(s) (via DAF, RO, or other technologies). Pretreating to concentrate the target contaminant(s) could reduce the required EDP system size and cost. It could also further reduce the system size by reducing or eliminating the need for bubbling process gas through diffusers in the EDP process tank.

Consequently, there is a need for the EDP system which is made by stacking multiple EDP channels in a common process tank. There is a growing need to develop a system and method for treating contaminants in liquid that are highly resistant to destruction. Thus, the present invention, which is devised

to solve the problems and disadvantages of prior art as described above.

Object of the Invention

This section is intended to introduce certain objects of the disclosed methods and systems in a simplified form, and is not intended to identify the key advantages or features of the present disclosure.

5 The main object of the present invention is to provide a plasma treatment system with multiple horizontal channels.

Another object of the present invention is to provide a plasma treatment system with multiple stacking EDP channels in a common process tank.

A further object of the present invention is to provide a plasma treatment

10 system to provide submerged EDP channel having a gas headspace and corresponding local water surface (i.e., gas/liquid interface).

It is still a further object of the present invention to provide a plasma treatment system for treating target contaminant(s) in liquid that are highly resistant to destruction.

15 These and other objects, features and advantages of the present invention will become more apparent from the following description when taken in connection with the accompanying drawing which shows, for the purpose of illustration only, one embodiment in accordance with the present invention.

Summary of the Invention

This summary is provided to introduce a selection of concepts in a simplified format that are further described in the detailed description of the invention. This summary is not intended to identify key or essential inventive concepts of

5 the invention, nor is it intended for determining the scope of the invention.

In order to overcome problems of conventional systems used for liquid plasma treatment, the present invention discloses the plasma treatment system with multiple horizontal channels.

The invention relates generally to plasma treatment system for destruction of contaminant(s) in liquid, and more particularly to an EDP treatment system with multiple, horizontal, parallel treatment channels.

The basic system comprises a sealed process tank with more than one EDP channels, positioned such that they are stacked vertically. In the basic system, each EDP channel consists of a gas diffuser at the bottom of the EDP channel, a cathode above the liquid surface, and an anode below the liquid surface. The basic submerged EDP channel is bounded by a plate at the bottom and a submerged gas hood at the top. The top of the gas hood for one EDP channel can function as the bottom plate for the EDP channel above it. For the top EDP channel, no gas hood is required. For the bottom EDP channel, no bottom plate is required.

There are numerous possible configurations for the EDP channels in a process tank. These include, but are not limited to, arranging vertically, side by side, and overlapping.

The gas hood is essentially a downturned tray that, when submerged, provides a headspace containing the process gas and the cathode. In the basic system, the influent enters the process tank and flows horizontally through the multiple EDP channels in parallel. As the liquid flows through each EDP channel, the gas bubbles (such as argon, recirculated from the top of the process tank) from a diffuser convey the contaminant(s) to the liquid/gas interface. There, plasma generated by electrical discharge acts on the contaminant(s), as described elsewhere by the Clarkson team. The

If the gas bubbles are introduced prior to multiple EDP channels, this could reduce or eliminate the need for diffusers in each EDP channel. This could also reduce the depth required for each channel, allowing more EDP channels in a given height process tank. This could be accomplished by locating a gas diffuser in or before the influent zone. Alternately, an eductortype gas injector could be used to inject the process gas, in the influent pipe, upstream of the EDP process tank.

treated effluent exits from the outlet end of the process tank.

15 If a concentration step is used for PFAS or target contaminant(s) in a separate, upstream process, this could significantly reduce the size of the required EDP process tank. There are various ways to concentrate PFAS. Reported alternatives include reverse osmosis (RO) and adsorption on synthetic resins (and subsequent regeneration, producing a concentrated 20 regenerant stream).

Another means of PFAS concentration would be conventional dissolved air flotation (DAF), with or without parallel plates or tubes. The use of DAF would concentrate PFAS (or other polar contaminants) at the liquid surface of the DAF, allowing removal of the contaminants in a concentrated stream of liquid and/or foam (instead of the floated sludge that is usually scraped from the

surface).

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It has been proposed to use EDP at the surface of a DAF unit. This would involve sealing the top of the DAF unit and recirculating the process gas. However, it is thought to be desirable to decouple the concentration step from the EDP treatment step, to be able to optimize the two operations separately.

In addition, using separate operations would allow use of commonly available DAF equipment with air, rather than a custom DAF unit with recirculating process gas (such as argon) and electrodes for plasma generation.

An equalization tank upstream of the EDP treatment system could also be used for the contaminant concentration step. This would involve installing fine bubble diffusers in the tank, and pumping liquid/foam from the surface of the

tank to the EDP treatment system. Any alternative using air bubbles to float the PFAS could require a degassing

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Any alternative using air bubbles to float the PFAS could require a degassing step ahead of the EDP treatment system, to avoid diluting the process gas in the EDP system.

15 Other continuous flow configurations are also possible. In a basic upflow configuration, a process tank could have one gas diffuser located at the bottom of the process tank, with EDP baffles placed at various levels in the tank. The influent would be introduced at the bottom of the tank. The multiple EDP baffles would cause the liquid to travel in a serpentine flow path as it rises in the process tank.

Batch treatment configurations are also possible. These could operate in a cycle similar to Sequencing Batch Reactors used for biological wastewater treatment. The cycle would include Fill, React, Degas (if needed), and Drain steps. Multiple tanks could be used, so one or more tanks could be filling while the active tank goes through the React, Degas, and Drain steps. A process gas reservoir could be used to conserve the process gas during filling and draining operations.

Another embodiment can be used to treat liquid in large tanks, reservoirs or natural water bodies. This embodiment would consist of one or more EDP levels. The top EDP level would have a gas hood floating on the surface of the liquid, to contain and allow for recirculation of the process gas.

5 To the accomplishment of the foregoing and related ends, certain illustrative aspects of the disclosure are described herein in connection with the following description and the annexed drawing. These aspects are indicative, however, of but a few of the various ways in which the principles of the disclosure can be employed and the subject disclosure is intended to include all such aspects and their equivalents. Other advantages and novel features will become apparent from the following detailed description of the disclosure when considered in conjunction with the drawing.

To further clarify advantages and features of the present invention, a more particular description of the invention will be rendered by reference to specific embodiments thereof, which is illustrated in the appended drawing. It is appreciated that this drawing depicts only typical embodiments of the invention and are therefore not to be considered limiting its scope. The invention will be described and explained with additional specificity and detail with the accompanying drawings.

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Brief Description of Drawing

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In order to better understand the present invention plasma treatment system with multiple horizontal channels, the characteristics of object of the present invention, will be better viewed from the detailed description hereinafter, which is only for a way of example, associated to the drawings referenced below, which are an integral part of this application. The parts in the drawings are not drawn to scale; the main objective is to understand the components, their arrangement and their working.

FIG. 1a and FIG. 1b are profile views of a basic, submerged EDP channel and a basic, submerged EDP baffle, respectively.

FIG. 2 is a profile view of a basic embodiment with four EDP channels.

FIG. 3 is a profile view of an embodiment with upward flow with serpentine EDP baffles.

- Further, skilled artisans will appreciate that elements in the drawings are
 illustrated for simplicity and may not have been necessarily been drawn to scale. Furthermore, in terms of the construction of the product, have been represented in the drawings by conventional symbols, and the drawings may show only those specific details that are pertinent to understanding the embodiments of the present invention so as not to obscure the drawings with
 details that will be readily apparent to those of ordinary skill in the art having
 - benefit of the description herein.

Detailed Description

For the purpose of promoting an understanding of the principles of the invention, reference will now be made to the embodiment illustrated in the drawings and specific language will be used to describe the same. It will

nevertheless be understood that no limitation of the scope of the invention is thereby intended, such alterations and further modifications in the illustrated system and/or method, and such further applications of the principles of the invention as illustrated therein being contemplated as would normally occur to one skilled in the art to which the invention relates.

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It will be understood by those skilled in the art that the foregoing general description and the following detailed description are explanatory of the invention and are not intended to be restrictive thereof.

- Reference throughout this specification to "an aspect", "another aspect" or similar language means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment of the present invention. Thus, appearances of the phrase "in an embodiment", "in another embodiment" and similar language throughout this specification may, but do not necessarily, all refer to the same embodiment.
- 15 As used herein, the singular forms "a", "an" and "the" are intended to include the plural forms as well, unless expressly stated otherwise. It will be further understood that the terms "includes", "comprises", "including" and/or "comprising" when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do
- 20 not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof. It will be understood that when an element is referred to as being "connected" or "coupled" to another element, it can be directly connected or coupled to the other element or intervening elements may be present. Furthermore, the term
- ²⁵ "and/or" includes any and all combinations and arrangements of one or more of the associated listed items.

Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs.

Any headings provided herein are for convenience only and do not necessarily affect the scope or meaning of the claimed invention.

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Embodiments of the present invention will be described below in detail with reference to the accompanying drawings

The detailed description of the plasma treatment system with multiple horizontal channels; object of the present invention will be made in accordance with the identification of components that form the basis of the figures described above.

As used herein, the following terms and variations thereof have the meanings given below, unless a different meaning is clearly intended by the context in which such term is used. Definitions, where the definition of terms departs from the commonly used meaning of the term, applicant intends to utilize the

definitions provided below, unless specifically indicated.

For purposes of the present disclosure, it should be noted that to provide a more concise description, some of the quantitative expressions given herein are not qualified with the term "about." It is understood that whether the term

- 20 "about" is used explicitly or not, every quantity given herein is meant to refer to the actual given value, and it is also meant to refer to the approximation to such given value that would reasonably be inferred based on the ordinary skill in the art, including approximations due to the experimental and/or measurement conditions for such given value.
- For purposes of the present disclosure, the term "liquid" refers to a substance that is capable of flowing. The liquid can be an aqueous liquid, including water

or wastewater, wherein water or wastewater refers to a liquid comprising one or more contaminants, which includes organic compounds, bacteria, and metal ions. Wastewater may also include solid inert materials such as undissolved polymeric materials, dirt, and sand.

- 5 For purposes of the present disclosure, the term "plasma treatment" refers to liquid plasma treatment, which can be performed in such a manner that contaminant can be removed from liquid, typified by gas as its main component is introduced into a reaction system to generate plasma.
- For purposes of the present disclosure, the term "electrode" refers to an electrical conductor used in contact with another material that is often nonmetallic in a device that can be incorporated into an electrical circuit. Herein both cathode and anode are used for liquid treatment.

For purposes of the present disclosure, the term "electrical discharge plasma" refers to a system for treating contaminant(s) from liquid by passing plasma,

15 wherein plasma is generated by electrical discharge; which acts on the contaminant(s).

For purposes of the present disclosure, the term "channel" refers to a conduit within the system which is primarily used to carry a liquid, wherein liquid includes, but not limited to, water or wastewater.

For purposes of the present disclosure, the term "contaminant(s)" refers to materials in the water or wastewater that are different from the target substance(s) and are desirably excluded from the final target substance product(s). Contaminants, refers to runoff, raw sewage, industrial wastewater, leachate, waste human, effluent and the like. Polymeric contaminant(s) include per- and polyfluoroalkyl substances (PFAS) compounds.

For purposes of the present disclosure, the term "process tank" refers to any container that is suitable for the removing contaminant(s) from liquid by plasma treatment.

For purposes of the present disclosure, the term "gas hood" refers to a gas holding unit and is segment of process tank.

After observing all above problems in the prior art, the idea of developing system for plasma treatment of water or wastewater with multiple horizontal channels is disclosed in the present invention detailed description which is plasma treatment system with multiple horizontal channels.

- 10 Plasma treatment of water and wastewater has been the subject of significant research. There are several different options for process gases (including gas mixtures) and numerous process configurations. The current invention applies to the EDP process, generally as implemented in the Clarkson pilot, although it would also apply to other processes requiring a gas headspace above each
- 15 treatment channel.

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A brief description of the EDP process is presented below, as implemented in the Clarkson prototype. This description is included as background for the invention and is not intended to be an exhaustive review of plasma technology.

- 20 The Clarkson prototype consists of a single, sealed process tank, comprising a gas diffuser at the bottom of the process tank, a grid of point-type cathodes above the water surface, and long rectangular strip anodes under the water surface. The process gas (argon) is drawn from the headspace of the process tank and bubbled through the diffuser. The process gas bubbles provide a
- 25 large surface area for polar surfactants such as PFAS to accumulate at the gas/liquid interface. At the water surface, plasma is produced by electrical

discharge between the electrodes. The plasma acts on the hydrocarbon chains on the hydrophobic portion of the PFAS molecules, which extend above the water surface.

- Referring to the figures, wherein like numerals indicate like or corresponding parts throughout the several views, FIG 1a shows a profile view of a basic, submerged EDP channel. The flow through the EDP channel (26) is horizontal. The gas diffuser (34) is located at the bottom of the EDP channel (26) and is used to bubble process gas through the water in the EDP channel (26) (recirculated from the process gas held under the gas hood (44) or from
- the top of the sealed process tank (22)). The process gas carries the target contaminant(s) to the local water surface (54), where polar contaminants are exposed to the process gas. The gas hood (44) remains full of process gas. Excess process gas flows to the open edge(s) of the gas hood (44), and then is released to rise in the process tank (22). The cathode (50) is located above
- 15 the local water surface (54). The anode (52) is located below the local water surface (54). The electrical connections and power supply are not shown, for clarity, but are familiar to those skilled in the art. Electrical discharge arcing between the cathode (50) and the local water surface (54) (en route to the anode (52)) creates plasma from the process gas in the gas hood (44). The

20 plasma reacts with the target contaminant(s) at the local water surface (54).

The gas hood front wall (58) and gas hood back wall (60) of the gas hood (44) are shown as having the same height, for simplicity. In another embodiment, either the gas hood front wall (58) or gas hood back wall (60) is shorter than the other, to direct the flow of process gas bubbles to rise at either end of the

25 process tank (22). Alternately, an inverted V notch in one of the gas hood (44) walls could be used to direct the gas bubbles to rise at a certain location. This could be desirable, in the event that an additional EDP layer is used to treat

any residual contaminant in the process gas bubbles as they arrive at the surface of the process tank (22).

A screen (not shown) can be placed below the process tank water surface (24) and/or local water surface (54) to reduce or eliminate the foam created by the process gas bubbles, if needed.

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FIG. 1b shows a profile view of an EDP baffle (28). The EDP baffle (28) can be used with upflow-type system, to provide EDP treatment at one or more locations/elevations in the flow path. As in other systems with baffles, there are numerous possible configurations. In FIG 1b, the EDP baffle (28) is joined

- to the side wall (48) of the process tank (22) (not shown). The gas hood (44) holds process gas and maintains a local water surface (54). The cathode (50) is located above the local water surface (54). The anode (52) is located below the local water surface (54). The electrical connections and power supply are not shown, for clarity, but are familiar to those skilled in the art.
- Process gas bubbles are introduced prior to or below the EDP baffle (28), using a gas diffuser (34) or other means (not shown). As the flow and the process gas bubbles travel up through the process tank (22), the target contaminant(s) move from the bulk liquid to the surface of the process gas bubbles. The water and process gas bubbles flow upward until the flow is redirected by the EDP baffle (28). Electrical discharge arcing between the
- cathode (50) and the anode (52) creates plasma from the process gas. The plasma reacts with the target contaminant(s) at the local water surface (54).

A screen (not shown) can be placed below the process tank water surface (24) and/or local water surface (54) to reduce or eliminate the foam created by the process gas bubbles, if needed.
FIG 2 shows a profile view of a basic embodiment of the EDP system (20), installed in a rectangular process tank (22). This embodiment includes four EDP channels (26) (three submerged), for clarity, but more or fewer EDP channels (26) can be installed in one process tank (22).

- 5 The water enters the influent zone (32) through the inlet (30), and splits between the multiple EDP channels (26). A gas diffuser (34) at the bottom of each EDP channel (26) is used to introduce process gas bubbles, which convey polar target contaminant(s) to the surface of the EDP channel (26). Electrical discharges between the cathode (50) and submerged anode (52)
- 10 degrade and/or destroy the target contaminant(s). The electrical connections and power supply are not shown, for clarity, but are familiar to those skilled in the art. Water exits the EDP channel (26) to the effluent zone (36) of the process tank (22) and flows from the process tank (22) as treated effluent through the outlet (38).
- The gas hood (44) may be attached to the side walls (48) of the process tank (22), with a shallow gas hood front wall (58) extending down at the influent zone (32) and a shallow gas hood end wall (60) at the outlet zone (36). The gas hood (44) could also be a downturned tray consisting of a top plate with four, short sides extending down, secured at the desired elevation in the process tank (22). Regardless of whether the gas hood (44) has sides in common with the process tank (22), baffle walls (56), etc., the main requirement is that the gas hood (44) maintain a gas headspace at the top of the EDP channel (26) for the cathode (50).

The treatment volume may have a baffle wall (56) between the influent zone (32) and the EDP channels (26), to dissipate energy and promote uniform flow distribution over the face of the EDP channels (26). There are also various options for structures in the effluent zone (36), including, but not

limited to, a baffle wall **(56)** to prevent short circuiting, an outlet weir (not shown), etc. These additional structures are familiar to those skilled in the art.

Another continuous flow embodiment is shown in FIG 3. Instead of parallel flow through horizontal, EDP channels (26), this embodiment has an upflow configuration, using the gas hoods (44) as EDP baffles (28) to direct the flow in a serpentine fashion. Water enters through the bottom (30) of the process tank (22). Process gas is bubbled into the process tank (22) using a gas diffuser (34) located at the bottom of the process tank (22). Supplemental diffusers (34) could also be used, if needed, in the upper parts of the process tank (22). Alternately, process gas could be introduced using a venturi-type injector (not shown), upstream of the process tank (22). The electrical connections and power supply are not shown, for clarity, but are familiar to

With some modification, the embodiment shown in FIG 2 could also be
operated in batch mode. The process tank (22) would be full of process gas
prior to the start of the treatment cycle. During the Fill step, water would enter
through the inlet (30) to the influent zone (32). The rising water level in the
process tank (22) would force process gas from the process tank (22) to a
separate process gas reservoir (62) (not shown). Once the water reaches the
normal operating level in the process tank (22), the influent flow would be
shut off and the EDP process started (React step). A water recirculation pump
(64) could be used to recirculate the contents of the process tank (22),
drawing water from the effluent zone (36) through the outlet and returning the
water to the influent zone (32). At the end of the React step, the EDP process

those skilled in the art.

and water recirculation pump (64) would be shut off. If a Degas step is needed, the process tank would sit idle for a set length of time to allow the process gas to come out of solution (with optional vacuum assist-not shown). After the Degas step, the process tank (22) would drain through the outlet (38). While water drains from the process tank, the process tank (22) would draw process gas from the process gas reservoir (62).

The continuous flow, upflow embodiment (FIG 3) could also be modified for batch treatment. The process tank (22) would be full of process gas prior to 5 the cycle. During the Fill step, water would enter through the bottom of the process tank (22), through inlet (30). The rising water level in the process tank (22) would force process gas from the process tank (22) to the process gas reservoir (62). Once the water reaches the normal operating level in the process tank (22), the influent flow would be shut off and the EDP process started (React step). A water recirculation pump (64) could be used to 10 recirculate the contents of the process tank (22), drawing water from the top of the process tank (22) and returning the water to the bottom of the process tank (22). At the end of the React step, the EDP process and recirculation pump 64 would be shut off. If a Degas step is needed, the process tank would sit idle for a set time to allow the process gas to come out of solution (with 15 optional vacuum assist-not shown). After the Degas step, the process tank (22) would drain through the outlet (38). While water drains from the process

tank (22), the process tank (22) would draw process gas from the process gas reservoir (62).

In another embodiment (not shown), the EDP system (20) would float or be suspended on a water surface. This embodiment could be used in large tanks, reservoirs or natural water bodies. This embodiment would consist of one or more EDP channels (26) or EDP baffles (28). The top EDP channel (26) or EDP baffle (28) would have a gas hood (44) extending below the

surface of the water, to contain and allow for recirculation of the process gas. Water would pass through the EDP channel (26) either by laterally moving the EDP system (20) or by pumping water through the EDP channel (26). The invention is not limited to this embodiment, and various modifications can be made therein within the scope of the concept of the invention.

The foregoing invention has been described in accordance with the relevant legal standards, thus the description is exemplary rather than limiting in nature. Variations and modifications to the disclosed embodiment may become apparent to those skilled in the art and fall within the scope of the invention. Furthermore, particular features of one embodiment can replace corresponding features in another embodiment or can supplement other embodiments unless otherwise indicated by the drawings or this specification.

The drawings and the forgoing description give examples of embodiments. Those skilled in the art will appreciate that one or more of the described elements may well be combined into a single functional element. Alternatively, certain elements may be split into multiple functional elements. Elements from one embodiment may be added to another embodiment. For example, orders of processes described herein may be changed and are not limited to the manner described herein. The scope of embodiments is at least

limited to the manner described herein. The scope of embodiments is at least as broad as given by the following claims.

Benefits, other advantages, and solutions to problems have been described above with regard to specific embodiments. However, the benefits,
advantages, solutions to problems, and any component(s) that may cause any benefit, advantage, or solution to occur or become more pronounced are not to be construed as a critical, required, or essential feature or component of any or all the claims.

SYSTEM AND METHOD FOR WATER TREATMENT INCLUDING GRANULAR ACTIVATED CARBON REGENERATION

CROSS REFERENCE TO RELATED APPLICATION

[1] This application claims priority from U.S. Provisional Patent Application No. 62/917,268 filed on November 30, 2018 entitled SYSTEM AND METHOD FOR WATER TREATMENT INCLUDING GRANULAR ACTIVATED CARBON REGENERATION, which is hereby incorporated by reference.

BACKGROUND

[2] Per- and polyfluoroalkyl substances (PFAS) are a group of man-made chemicals that are becoming the focus of increasingly intense regulatory attention. Their thermal stability and lipid and water repelling properties have contributed to the extensive use of PFAS in a wide range of applications, such as in aqueous film forming foams (AFFFs), Teflon production, chromium electroplating, textile manufacturing, and household products. The most attention has been given to the sulfonate and carboxylate PFAS forms, and most recent regulatory actions focus on perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA). *See* Kucharzyk, K.H., et al., *Novel treatment technologies for PFAS compounds: A critical review.* Journal of environmental management, 2017. 204: p. 757-764.

[3] The most commonly used treatment method for PFOA and PFOS removal from groundwater is adsorption onto granular activated carbon (GAC), followed by incineration of the spent GAC. This technology is well-established and commonly used

for a variety of environmental contaminants and the currently accepted remediation technology for groundwater impacted by PFOS and PFOA. *See Id.*

[4] GAC is deployed at a broad range of scales between municipal water treatment and domestic point of entry systems, either as a standalone technology or part of a treatment train. GAC can consistently remove PFOS at parts per billion (ppb) or micrograms per liter (µg/L) concentrations with an efficiency of more than 90 percent. See Ross, I., et al., A review of emerging technologies for remediation of PFASs. Remediation Journal, 2018. 28(2): p. 101-126. GAC systems have become the baseline against which all new adsorbent technologies targeting PFAS removal from water are compared. See Id. For example, although ion exchange resins previously used for perchlorates can provide higher treatment flow rates for PFAS than GAC due to their shorter empty bed contact times, they are much more costly and subject to interference and scavenging by other contaminants. Membranes on the other hand, while highly effective, create a 25% reject stream that leaves a secondary treatment gap. GAC remains the de facto, low-cost standard treatment modality, however, GAC can be inefficient for removing PFOA and progressively less effective for removing shorter chain perfluorinated carboxylic acids (PFCAs) such as perfluorohexanoic acid (PFHxA), perfluoropentanoic acid (PFPeA), perflorobutane sulfonate (PFBS), and perfluorobutanoic acid (PFBA) as the chain length diminishes. See Oliaei, F., et al., PFOS and PFC releases and associated pollution from a PFC production plant in Minnesota (USA). Environmental Science and Pollution Research, 2013. 20(4): p. 1977-1992; Inyang, M. and E.R. Dickenson, The use of carbon adsorbents for the removal of perfluoroalkyl acids from potable reuse systems. Chemosphere, 2017. 184: p. 168-175.

[5] Competition for sorption sites on GAC either from longer chain PFASs, natural organic matter, or co-contaminants such as chlorinated solvents can lead to desorption and release of previously adsorbed PFHxA and PFBA. *See* Kucharzyk, K.H., et al., *Novel treatment technologies for PFAS compounds: A critical review.* Journal of environmental management, 2017. 204: p. 757-764; Ross, I., et al., *A review of emerging technologies for remediation of PFASs.* Remediation Journal, 2018. 28(2): p. 101-126. Use of GAC may not be feasible if natural organic matter is also present in water to be treated. The presence of natural organic matter (*e.g.*, levels of 1.7 mg/L or higher in creek water) has been reported to cause a significant inhibitory effect on the efficiency of removal for all PFAAs, including long-chain species such as perfluorononanoic acid. PFAS adsorption may be diminished by the presence of other organic compounds with similar molecular weights that have higher sorption potential. See Qiu, Y., *Study on treatment technologies for perfluorochemicals in wastewater, Ph.D. Thesis, Kyoto University, Kyoto, Japan.* 2007, Kyoto University, Japan.

[6] A number of chemical contaminants including PFAS can be removed from water through the adsorption process by the exceptionally large surface areas available in GAC, which has a unique pore structure consisting of micro-pores, meso-pores and macro-pores. For example, a single gram of GAC can have a surface area exceeding 1000 m². Accessibility to the adsorption sites within the GAC pore structure and the surface area available are the key to maximizing performance. This is a function of (1) the degree of activation of the carbon base, which is measured by its carbon tetrachloride number (CTC), and (2) the relative surface area of carbon measured by the iodine number. The mesh size of a particular GAC form factor may not affect its

ultimate adsorptive performance but does affect hydraulic performance (*i.e.*, pressure drop) and kinetics (*i.e.*, the rate of reaction).

[7] Importantly, when the GAC surface is covered by chemical contaminants, its adsorption efficiency dramatically decreases. Recent research indicates that high-temperature (800 – 1,100°C) incineration is necessary to completely destroy PFOS and PFOA adsorbed to GAC. *See* Ross, I., et al., *A review of emerging technologies for remediation of PFASs.* Remediation Journal, 2018. 28(2): p. 101-126; Lee, Y.-C., et al., *Promoted degradation of perfluorooctanic acid by persulfate when adding activated carbon.* Journal of hazardous materials, 2013. 261: p. 463-469. The required degradation temperature has been demonstrated to increase with longer perfluoroalkyl chain lengths. *See* Rayne, S. and K. Forest, *Perfluoroalkyl sulfonic and carboxylic acids: a critical review of physicochemical properties, levels and patterns in waters and wastewaters, and treatment methods.* Journal of Environmental Science and Health Part A, 2009. 44(12): p. 1145-1199.

[8] Because of challenging economic and solid waste disposal considerations, it is generally more preferable to regenerate spent carbon for subsequent reuse than to dispose of it. See Perrich, J.R., *Activated carbon adsorption for wastewater treatment*. 2018: CRC press, Boca Raton. In the regeneration process, the objective is to remove the previously adsorbed materials from the carbon porous structure, thus reinstituting its ability to adsorb impurities. There are several methods of regeneration, such as thermal, steam treatment, solvent extraction, acid or base treatment, and chemical oxidation. See Dombrowski, P.M., et al., *Technology review and evaluation of different chemical oxidation conditions on treatability of PFAS.*

Remediation Journal, 2018. 28(2): p. 135-150. Of these methods, only thermal regeneration is widely applied in wastewater treatment. *See* Perrich, J.R., *Activated carbon adsorption for wastewater treatment*. 2018: CRC press, Boca Raton. Thermal regeneration is the process, performed in large reactivation kilns, of drying, thermal desorption, and application of high temperature (800-1,000°C) in the presence of limited quantities of oxidizing gases such as water vapor and oxygen. *See Id.* Since thermal regeneration is an energy-intensive process, and requires additional capital cost associated with a conveyor transportation system to move wet spent GAC from reactor to furnace, it is used only for very large GAC systems.

[9] Therefore, there is a need for an *in-situ* energy-efficient regeneration process, ideally, one that is versatile enough to be adapted for small, medium, and large GAC systems.

SUMMARY

[10] Various embodiments described herein relate to systems and methods for removing contaminants such as PFAS from wastewater and leachates and decompose them directly on the spent GAC using high-voltage arc plasma. In so far as high-voltage plasma can be ignited and well controlled between carbon granules, then the spent GAC can be regenerated *in situ* with dramatic increases in energy efficiency. In accordance with one or more embodiments, a water treatment system includes an adsorption column including granular activated carbon (GAC) that adsorbs contaminants from untreated water onto the GAC, thereby producing treated water, a first electrode disposed at a proximal side of the adsorption column, with a gap between

the first electrode and the GAC, a second electrode disposed at a distal side of the adsorption column, a drain outlet in fluid communication with the adsorption column for draining water out of the adsorption column, a gas inlet in fluid communication with the adsorption column for injecting a displacement gas into the adsorption column, a high voltage power supply electrically connected to one of the first electrode and the second electrode for generating a plasma discharge within the GAC, thereby regenerating the GAC within the adsorption column, and a gas outlet in fluid communication with the adsorption column for venting waste gas produced by the plasma discharge. In certain embodiments, the first electrode can be a high voltage electrode, the second electrode can be a ground electrode, and the high voltage power supply can be electrically connected to the first electrode. In certain other embodiments, the first electrode can be a ground electrode, the second electrode can be a high voltage electrode, and the high voltage power supply can be electrically connected to the second electrode. In some embodiments, the plasma discharge can be an arc plasma discharge. In certain embodiments, the second electrode can be embedded in the GAC at the distal side of the adsorption column. In some embodiments, the proximal side can be a top side and the distal side can be a bottom side of the adsorption column. In certain embodiments, the water treatment system can further include a temperature sensor that measures temperature of the GAC. In some embodiments, contaminants can include perfluorooctane sulfonate, perfluorooctanoic acid, or any combination thereof. In certain embodiments, the displacement gas can be a hydrocarbon gas heavier than air, such as propane, butane, or a mixture thereof. In some embodiments, the gap can be in a range of between 0.5 cm and 1 cm. In certain embodiments, the water treatment

system further includes an untreated water inlet into the adsorption column and a treated water outlet out of the adsorption column. In these embodiments, the water treatment system can further include a pump in fluid communication with the untreated water inlet. In some embodiments, the pump can further include a variable frequency motor.

[11] In accordance with one or more embodiments, a method of regenerating granular activated carbon (GAC) in a water treatment system includes draining water out of an adsorption column containing GAC of a water treatment system, injecting a displacement gas into the adsorption column, generating an electrical voltage between a first electrode disposed at a proximal side of the adsorption column and a second electrode disposed at a distal side of the adsorption column to form a plasma discharge within the GAC, thereby regenerating the GAC within the adsorption column, and venting waste gas produced by the plasma discharge. In certain embodiments, the first electrode can be a high voltage electrode, the second electrode can be a ground electrode, and a high voltage power supply can be electrically connected to the first electrode. In certain other embodiments, the first electrode can be a ground electrode, the second electrode can be a high voltage electrode, and a high voltage power supply can be electrically connected to the second electrode. In some embodiments, the method can further include adjusting output power of the high voltage power supply based on a thermostatic feedback signal from a temperature sensor that measures temperature of the GAC. In certain embodiments, the electrical voltage can be generated for a regeneration time that is less than 30 min, such as less than 10 min, or less than 1 min.

[12] In accordance with one or more embodiments, a method of treating water includes flowing untreated water into an adsorption column including granular activated carbon (GAC) that adsorbs contaminants from the water onto the GAC, thereby producing treated water, flowing the treated water out of the adsorption column, draining water out of the adsorption column, injecting a displacement gas into the adsorption column, generating an electrical voltage between a first electrode disposed at a proximal side of the adsorption column and a second electrode disposed at a distal side of the adsorption column to form a plasma discharge within the GAC, thereby regenerating the GAC within the adsorption column, and venting waste gas produced by the plasma discharge. In certain embodiments, the first electrode can be a high voltage electrode, the second electrode can be a ground electrode, and a high voltage power supply can be electrically connected to the first electrode. In certain other embodiments, the first electrode can be a ground electrode, the second electrode can be a high voltage electrode, and a high voltage power supply can be electrically connected to the second electrode. In some embodiments, the method can further include adjusting output power of the high voltage power supply based on a thermostatic feedback signal from a temperature sensor that measures temperature of the GAC. In certain embodiments, the electrical voltage can be generated for a regeneration time that is less than 30 min, such as less than 10 min, or less than 1 min.

[13] The approach described herein leverages the exceptionally large surfaces of GAC to remove PFAS from water and then decomposes/destroys PFAS collected on the GAC surface with *in-situ* arc plasma (ISAP). In other words, the approach described

herein enables GAC to remove PFAS continuously or virtually continuously -- almost indefinitely with the help of arc plasma.

BRIEF DESCRIPTION OF THE DRAWINGS

[14] The foregoing purposes and features, as well as other purposes and features, will become apparent with reference to the description and accompanying figures below, which are included to provide an understanding of the invention and constitute a part of the specification, in which like numerals represent like elements. The figures are not necessarily drawn to scale, emphasis instead being placed upon illustrating embodiments.

[15] FIG. 1A is a simplified cross-section view of a water treatment system in accordance with one or more embodiments.

[16] FIG. 1B is a simplified electrical wiring diagram for a water treatment system in accordance with one or more embodiments.

[17] FIG. 1C is a simplified cross-section view of a water treatment system including three adsorption columns in accordance with one or more embodiments.

[18] FIG. 2A is a photograph of granular activated carbon particles having 20x40 mesh particle size.

[19] FIG. 2B is a scanning electron microscope image of granular activated carbon particles.

[20] FIG. 2C is a schematic illustration of arc plasma developing in the space between GAC particles in accordance with one or more embodiments.

[21] FIG. 3A is a photograph of arc plasma at the beginning of a preliminary test with wet sand in accordance with one or more embodiments.

[22] FIG. 3B is a photograph of arc plasma and sand slag melted by the arc plasma in accordance with one or more embodiments.

[23] FIG. 4 is a flow chart of a method of regenerating GAC in a water treatment system in accordance with one or more embodiments.

[24] FIG. 5 is a flow chart of a method of treating water in accordance with one or more embodiments.

DETAILED DESCRIPTION

[25] It is to be understood that the figures and descriptions of the present invention have been simplified to illustrate elements that are relevant for a clearer comprehension of the present invention, while eliminating, for the purpose of clarity, many other elements found in systems and methods of plasma discharge in liquid. Those of ordinary skill in the art may recognize that other elements and/or steps are desirable and/or required in implementing the present invention. However, because such elements and steps are well known in the art, and because they do not facilitate a better understanding of the present invention, a discussion of such elements and steps is not provided herein. The disclosure herein is directed to all such variations and modifications to such elements and methods known to those skilled in the art.

[26] Unless defined otherwise, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which

this invention belongs. Although any methods and materials similar or equivalent to those described herein can be used in the practice or testing of the present invention, the preferred methods and materials are described.

[27] As used herein, each of the following terms has the meaning associated with it in this section.

[28] The articles "a" and "an" are used herein to refer to one or to more than one (*i.e.*, to at least one) of the grammatical object of the article. By way of example, "an element" means one element or more than one element.

[29] "About" as used herein when referring to a measurable value such as an amount, a temporal duration, and the like, is meant to encompass variations of $\pm 20\%$, $\pm 10\%$, $\pm 5\%$, $\pm 1\%$, and $\pm 0.1\%$ from the specified value, as such variations are appropriate.

[30] "HV" as used herein means high-voltage, such as a voltage in excess of 1,000 V.

[31] Ranges: throughout this disclosure, various aspects of the invention can be presented in a range format. It should be understood that the description in range format is merely for convenience and brevity and should not be construed as an inflexible limitation on the scope of the invention. Where appropriate, the description of a range should be considered to have specifically disclosed all the possible subranges as well as individual numerical values within that range. For example, description of a range such as from 1 to 6 should be considered to have specifically disclosed subranges as well as from 1 to 3, from 1 to 4, from 1 to 5, from 2 to 4, from 2 to 6, from 3

to 6 etc., as well as individual numbers within that range, for example, 1, 2, 2.7, 3, 4, 5, 5.3, and 6. This applies regardless of the breadth of the range.

[32] The objective of the systems and methods described herein is to remove contaminants such as PFAS in wastewater and leachates and decompose them directly on the spent GAC using high-voltage arc plasma. Insofar as high-voltage plasma can be ignited and well-controlled between carbon granules, then the spent GAC can be regenerated *in situ* with dramatic increases in energy efficiency. Accordingly, such GAC can be used to remove chemical contaminants in wastewater and leachate without leaving any treatment gap or secondary waste problems.

[33] The approach described herein uses *in-situ* arc plasma (ISAP) for the regeneration of wet spent GAC. ISAP utilizes two metal electrodes--one high-voltage (HV) and the other ground, which, in one embodiment, are positioned at the top and bottom, respectively, of each wet spent GAC column or vessel. In accordance with one or more embodiments, a water treatment system 100 shown in FIG. 1A includes an adsorption column 110 including granular activated carbon (GAC) 111 that adsorbs contaminants onto the GAC 111 from untreated water 112 that flows into the adsorption column 110 through the untreated water inlet 113, thereby producing treated water 114 that flows out of the adsorption column 110 through the treated water outlet 116, a first electrode 120 disposed at a proximal side 115 of the adsorption column 110, with a gap 130 between the first electrode 120 and the GAC 111, a second electrode 140 disposed at a distal side 145 of the adsorption column 110, a drain outlet 150 in fluid communication with the adsorption column 110 for draining water out of the adsorption column 110 for draining water out of the adsorption column 110 for draining water out of the adsorption column 110 for draining water out of the adsorption column 110 for draining water out of the adsorption column 110 for draining water out of the adsorption column 110 for draining water out of the adsorption column 110 for draining water out of the adsorption column 110 for draining water out of the adsorption column 110 for draining water out of the adsorption column 110 for draining water out of the adsorption column 110 for draining water out of the adsorption column 110 for draining water out of the adsorption column 110 for draining water out of the adsorption column 110 for draining water out of the adsorption column 110 for draining water out of the adsorption column column 110 for draining water out of the adsorption column column 110 for draining water out of the adsorption column column 110 for draining water out of the adsorption co

injecting a displacement gas into the adsorption column 110, a high voltage power supply 170 electrically connected to one of the first electrode 120 and the second electrode 140 for generating a plasma discharge within the GAC 111, thereby regenerating the GAC 111 within the adsorption column 110, and a gas outlet 180 in fluid communication with the adsorption column 110 for venting waste gas produced by the plasma discharge. In one embodiment, as shown in FIG. 1A, the first electrode 120 is a high voltage electrode, the second electrode 140 is a ground electrode, and the high voltage power supply 170 is electrically connected to the first electrode 120. Alternatively, the first electrode 120 can be a ground electrode, the second electrode 140 can be a high voltage electrode, and the high voltage power supply 170 can be electrically connected to the second electrode 140. The plasma discharge can be an arc plasma discharge, a micro-arc plasma discharge, a corona plasma discharge, or the like. As shown in FIG. 1A, the proximal side 115 is a top side and the distal side 145 is a bottom side of the adsorption column 110. The system 100 optionally also includes a temperature sensor 190 that measures temperature of the GAC 111.

[34] Since it is essential to minimize or completely eliminate oxygen from the adsorption column 110 during the regeneration process for spent GAC, one embodiment employs as a displacement gas a hydrocarbon heavier than air inside the GAC reactor 110, such as propane (C_3H_8) or butane (C_4H_{10}), or a mixture thereof, introduced through the gas inlet 160. Furthermore, as shown in FIG. 1B, since the ISAP-regeneration time is expected to be relatively short (*i.e.*, less than 30 min), one HV power supply 170 can be used to regenerate multiple GAC systems 110A, 110B, and

110C *in situ*, significantly improving the regeneration efficiency of the spent GAC system.

[35] In general, the regeneration time for spent GAC depends on the power of the plasma discharge (*i.e.*, current and voltage). Regeneration efficiency can be determined from adsorption equilibrium isotherms. See Qu et al., DBD regeneration of GAC loaded with acid orange 7. Asia-Pac J. Chem. Eng. 2009. 4: p. 649-653. One embodiment enables the regeneration of one spent GAC column to be completed in less than 30 min, such as less than 10 min, or less than 1 min. This regeneration time is appropriate relative to the 10 min empty bed contact times commonly reported by industry for PFAS adsorption by GAC in water and wastewater. It is important that the regeneration time should be relatively short, such that a single HV power supply can regenerate multiple spent GAC columns, thus significantly improving the energy efficiency of the ISAP regeneration method and enabling this regeneration method to be developed in small (e.g, 1-5 gallon per minute (gpm)), medium (e.g, 5-50 gpm), and large (e.g, 50-500 gpm) water treatment systems. FIG. 1C shows a schematic diagram of an ISAP regeneration system where three GAC columns 110A, 110B, and 110C are connected in series, and the HV 120A, 120B, and 120C and ground 140A, 140B, and 140C electrodes for generation of arc plasma are positioned at the top and bottom of each GAC column, respectively. One embodiment uses multiple cylindrical GAC columns (i.e., 3-9 ft in height) to remove chemical contaminants from wastewater/leachates and regenerate GAC within the columns using arc plasma. Note, if one applies plasma directly to water, arc plasma alone cannot break the carbon-fluorine bonds in PFAS

since the distance between plasma and PFAS molecules is too large if mediated by water.

[36] FIGS. 1B and 1C show a simplified electrical wiring diagram and a simplified cross-section view, respectively, of ISAP-based regeneration for spent GAC. Although FIGS. 1B and 1C show only three GAC columns 110A, 110B, and 110C, additional columns can be added as needed. In the field, GAC vessels having 12-foot diameter are commonly used. FIG. 1B shows the HV electrodes 120A, 120B, and 120C at the top of the GAC and the ground electrodes 140A, 140B, and 140C at the bottom in each column. One HV power supply 170 can be used for the regeneration of multiple spent GAC columns via a HV relay switch 175 shown in FIG. 1B. Larger, higher current HV power supplies can be employed for simultaneous treatment of multiple columns. Note that the HV electrode 120 does not touch the GAC and is positioned at a gap or suspended distance 130 in a range of between 0.5 cm and 1 cm from the top of GAC column (*i.e.*, when water is drained prior to the application of plasma). The appropriate size for the gap 130 can be determined from the Paschen curve.

[37] In one embodiment, a HV rod-shaped metal electrode 120 is used whose diameter is 0.5 inches. A range of different HV electrode materials whose melting temperatures are shown in Table 1 can be used, such as titanium, stainless steel, and tungsten.

Matal	Molting Temperature (°C)
Ivietai	
Stainless Steel	1,510
Titanium	1,670
Tungsten	3,400

Table 1. Melting temperatures of stainless steel, titanium, and tungsten.

[38] Note that the volume of GAC 111 may be reduced due to GAC losses over time during the regeneration process, changing the relative geometric position of the top surface of the GAC. Thus, it may become necessary to adjust the position of the HV electrode 120 to maintain the constant gap distance 130 over time. The ground electrode 140 is embedded in the GAC column 110 at the bottom in this embodiment. Alternatively, the GAC can be disposed on top of the ground electrode 140. Since the regeneration time for one spent GAC column is relatively short, a number of spent GAC columns can be regenerated, one at a time, with one HV power supply 170 via the HV relay switch 175, reducing capital cost as well as operating cost of GAC regeneration. Alternatively, a large power supply 170 can be used to treat multiple GAC vessels simultaneously.

[39] Turning back to FIG. 1A, in accordance with one or more embodiments, the water treatment system 100 includes a pump 125, optionally including a variable-frequency motor (not shown), so that the flow rate can be varied over a range (*i.e.*, 5 to 25 gpm). The height of the GAC column 110 can be varied in the lab from 3 to 9 ft, whereas the diameter of the GAC column 110 can be constant at 2 inches. These dimensions are appropriate for laboratory simulation of standard 12-foot diameter vessels each flowing 500 gpm, typically employed in industrial processes. Prior to the application of plasma to spent GAC, water is drained from the GAC column through a drain outlet 150 located at the bottom of the GAC columns, and the reactor is filled with a displacement gas heavier than air, such as propane or butane, through the gas inlet 160.

[40] The ISAP approach generates arc plasma 210 between GAC particles shown in FIG. 2C, using HV electrode 220, ground electrode 230, and the high electric conductivity of GAC itself, *i.e.*, creating arc plasma 215 literally on the surface of GAC particles 211 shown in FIG. 2B, and schematically illustrated in FIG. 2C, enabling the chemical contaminants adsorbed on the surface of the GAC to be exposed to very high temperatures (*i.e.*, greater than 2,000°C)—which are localized to focal areas 215 at the surfaces of the granules 211, as illustrated in FIG. 2C, with limited bulk heating of vessels. This technique is applicable to any other conductive granular media, besides the granular activated carbon particles having 20x40 mesh particle size shown in FIG. 2A, and also exposes GAC to a number of active plasma species (*e.g.*, ${}^{1}O_{2}$, $OH', H', O', HO'_{2}, O'_{2}, O'_{3}, H_{2}O_{2}, N', NO_{x}, NO'$,) which are created by ISAP.

[41] Turning back to FIG 1A, in ISAP regeneration of spent GAC described herein, waste off-gas is released from the GAC reactor through gas outlet 180 and a valve positioned at the top of the test apparatus, to an activated carbon scrubber (not shown), such that the pressure inside the reactor is always one atmosphere, *i.e.*, zero gauge pressure, for safe operation. In other words, it should be impossible for pressure to build up or for the reactor to rupture, because of the presence of a safety vent 180. In cases where the waste off-gas contains hazardous materials, the waste off-gas can be collected in a separate tank and treated with a separate plasma system such as a gliding arc discharge (a well-established air plasma system).

[42] Although the thermal regeneration process of spent GAC has been used for the purpose of PFAS removal at high temperatures of 800 - 1,000°C without major problems, there are several safety issues when PFAS is exposed to high temperature.

[43] Any GAC regeneration process should not produce elemental fluorine F because it is highly toxic to living organisms. Its effects in humans start at concentrations lower than those of hydrogen cyanide (50 parts per million (ppm)) and are similar to those of chlorine: significant irritation of the eyes and the respiratory system as well as liver and kidney damage occur above 25 ppm, which is immediately dangerous to life and human health. The eyes and nose are seriously damaged at 100 ppm, and inhalation of 1,000 ppm fluorine will cause death in minutes.

[44] Hydrogen gas (H₂) should not be present in GAC regeneration involving PFAS as hydrogen reacts explosively with fluorine. Since graphite combines with fluorine F above 400°C to produce carbon monofluoride, and higher temperatures generate potentially explosive gaseous fluorocarbons, any GAC regeneration process, including those employed in innovative research studies, must not produce fluorine F to avoid gaseous fluorocarbons.

[45] Conventional thermal regeneration is simply unsuitable when GAC is used for PFAS removal. The reason for this is, although oxygen is deliberately depleted in the reaction zone in thermal regeneration, CO_2 and H_2O accumulate as combustion products in furnaces. For this reason and others, specialized reactivation kilns are used to incinerate PFAS-laden GAC by industry. When carbon in GAC reacts with water (H_2O) at elevated temperatures, carbon monoxide (CO) and H_2 can be produced as shown below:

$$C(s) + CO_2 \rightarrow 2CO \tag{1}$$

$$C(s) + H_2O \rightarrow CO + H_2$$
 (2)

[46] Carbon monoxide reacts with fluorine at or just above room temperature. In addition, GAC is being destroyed if this reaction occurs, while generating an explosive gas, H_2 . Thus, the production of CO and H_2 must be avoided during the GAC regeneration process by eliminating CO₂ and water from the GAC reactor.

[47] Oxygen does not combine with fluorine under ambient conditions, but can react with fluorine when electric discharges are used at low temperatures and pressures, resulting in oxyfluoride, which is potentially explosive. However, the products tend to disintegrate into their constituent elements when heated.

[48] Therefore, one embodiment described herein displaces air with higher hydrocarbons such as propane (C_3H_8) or butane (C_4H_{10}), which are almost two times heavier than air. Prior to applying plasma discharge to spent GAC, liquid water is completely drained, and no oxygen is left in the GAC column. The plasma discharge then evaporates liquid water from the GAC to water vapor, so that that GAC dries during the regeneration process. The most ideal chemical reaction in the GAC regeneration process may be the one that converts PFOS to hydrogen fluoride HF (gas) with the help of hydrocarbon as shown in the following equation: $C(s)(GAC) + \frac{17}{8}C_{3}H_{8}(Propane) + C_{8}F_{17}HO_{3}S(PFOS) \rightarrow HF(gas) + C(s) + SO_{2} + H_{2}O$ (3) [49] Hydrogen fluoride HF (gas), upon contact with moisture or water, immediately converts to hydrofluoric acid, which is a weak acid at low concentrations but corrosive and toxic. Nevertheless, HF is relatively safe and easier to manage compared with fluorine F. Furthermore, this chemical reaction does not involve hydrogen gas or oxygen, significantly reducing the risk of explosion. HF is a scavenger of oxygen, creating a positive safety mechanism, further reducing the risk of explosion.

[50] In order to demonstrate the feasibility of thermal reforming, a preliminary test was performed with wet sand whose melting temperature is about 1,600°C using a HV power supply of 3 kW. The photograph shown in FIG. 3A depicts arc plasma 310 generated between HV electrode 320 and ground electrode 330 in wet sand 340 at the beginning of the test, whereas the photograph shown in FIG. 3B depicts sand slag 350 after the wet sand was melted by arc plasma 310. Sand slag 350 formed beneath the HV electrode 320 within one minute, and the size of fused slag volume grew with time over the following 10 min. This melting clearly indicates that the temperature of the arc plasma 310 was well above 1,600°C. While wet sand changed to slag, the container did not burn or melt because it still had liquid water in it, creating significant observable discharge steam while maintaining a temperature of 100°C or lower-since the top of the plastic container was open to the atmosphere and could not exceed the boiling temperature of water. Because the melting temperature of GAC is relatively high (*i.e.*, 3,550°C), thermal reforming of spent GAC using ISAP, without melting or burning GAC, is practical in water vapor and an oxygen-limited environment. In order to ensure that the temperature of spent GAC does not approach its melting temperature of 3,550°C. GAC temperature can be monitored using a temperature sensor 190, shown in FIG. 1A, and the temperature of the GAC 111 can be limited to below a threshold number (e.g., 2,000°C) by adjusting the output power of the HV power supply 170 using a thermostatic feedback signal from the temperature sensor 190.

[51] In accordance with one or more embodiments, a method 400 shown in FIG. 4 of regenerating granular activated carbon (GAC) in a water treatment system includes draining 410 water out of an adsorption column containing GAC of a water treatment

system, injecting 420 a displacement gas into the adsorption column, generating 430 an electrical voltage between a first electrode disposed at a proximal side of the adsorption column and a second electrode disposed at a distal side of the adsorption column to form a plasma discharge within the GAC, thereby regenerating the GAC within the adsorption column, and venting 440 waste gas produced by the plasma discharge. In certain embodiments, the first electrode can be a high voltage electrode, the second electrode can be a ground electrode, and a high voltage power supply can be electrically connected to the first electrode. In certain other embodiments, the first electrode can be a ground electrode, the second electrode can be a high voltage electrode, and a high voltage power supply can be electrically connected to the second electrode. In some embodiments, the method can optionally include adjusting 435 output power of the high voltage power supply based on a thermostatic feedback signal from a temperature sensor that measures temperature of the GAC. In certain embodiments, the electrical voltage can be generated for a regeneration time that is less than 30 min, such as less than 10 min, or less than 1 min.

[52] In accordance with one or more embodiments, a method 500 shown in FIG. 5 of treating water includes flowing 510 untreated water into an adsorption column including granular activated carbon (GAC) that adsorbs contaminants from the water onto the GAC, thereby producing treated water, flowing 520 the treated water out of the adsorption column, draining 530 water out of the adsorption column, injecting 540 a displacement gas into the adsorption column, generating 550 an electrical voltage between a first electrode disposed at a proximal side of the adsorption column and a second electrode disposed at a distal side of the adsorption column to form a plasma

discharge within the GAC, thereby regenerating the GAC within the adsorption column, and venting 560 waste gas produced by the plasma discharge. In certain embodiments, the first electrode can be a high voltage electrode, the second electrode can be a ground electrode, and a high voltage power supply can be electrically connected to the first electrode. In certain other embodiments, the first electrode can be a ground electrode, the second electrode can be a high voltage electrode, and a high voltage power supply can be electrically connected to the second electrode. In some embodiments, the method can optionally include adjusting 555 output power of the high voltage power supply based on a thermostatic feedback signal from a temperature sensor that measures temperature of the GAC. In certain embodiments, the electrical voltage can be generated for a regeneration time that is less than 30 min, such as less than 10 min, or less than 1 min.

[53] Beyond the primary thermal reforming mechanism, the aforementioned plasma reforming of spent GAC is also beneficial as arcs develop between GAC particles. Plasma discharges produce not only UV but also various active plasma species such as ${}^{1}O_{2}$, OH^{*} , H^{*} , O^{*} , HO_{2}^{*} , O_{2}^{*} , O_{3} , $H_{2}O_{2}$, N^{*} , NO_{x} , NO^{*} , and charged particles, most of which are powerful oxidizing agents, and thus potentially useful in enhancing the destruction of chemical contaminants. See Yang, Y., Y.I. Cho, and A. Fridman, *Plasma Discharge in Liquid: Water Treatment and Applications*. 2012, New York: CRC Press. Although the half-lives of most active plasma species are relatively short, the arc plasma develops directly on the surface of the GAC, and thus one can say that plasma is generated on the surface of granules at the very locus of chemical contaminants. As

such, plasma reforming of the spent GAC is a practical mechanism that can increase PFAS destruction efficiency.

[54] The concept of regenerating spent GAC *in situ* and without the use of a reactivation kiln is a major breakthrough, allowing the GAC system to be used in small and medium water treatment systems, as well as in large water treatment facilities. In summary, the ISAP-based GAC regeneration method enables GAC to remove and ISAP to destroy PFAS in water *in-situ* while minimizing capital and operating costs, thus providing an economically viable solution in removing PFAS from wastewater and leachate. Considering the widespread incidence of PFAS contamination and its high recalcitrance to most treatment approaches, the approach described herein employs a versatile technique that is both energy-efficient and robust in destructive potency, without migrating away from GAC as the primary treatment over to more costly and complex methods like ion exchange or membrane filtration. In this regard, the approach described herein provides an improved method to simultaneously remove and destroy PFAS in contaminated surface water, groundwater and wastewater.

[55] A key aspect is the regeneration of spent GAC with *in situ* arc plasma rather than just altering the adsorption performance/efficiency of GAC for various PFAS. The ISAP not only provides thermal reforming but also plasma reforming when arcs develop between GAC particles. The thermal reforming of spent GAC is feasible without ruining the GAC, as the melting temperature of typical activated carbon is around 3,550°C whereas the arc surface temperature is about 2,000°C. See Fridman, A., *Plasma Chemistry*. 2008: Cambridge University Press, Cambridge, UK. Considering that conventional thermal regeneration of spent GAC is often conducted at a temperature in

a range of 800-1,000°C in reactivation kilns, ISAP provides a significantly higher temperature, localized directly on carbon granules with less bulk- and vessel heating losses, providing extremely high energy efficiency. *See* Kucharzyk, K.H., et al., *Novel treatment technologies for PFAS compounds: A critical review.* Journal of environmental management, 2017. 204: p. 757-764; Guo, Y. and E. Du, *The Effects of Thermal Regeneration Conditions and Inorganic Compounds on the Characteristics of Activated Carbon Used in Power Plant* Energy Procedia, 2012. 17: p. 444-449. In this regard, ISAP is ideal for PFAS destruction on GAC.

Further Example Embodiments

[56] Example 1 is a water treatment system that includes an adsorption column including granular activated carbon (GAC) that adsorbs contaminants from untreated water onto the GAC, thereby producing treated water, a first electrode disposed at a proximal side of the adsorption column, with a gap between the first electrode and the GAC, a second electrode disposed at a distal side of the adsorption column, a drain outlet in fluid communication with the adsorption column for draining water out of the adsorption column, a gas inlet in fluid communication with the adsorption column, a high voltage power supply electrically connected to one of the first electrode and the second electrode for generating a plasma discharge within the GAC, thereby regenerating the GAC within the adsorption column, and a gas outlet in fluid communication with the adsorption column for the adsorption column for venting waste gas produced by the plasma discharge.

[57] Example 2 includes the subject matter of Example 1, wherein the first electrode is a high voltage electrode, the second electrode is a ground electrode, and the high voltage power supply is electrically connected to the first electrode.

[58] Example 3 includes the subject matter of Example 1, wherein the first electrode is a ground electrode, the second electrode is a high voltage electrode, and the high voltage power supply is electrically connected to the second electrode.

[59] Example 4 includes the subject matter of any of Examples 1-3, wherein the plasma discharge is an arc plasma discharge.

[60] Example 5 includes the subject matter of any of Examples 1-4, wherein the second electrode is embedded in the GAC at the distal side of the adsorption column.

[61] Example 6 includes the subject matter of any of Examples 1-5, wherein the proximal side is a top side and the distal side is a bottom side of the adsorption column.

[62] Example 7 includes the subject matter of any of Examples 1-6, further including a temperature sensor that measures temperature of the GAC.

[63] Example 8 includes the subject matter of any of Examples 1-7, wherein contaminants include perfluorooctane sulfonate, perfluorooctanoic acid, or any combination thereof.

[64] Example 9 includes the subject matter of any of Examples 1-8, wherein the displacement gas is a hydrocarbon gas heavier than air.

[65] Example 10 includes the subject matter of any of Examples 1-9, wherein the displacement gas is propane, butane, or a mixture thereof.

[66] Example 11 includes the subject matter of any of Examples 1-10, wherein the gap is in a range of between 0.5 cm and 1 cm.

[67] Example 12 includes the subject matter of any of Examples 1-11, further including an untreated water inlet into the adsorption column and a treated water outlet out of the adsorption column.

[68] Example 13 includes the subject matter of Example 12, further including a pump in fluid communication with the untreated water inlet.

[69] Example 14 includes the subject matter of Example 13, wherein the pump includes a variable frequency motor.

[70] Example 15 is a method of regenerating granular activated carbon (GAC) in a water treatment system that includes draining water out of an adsorption column containing GAC of a water treatment system, injecting a displacement gas into the adsorption column, generating an electrical voltage between a first electrode disposed at a proximal side of the adsorption column and a second electrode disposed at a distal side of the adsorption column to form a plasma discharge within the GAC, thereby regenerating the GAC within the adsorption column, and venting waste gas produced by the plasma discharge.

[71] Example 16 includes the subject matter of Example 15, wherein the first electrode is a high voltage electrode, the second electrode is a ground electrode, and a high voltage power supply is electrically connected to the first electrode.

[72] Example 17 includes the subject matter of Example 15, wherein the first electrode is a ground electrode, the second electrode is a high voltage electrode, and a high voltage power supply is electrically connected to the second electrode.

[73] Example 18 includes the subject matter of any of Examples 15-17, further including adjusting output power of the high voltage power supply based on a thermostatic feedback signal from a temperature sensor that measures temperature of the GAC.

[74] Example 19 includes the subject matter of any of Examples 15-18, wherein the electrical voltage is generated for a regeneration time that is less than 30 min, such as less than 10 min, or less than 1 min.

[75] Example 20 is a method of treating water that includes flowing untreated water into an adsorption column including granular activated carbon (GAC) that adsorbs contaminants from the water onto the GAC, thereby producing treated water, flowing the treated water out of the adsorption column, draining water out of the adsorption column, injecting a displacement gas into the adsorption column, generating an electrical voltage between a first electrode disposed at a proximal side of the adsorption column and a second electrode disposed at a distal side of the adsorption column to form a plasma discharge within the GAC, thereby regenerating the GAC within the adsorption column, and venting waste gas produced by the plasma discharge.

[76] Example 21 includes the subject matter of Example 20, wherein the first electrode is a high voltage electrode, the second electrode is a ground electrode, and a high voltage power supply is electrically connected to the first electrode.

[77] Example 22 includes the subject matter of Example 20, wherein the first electrode is a ground electrode, the second electrode is a high voltage electrode, and a high voltage power supply is electrically connected to the second electrode.

[78] Example 23 includes the subject matter of any of Examples 20-22, further including adjusting output power of the high voltage power supply based on a thermostatic feedback signal from a temperature sensor that measures temperature of the GAC.

[79] Example 24 includes the subject matter of any of Examples 20-23, wherein the electrical voltage is generated for a regeneration time that is less than 30 min, such as less than 10 min, or less than 1 min.

[80] The disclosures of each and every patent, patent application, and publication cited herein are hereby incorporated herein by reference in their entirety. While this invention has been disclosed with reference to specific embodiments, it is apparent that other embodiments and variations of this invention may be devised by others skilled in the art without departing from the true spirit and scope of the invention.

Appendix B: Calculations and ASPEN Models

The following section includes the following items, in the order given:

- Calculation of the Number of GAC Changeouts Required per Year
- EPA Work-Breakdown Structure Based Model used for GAC Capital Costing
- Equations used for NF process design
- Calculation of the mass of salt precipitating from NF process
- Equipment Costing Spreadsheet
- ASPEN Plus Report for IX Alternatives Analysis
- ASPEN Plus Report for HX-1 Design

Calculation of the Number of GAC Changeouts Required per Year

Given the product specifications for the Filtrasorb-400, an estimate for the pounds of

carbon consumed per million gallons of water treated can be calculated as follows:

$$30 \ \frac{lbs}{ft^3} C \ \times \ \frac{1 ft^3}{7.481 \ gal} = \ 4 \ \frac{lbs}{gal} C$$

For 1,600 gpm well flowing through 40,000 lbs in one vessel:

40,000 lbs
$$C \times \frac{gal}{4 \, lbs \, C} = 10,000 \, gallons = Volume \, of \, one \, Bed \, Volume$$

 $\frac{10,000 \text{ gallons}}{1 \text{ BV}} \times 4090 \text{ BV} \times \frac{1 \text{ MG}}{1,000,000 \text{ gallons}} \approx 41 \text{ MG} \text{ treated until detection in lead vessel}$

$$\frac{40,000 \ lbs \ C}{41 \ MG \ water} = 976 \ \frac{lbs \ carbon \ consumed}{MG \ water}$$

For 2.33 MGD,

976
$$\frac{lbs \ carbon \ consumed}{MG \ water}$$
 × 2.33 $\frac{million \ gallons}{day}$ = 2270 lbs. carbon consumed daily

For this amount of carbon consumed daily, the number of days until breakthrough was calculated as follows:

80,000 lbs. carbon
$$\div$$
 2270 lbs. consumed daily = 35 days until breakthrough

At this rate, there would be about 10 changeouts required each year.

EPA Work-Breakdown Structure Based Model used for GAC Capital costing

The EPA developed a Work-Breakdown Structure-Based Model in accordance with the Safe Water Drinking Act Amendments of 1996 for the purpose of developing cost estimates for the GAC process (EPA, 2017). Due to factors and equipment not shown in the process flow diagram, cost estimates used were included in the appendices with all inputs and outputs included. This spreadsheet was used to calculate the total capital costs associated with all GAC equipment, excluding the GAC adsorption vessels, whose costs were calculated based on values provided by Calgon Carbon Corporation. O&M costs were calculated independently based on the energy requirements for this project scope. The process inputs and outputs are shown below, and the model is cited in section 21.

Inputs:

GRANULAR ACTIVATED CARBON (GAC) SYSTEM DESIGN AND COST INPUT

Select Contaminant	Other	 To estimate costs for other contamina
<u>STEP 2</u> Select Design Type	Pressure	•
STEP 3		
Select one of the eight standard designs at right		
OR		
Select "CLEAR FOR MANUAL ENTRY"		
STEP 4 (Ontional for standard designs)		Using a manual design
(optional for standard doorg/lo)		

Enter or change values in the $\operatorname{{\sf goid}}$ and $\operatorname{{\sf blue}}$ cells below, under "Manual Inputs"

Input Complete -- Results Ready

STEP 5

Results are ready (no need to click button)

MANUAL INPUTS Cells in gold are required; cells in blue are optional

		Select units
Design Flow (including bypass)	2.330	MGD
Average Flow (including bypass)	2.330	MGD
For information:		
Treatment system design flow	#NAME?	MGD
Bypass design flow	0.000	MGD
		System size inputs OK

Select carbon life input type	carbon life value- bed volumes	< pick one
Carbon life	7,567	bed volumes
no additonal input required		not required
no additonal input required		not required
no additonal input required		not required
For information: Carbon Life	2.3	months
		Carbon input OK

Contaminant removal input type	EBCT	< pick one
Total Theoretical Empty Bed Contact Time (EBCT)	12.7	minutes
no additonal input required		not required
no additonal input required		not required
Minimum number of contactors in series (i.e., parallel or series operation)	2	< enter 1 for parallel, 2 or more for series

Vessel geometry	upright	< pick one
Height (straight)	26.917	feet
Diameter	15.374	feet
For information: Number of treatment trains	1	trains
Number of operating vessels	2	units
Total vessels (incl. redundancy, below)	3	units
		Bed Depth OK
		Diameter OK
		Volume OK
		Loading OK

itoSizing.

Interval Between backwashes	170	hours
Discharge option for spent backwash	septic system	< pick one
Holding tank for spent backwash		not required
Management option for spent carbon	regeneration off-site (hazardous)	< pick one
GAC transfer method	eductors	< pick one
Characteristics of holding tank solids		not required
		Residuals Input OK

Number of booster pumps	1	pumps
For information: # of booster pumps	1	pumps
Number of redundant contactors to be added		units
For information: Redundant contactors	1	units
Backwash pumping		< pick or leave blank
Backwash storage		< pick or leave blank
For information: # of backwash pumps	2	units
# of backwash tanks	1	units
Component level		< pick or leave blank
System automation		< pick or leave blank
For information: Component level	low cost	
Automation	manual	
Add-on (pre- or post-treatment)		< pick or leave blank
		Optional Inputs OK

Retrofit (operational modification)	< pick or leave blank
Select new carbon life input type	not required
New carbon life	not required
no additonal input required	not required
no additonal input required	not required
no additonal input required	not required
For information:	
Retrofit Carbon Life	months
	Retrofit input OK
Outputs:

OUTPU	TSUMMARY									
	Parameter	Value Units		_						
	Contaminant	Other		Record	Output in a New Workbook					
	System Size Category	large								
	Technology	GAC								
	Design Type	Pressure								
	Design Flow	2.33 MGD (excludes	s bypass flow)							
	Average Flow	2.33 MGD (excludes	s bypass flow)		Generate Results					
	# of treatment trains	1 trains								
	# of contactors in series	2 (i.e. parallel c	or series operation)							
	# of contactors	3 (including red	fundancy)							
	Total EBCT	12.7 minutes	and ano yy							
	EBCT per contactor	6 25 minutos								
	Ded death	15 275 feet								
	Bed deput	15.375 leet								
	vessei geometry	upright								
	Height (straight)	26.917 feet								
	Diameter	15.374 feet								
1	Resulting Costs (in year 2013 dollars)									
	Direct Capital Cost	\$ 335,093 <u>Details</u>								
	Add-on Cost	\$ 2,355 Details								
	Indirect Capital Cost	\$ 1,350,193 Details								
	Total Capital Cost	\$ 1,687,641 Details								
	Annual O&M Cost	\$ 38,370 Details								
	Annualized Cost (24.9 years at 7%)	\$ 183,410 Details								
	Annualized cost per 1 000 gallons average flow	\$ 0.22								
	Annualized cost ner household ner vear	\$ 31								
	randalized cool per nedecificit per year	• •								
Direct (Capital Cost Dotallo (dama in dalian without a 4 in the Star 25 actions and	report ellemete seate and are such-	ded from total)							
Direct	apital Cost Details (items in lancs, winout a 1 in the Ose? column, rep	resent alternate costs and are exclut	ded from total)							
WBS#	Item	Design Quanitity	Design Size		Size used in estimat	te	Unit Cost	Total Cost	Useful Life	Use?
	GAC Contactors									
10										
1.1	Pressure Vessels									
1.1	Pressure Vessels Stainless Steel	3 units	37,376	gal	37,376	gal	contact vendor		0	0
1.1 1.1.1 1.1.1	Pressure Vessels Stainless Steel Carbon Steel - Stainless Internals	3 units 3 units	37,376 37,376	gal gal	37,376 37,376	gal gal	contact vendor contact vendor		0 35	0
1.1 1.1.1 1.1.1 1.1.1 1.1.1	Pressure Vessels Stainless Steel Carbon Steel - Stainless Internals Carbon Steel - Plastic Internals	3 units 3 units 3 units	37,376 37,376 37,376 37,376	gal gal gal	37,376 37,376 37,376	gal gal gal	contact vendor contact vendor contact vendor		0 35 35	0 0 0
1.1 1.1.1 1.1.1 1.1.1 1.1.1 1.1.1	Pressure Vessels Stainless Steef Carbon Steef - Stainless Internals Carbon Steef - Plastic Internals Fiberglass	3 units 3 units 3 units 3 units	37,376 37,376 37,376 37,376 37,376	gal gal gal gal	37,376 37,376 37,376 37,376 37,376	gal gal gal gal	contact vendor contact vendor contact vendor contact vendor		0 35 35 25	0 0 0 0
1.1 1.1.1 1.1.1 1.1.1 1.1.1 1.2	Pressure Vessels Stanless Site Carbon Sieel - Stainless Internals Carbon Sieel - Pastic Internals Fabergass GAC Contact Basins	3 units 3 units 3 units 3 units	37,376 37,376 37,376 37,376 37,376	gal gal gal gal	37,376 37,376 37,376 37,376	gal gal gal gal	contact vendor contact vendor contact vendor contact vendor		0 35 35 25	0 0 0 0
1.1 1.1.1 1.1.1 1.1.1 1.1.1 1.2 1.2.1	Presure Versels Stainless Steel Carbon Steel - Stainless Internals Carbon Steel - Plastic Internals Fiberglass GAC Contact Basins Concrete	3 units 3 units 3 units 3 units 0 units	37,376 37,376 37,376 37,376 37,376	gal gal gal gal	37,376 37,376 37,376 37,376 37,376	gal gal gal gal	contact vendor contact vendor contact vendor contact vendor NA		0 35 35 25 NA	0 0 0 0
1.1 1.1.1 1.1.1 1.1.1 1.1.1 1.2 1.2.1 1.2.2	Pressure Versels Stainless Site Carbon Steel - Stainless Internals Carbon Steel - Patatic Internals Carbon Steel - Patatic Internals Faberglass GAC Contact Basins Concrete Unternals (Internativn) Liternats (Internativn)	3 units 3 units 3 units 3 units 0 units 0 units	37,376 37,376 37,376 37,376 37,376 NA NA	gal gal gal gal	37,376 37,376 37,376 37,376 37,376 NA NA	gal gal gal gal	contact vendor contact vendor contact vendor contact vendor NA		0 35 35 25 NA	0 0 0 0
1.1 1.1.1 1.1.1 1.1.1 1.1.1 1.2 1.2.1 1.2.2 1.2.3	Pressure Versels Stainless Steel Carbon Steel - Stainless Internals Carbon Steel - Plastic Internals Fiberglass GAC Contact Basins GAC Contact Basins Concrete Internals (Underdrain/Backwash System) Atuminum Bainn	3 units 3 units 3 units 3 units 0 units 0 units 0 units	37,376 37,376 37,376 37,376 NA NA NA	gal gal gal gal	37, 376 37, 376 37, 376 37, 376 37, 376 NA NA NA	gal gal gal gal	contact vendor contact vendor contact vendor contact vendor NA NA		0 35 35 25 NA NA	0 0 0 0 0
1.1 1.1.1 1.1.1 1.1.1 1.1.1 1.2 1.2.1 1.2.2 1.2.3 1.2.4	Pressure Versels Stainless Sites Carbon Steel - Stainless Internals Carbon Steel - Plastic Internals Carbon Steel - Plastic Internals Faberglass GAD Contact Basins Concrete Internals (Underdrain/Backwash System) Aluminum Railing Aluminum Railing	3 units 3 units 3 units 3 units 0 units 0 units 0 units 0 lif 0 care	37,376 37,376 37,376 37,376 37,376 NA NA NA	gal gal gal gal	37,376 37,376 37,376 37,376 37,376 NA NA NA	gal gal gal gal	contact vendor contact vendor contact vendor contact vendor NA NA NA		0 35 25 NA NA NA	0 0 0 0 0 0 0 0
1.1 1.1.1 1.1.1 1.1.1 1.1.1 1.2.1 1.2.2 1.2.3 1.2.4 1.2.5	Pressure Vessels Stanless Steel - Stanless Internals Carbon Steel - Natic Internals Carbon Steel - Natic Internals Fiberglass GAC Contact Basins Concrete Internals (Underdrain/Backwash System) Aluminum Railing Aluminum Railing	3 units 3 units 3 units 3 units 0 units 0 units 0 units 0 units 0 units	37, 376 37, 376 37, 376 37, 376 NA NA NA NA NA	gal gal gal gal	37,376 37,376 37,376 37,376 NA NA NA NA NA	gal gal gal gal	contact vendor contact vendor contact vendor contact vendor NA NA NA		0 35 25 NA NA NA NA	0 0 0 0 0 0 0 0 0
1.1 1.1.1 1.1.1 1.1.1 1.1.1 1.2.1 1.2.2 1.2.3 1.2.4 1.2.5	Pressure Versels Stainless Silver Carbon Steel - Stainless Internals Carbon Steel - Plastic Internals Carbon Steel - Plastic Internals Cancert BAC Contact Basins Cancert Internals (Underchan/Backwash System) Adminium Railing Adminium Stairs Ercovation Ercovation Ercovation Encovation E	3 units 3 units 3 units 3 units 0 units 0 units 0 if 0 fr 0 frsers - CY	37,376 37,376 37,376 37,376 NA NA NA NA NA	gal gal gal gal	37,376 37,376 37,376 37,376 37,376 NA NA NA NA	gal gal gal gal	contact vendor contact vendor contact vendor contact vendor NA NA NA		0 35 25 NA NA NA NA	0 0 0 0 0 0 0 0 0
1.1 1.1.1 1.1.1 1.1.1 1.2 1.2.1 1.2.2 1.2.3 1.2.4 1.2.5 1.2.6	Pressure Vessels Stanless Steel Carbon Steel - Stanless Internals Carbon Steel - Static Internals Charbon Steel - Static Internals Charbon Steel - Static Internals Concrete Internals (Inderdrain/Backwash System) Alumnium Rating Alumnium Rating Excavation Backtill and Compaction	3 units 3 units 3 units 3 units 0 units 0 units 0 ff 0 risers - cy - cy	37,376 37,376 37,376 37,376 NA NA NA NA NA NA	gal gal gal gal	37,376 37,376 37,378 37,378 NA NA NA NA NA NA	gal gal gal gal	contact vendor contact vendor contact vendor contact vendor NA NA NA NA NA		0 35 35 25 NA NA NA NA	0 0 0 0 0 0 0 0 0 0 0 0
1.1 1.1.1 1.1.1 1.1.1 1.1.1 1.2.1 1.2.1 1.2.2 1.2.3 1.2.4 1.2.5 1.2.6 2	Pressure Versels Stainless Silver Carbon Steel - Stainless Internals Carbon Steel - Plastic Internals Fiberplass BAC Contact Basins Concret Internals (Underdrain/Backwash System) Aluminum Stains Aluminum Stains Excavation Backfill and Compaction Tants	3 units 3 units 3 units 3 units 0 units 0 units 0 if 0 risers - cy - cy	37,376 37,376 37,376 37,376 37,376 NA NA NA NA NA	gal gal gal gal	37,376 37,376 37,376 37,376 37,376 MA MA MA MA MA MA	gal gal gal gal	contact vendor contact vendor contact vendor contact vendor NA NA NA NA NA NA	** ** ** ** ** ** **	0 35 25 NA NA NA NA NA	0 0 0 0 0 0 0 0 0 0 0
1.1 1.1.1 1.1.1 1.1.1 1.2.1 1.2.1 1.2.2 1.2.3 1.2.4 1.2.5 1.2.6 2. 2.1	Pressure Verseds Stanless Steel Carbon Steel - Stanless Internals Carbon Steel - Pastic Internals Carbon Steel - Pastic Internals Cancortet Internals (Inderdrain/Backwash System) Alurnium Railing Alurnium Railing Exceivation Backtill and Compacton Tanks Residuali Holding Tanks/Basins	3 units 3 units 3 units 3 units 0 units 0 units 0 tf 0 orisers - cy - cy	37,376 37,376 37,378 37,378 37,376 37	gal gal gal gal	37,376 37,376 37,378 37,378 NA NA NA NA NA NA	gal gal gal gal	contact vendor contact vendor contact vendor NA NA NA NA NA		0 35 25 NA NA NA NA	0 0 0 0 0 0 0 0 0 0
1.1 1.1.1 1.1.1 1.1.1 1.2.1 1.2.2 1.2.3 1.2.4 1.2.5 1.2.6 2.2 2.1 2.1	Pressure Versels Stainless Steel Carbon Skeel - Stainless Internals Carbon Skeel - Plastic Internals BMC Contract Basins Concrete Internals (Inderdrain/Backwash System) Aluminum Raling Aluminum Stars Excavation Backfill and Compaction Tans Residuals Holding Tanks/Basins Concrete Basins (Includes Excavation, Backfill, and Compaction)	3 units 3 units 3 units 3 units 0 units 0 if 0 risers - cy - cy 1 units	37,376 37	gal gal gal gal	37,376 37,376 37,376 37,376 NA NA NA NA NA NA NA NA NA NA NA	gal gal gal gal	contact vendor contact vendor contact vendor contact vendor NA NA NA NA NA S 60,856		0 35 35 25 NA NA NA NA NA	
1.1 1.1 1.1.1 1.1.1 1.2 1.2.1 1.2.2 1.2.3 1.2.4 1.2.5 1.2.6 2 2.1 2.1.1 2.1.1	Pressure Verseds Stanless Steel Carbon Steel - Stanless Internals Carbon Steel - Pastic Internals Carbon Steel - Pastic Internals Charbon Steel - Stanless Basic Concrete Internals (Undertrain/Backwash System) Aluminum Railing Aluminum Railing Aluminum Staris Excavation Backfill and Compaction Tants Residual Holding TanksiBasins Concrete Basins (includes Excavation, Backfill, and Compaction) Steel	3 units 3 units 3 units 3 units 0 units 0 units 0 if 0 orisers - cy - cy - cy 1 units 1 units	37,376 37,376 37,378 37,378 37,378 37,378 37,378 37,378 37,378 37,378 37,378 37,378 37,378 37,378 37,378 37,378 37,378 37,376 37	gal gal gal gal gal gal gal	37,376 37,3776 37,37776 37,3776 37,3776 37,3776 37,377	gal gal gal gal gal gal	contact vendor contact vendor contact vendor contact vendor NA NA NA NA S 60,856 \$ 27,574		0 35 25 NA NA NA NA NA NA 35	
1.1 1.1.1 1.1.1 1.1.1 1.2.1 1.2.2 1.2.3 1.2.4 1.2.2 1.2.5 2. 2.1 2.1.1 2.1.1 2.1.1	Pressure Vessels Stankes Steel - Stankes Internals Carbon Steel - Natic Internals Carbon Steel - Natic Internals Charbon Steel - Natic Internals Charbon Steel - Stankes (Internals Concrete Backetti And Compaction Backetti and Compaction Backetti and Compaction Tants Residuals Holding Tanks/Baens Concrete Basing (Includes Excavation, Backfill, and Compaction) Steel Fiberglass	3 units 3 units 3 units 3 units 0 units 0 if 0 risers - cy - cy 1 units 1 units	37,376 37	gal gal gal gal gal gal	37,376 37,376 37,376 37,376 NA NA NA NA NA NA NA NA NA NA NA NA NA	gal gal gal gal gal gal gal ga	contact vendor contact vendor contact vendor contact vendor NA NA NA NA S 60,856 \$ 27,574 \$ 25,516		0 35 35 25 NA NA NA NA NA 40 35 28	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
1.1 1.1.1 1.1.1 1.1.1 1.2.1 1.2.2 1.2.3 1.2.4 1.2.5 1.2.6 2.1 2.1.1 2.1.1 2.1.1	Pressure Verseds Stanless Site Carbon Site Carbon Site Pastic Internals Cancon Site Pastic Internals Cancorte Internals Cancorte Internals (Inderdran/Backwash System) Aluminum Railing Aluminum Railing Aluminum Site Excevation Backfill and Compaction Tants Residuals Holding Tanks/Basins Concrete Basins (includes Excavation, Backfill, and Compaction) Steel Fiberglass Fiberg	3 units 3 units 3 units 3 units 0 units 0 units 0 df 0 orisers - cy - cy 1 units 1 units 1 units 1 units	37,376 37,376 37,376 37,376 37,376 NA NA NA NA NA S2,403 22280 22280 22280 22280 22280 22280	gal gai gai gal gal gal gai gai	37,376 37,376 37,376 37,376 37,376 40,47740,477 40,47740,477 40,477 40,477 40,47740,477 40,477 40,477 40,4777 40,4777 40,4777 40,477740,4777 40,47777 40,477770	gal gai gai gal gal gai ga ga ga	contact vendor contact vendor contact vendor contact vendor NA NA NA NA S 60,856 \$ 27,574 \$ 25,576 \$ 25,574		0 35 35 25 NA NA NA NA NA NA 40 35 25	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
1.1 1.1 1.1.1 1.1.1 1.1.1 1.2.1 1.2.2 1.2.3 1.2.4 1.2.5 1.2.6 2.1 2.1.1 2.2 2.1 2.1	Pressure Vessels Stanlves Steel - Carbon Steel - Stanlves Internals Carbon Steel - Patatic Internals Carbon Steel - Phatic Internals Charbon Steel - Static Internals Concrete Internals (Inderdrain/Backwash System) Aluminum Railing Aluminum Railing Aluminum Stars Excavation Backell and Compaction Backell and Compaction Backell And Compaction Concrete Bains (includes Excavation, Backfill, and Compaction) Steel PlastorHOPE Backwash Tanke/Basins	3 units 3 units 3 units 0 units 0 units 0 if 0 forers - cy - cy - cy 1 units 1 units 1 units 1 units	37,376 37,376 37,376 37,376 MA NA NA NA NA NA NA NA NA NA 22260 22280 22280 22280	gal gal gal gal gal gal gal gal	27,376 37,376 37,376 37,376 37,376 37,376 NA NA NA NA NA NA NA NA NA NA NA NA NA	gal gal gal gal gal gal ga ga ga	contact vendor contact vendor contact vendor contact vendor NA NA NA NA S 60,856 \$ 27,574 \$ 25,516 contact vendor		0 35 35 25 NA NA NA NA NA A 40 35 25	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
1.1 1.1 1.1.1 1.1.1 1.1.1 1.2.1 1.2.2 1.2.3 1.2.4 1.2.5 1.2.6 2. 2.1 2.1.1 2.1.1 2.1.1 2.1.1 2.2.1 2.2.1	Pressure Versexis Stanless Site Carbon Steel - Stanless Internals Carbon Steel - Patatic Internals Carbon Steel - Patatic Internals Carbon Steel - Patatic Internals Cancrete Internals (Inderdran/Backwash System) Aluminum Railing Aluminum Railing Aluminum Staris Excavation Backfill and Compacton Tants Residuals Holding Tanks/Bacins Concrete Basis (Includes Excavation, Backfill, and Compaction) Steel Fiberglass Fiberglass Fiberglass Fiberglass Fiberglass Fiberglass Concrete Basis (Includes Excavation, Backfill, and Compaction) Steel Fiberglass Concrete Basis (Includes Excavation, Backfill, and Compaction) Steel Concrete Basis (Includes Excavation, Backfill, and Compaction) Steel Concrete Basis (Includes Excavation, Backfill, and Compaction)	3 units 3 units 3 units 3 units 0 units 0 units 0 units 0 ff 0 ff 0 ff 0 ff 0 ff 0 ff 0 ff 0 units 1 units 1 units 1 units 1 units 0 units 0 units 0 ff 0 ff	37,376 37	gal gal gal gal gal gal gal gal	37,376 37,376 37,376 37,376 4,37,376 4,44 4,44 4,44 32,403 22,280 20,280 22,280 20,280 20,280 20,280 20,280 20,280	gal gal gal gal gal gal ga gai gai	contact vendor contact vendor contact vendor contact vendor NA NA NA NA NA S 60,856 S 27,574 S 25,516 Contact vendor NA		0 35 35 25 NA NA NA NA NA 40 35 25 25	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
1.1 1.1 1.1.1 1.1.1 1.1.1 1.2.1 1.2.2 1.2.3 1.2.4 1.2.5 1.2.6 2. 1.2.6 2. 1.2.6 2. 1.2.6 2. 1.2.1 2.1.1 2.1.1 2.2.1 2.2.1 2.2.1	Pressure Vessels Stanless Steel Carbon Steel - Stanless Internals Carbon Steel - Patic Internals Carbon Steel - Patic Internals Carbon Steel - Patic Internals Cancortel Internals (Inderdrain/Backwash System) Alurnium Railing Alurnium Railing Alurnium Railing Exceivation Backfill and Compaction Tants Resultati Stoditing Tanks/Basins Concrete Basins (includes Excavation, Backfill, and Compaction) Statistication Carbon Basins (includes Excavation, Backfill, and Compaction) Steel Tanks	3 units 3 units 3 units 3 units 0 units 0 units 0 units 0 units 0 rfsers - cy - cy 1 units 1 units 1 units 1 units 1 units 0 units	37,376 37,376 37,376 37,376 MA MA MA MA MA MA MA MA MA MA MA MA MA	gal gal gal gal gal gal gal gal gal	37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,400 32,200 32,300 32,2000 32,2000 30,2000 30,2000 30,2000 30,2000 30,2000 30	gal gal gal gal gal gal ga ga ga	contact vendor contact vendor contact vendor contact vendor NA NA NA NA S 60,856 \$ 27,574 \$ 25,516 contact vendor NA NA		0 35 35 25 NA NA NA NA A 40 35 25 NA NA	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
1.1 1.1 1.1.1 1.1.1 1.1.1 1.2.1 1.2.2 1.2.3 1.2.4 1.2.5 1.2.6 2.1 2.1 2.1 2.1 2.1 2.1 2.1 2.1 2.1 2.1	Pressure Versexis Stainless Silver Carbon Steel - Stainless Internals Carbon Steel - Patatic Internals Carbon Steel - Patatic Internals Carbon Steel - Patatic Internals Concrete Internals (Inderdram/Backwash System) Atuminum Railing Atuminum Railing Atuminum Stains Excavation Backfill and Compaction Tanis Residuals Holdma Tanks/Basins Concrete Basins (Includes Excavation, Backfill, and Compaction) Steel Flaetglass PlastcyHOPE Backwash Tanks/Basins Concrete Rains (Includes Excavation, Backfill, and Compaction) Steel Tanks Flaetglass PlastcyHOPE	3 units 3 units 3 units 3 units 0 units 0 units 0 drafts 0 f 0 nsers - cy - cy - cy - cy - units 1 units 1 units 1 units 0 units 0 drafts 0 drafts 0 drafts 0 drafts 0 drafts 0 units 0 un	37,376 37	gal gal gal gal gal gal gal gal	37,376 37,376 37,376 37,376 44 44 44 44 44 44 44 44 44 44 44 44 44	gal gal gal gal gal gal ga ga ga	contact vendor contact vendor contact vendor contact vendor NA NA NA NA S \$ 60,856 \$ 27,574 \$ 25,514 \$ 25,514 \$ 25,514 \$ 25,514 \$ 25,514 \$ 25,514		0 35 35 25 25 NA NA A 40 35 25 25 NA NA	
11 1.1 1.1.1 1.1.1 1.1.1 1.1.1 1.2.1 1.2.2 1.2.4 1.2.5 2.1 2.1.1 2.1.1 2.1.1 2.1.1 2.2.1 2.1.1 2.1.1 2.1.1 2.2.5 1.2.6 2.1 2.1.1 2.2.1 2.1	Pressure Verseds Starliess Steel - Starliess Starlies Steel -	3 units 3 units 3 units 3 units 3 units 0 units 0 units 0 units - cy - cy - cy 1 units 1 units 1 units 1 units 1 units 1 units 0 units	37,376 37,376 37,376 37,376 NA NA NA NA NA 32,403 32,2280 22280 22280 22280 22280 22280 22280 22280 22280 22280 22280 22280 22280 22280 22280 2080 2080 209 209 200 209 200 200 200 200 200 20	gal gai gal gal gal gal gal gal	37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 32,280 32,376 32,276 32,3776 32,276 32,276 32,276 32,276 32,276 32,276 32,276 32,276 3	gal gal gal gal gal gal gal gal gal	contact vendor contact vendor contact vendor contact vendor NA NA NA NA S 60,856 S 27,574 S 25,516 contact vendor NA NA NA NA		0 35 35 25 NA NA NA NA NA 40 335 25 25 NA NA NA	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
1.1 1.1 1.1.1 1.1.1 1.1.1 1.2.1 1.2.2 1.2.2 1.2.4 1.2.5 1.2.6 2. 2. 1.2.6 2. 2.1.1 2.1.1 2.1.1 2.1.1 2.1.1 2.1.1 2.1.1 2.1.1 2.1.1 2.1.1 2.1.1 2.1.1 2.1.1 2.1.1 2.1.1 2.2.1 2.2.1 2.2.1 2.1.1 2.1.1 2.1.1 2.1.1 2.2.1 2.2.1 2.1.1 2.1.1 2.1.1 2.2.1 2.2.1 2.1.1 2.2.1 2.2.1 2.2.1 2.2.1 2.1.1 2.1.1 2.2.1 2.2.1 2.1.1 2.1.1 2.2.1 2.2.1 2.1.1 2.1.1 2.2.1 2.2.1 2.1.1 2.1.1 2.2.1 2.2.1 2.1.1 2.2.1 2.2.1 2.1.1 2.2.1 2	Pressure Vessels Stanless Steel Carbon Steel - Stanless Internals Carbon Steel - Natic Internals Carbon Steel - National - Nation	3 units 3 units 3 units 3 units 0 units 0 units 0 f 0 nisers - cy - cy - cy - cy - units 1 units 1 units 1 units 0 units 0 units 0 d 0 nisers - cy -	37,376 37	gal gal gal gal gal gal gal gal	37,376 37,376 37,376 37,376 44 44 44 44 44 44 44 44 44 44 44 44 44	gal gal gal gal gal gal gal gai gai	contact vendor contact vendor contact vendor NA NA NA NA NA S 60,056 S 27,574 \$ 25,516 contact vendor NA NA NA NA		0 35 25 NA NA NA NA 40 35 25 25 25 NA NA NA	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
11 1.1 1.1 1.1 1.1 1.1 1.1 1.1	Pressure Verseds Stanless Steel Carbon Steel - Stanless Internals Carbon Steel - Paratic Internals Cancerte Internals (Undertrain/Backwash System) Aluminum Railing Aluminum Railing Aluminum Railing Aluminum Staris Excavation Backtill and Compaction Tants Residuals Holding Tanks/Basins Concrete Basins (includes Excavation, Backfill, and Compaction) Steel Fibergiass Fibergiass Concrete Basins (includes Excavation, Backfill, and Compaction) Steel Backwash Tanks/Basins Concrete Basins (includes Excavation, Backfill, and Compaction) Steel Taris Fibergiass Fibergiass Fibergiass Fibergias Fibergia	3 units 3 units 3 units 3 units 0 units 0 units 0 lf 0 nisers - cy - cy 1 units 1 units 1 units 1 units 1 units 0 unit	37 376 37 3776 37 376 37 376 37 376 37 376 37 376 37 376 37 376 3	gal gai gai gal gal gal gai gai	37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 32,403 32,403 32,280 32,376 32,403 32,280 32,280 32,280 32,280 32,280 32,280 32,280 32,280 32,280 32,280 32,280 32,280 32,280 32,280 32,280 32,280 32,280 32,2780 32,2780 32,2780 32,2780 32,2780 32,2780 32,2780 32,2780 32,2780 32,2780 32,2780 32,2780 32,2780 34,3777 34,37777 34,3777777777777777777	gal gai gai gal gal gai ga ga ga	contact vendor contact vendor contact vendor contact vendor contact vendor NA NA NA NA NA NA S 60.856 S 25.7574 S 25.616 contact vendor NA NA NA NA NA NA		0 35 25 NA NA NA NA NA 40 35 25 25 NA NA NA NA	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.2 1.2	Pressure Vessels Stanless Steel Carbon Steel - Stanless Internals Carbon Steel - Patatic Internals Carbon Steel - Patatic Internals Charbon Steel - Patatic Internals Concrete Internals (Interdrain/Backwash System) Aluminum Raing Aluminum Raing Aluminum Raing Concrete Basing (Includes Excavation, Backfill, and Compaction) Steel Residuals Holding Tanks/Basins Concrete Basing (Includes Excavation, Backfill, and Compaction) Steel Plastich/HDPE Backwash Tanks/Basins Concrete Basing (Includes Excavation, Backfill, and Compaction) Steel Plastich/HDPE Backwash Tanks/Basins Concrete Basing (Includes Excavation, Backfill, and Compaction) Steel Tanks Plastich/HDPE Tanks Paymet Storage Tanks Paymet Storage Tanks	3 units 3 units 3 units 0 units 0 units 0 units 0 tf 0 offsers - cy - cy 1 units 1 units 1 units 1 units 0	37,376 37,376 37,376 37,376 MA NA NA NA NA 22260 22280 2280 2280 200 20	gal gai gai gai gai gai gai gai	27,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 22,280 22,376 22,376 22,376 22,376 22,376 22,376 22,377 37,376 37,377 37,376 37,377 37,376 37,377 37,376 37,377 37,376 37,377 37,376 37,377 37,377 37,377 37,377 37,377 37,377 37,377 37,377 37,377 37,377 37,377 37,377 37,377 37,377 37,377 37,376 37,377 37,377 37,377 37,376 37,377 37,377 37,377 37,377 37,377 37,376 37,377 37,377 37,376 37,377 37,376 37,377 37,376 37,376 37,376 37,376 37,377 37,376 37,377 37,376 37,377 37,377 37,377 37,377 37,377 37,377 37,377 37,377 37,377 37,377 37,377 37,377 37,377 37,377 37	gal gal gal gal gal gal ga ga ga ga	Contact vendor contact vendor contact vendor contact vendor MA MA MA MA MA S 60,856 S 22,541 S 22,541 Contact vendor MA MA MA	5 60,856 5 22,574 \$ 22,516 	0 35 35 25 25 NA NA NA 40 35 25 25 NA NA NA	
1.1 1.1 1.1 1.1 1.1 1.1 1.2 1.2	Pressure Verseds Starikes Steel Carbon Steel - Starikes Internals Carbon Steel - Paratic Internals Carbon Steel - Paratic Internals Carbon Steel - Paratic Internals Cancorete Internals (Inderdrain/Backwash System) Aluminum Railing Aluminum Railing Aluminum Railing Backfill and Compaction Tants Residuals Holding Tanks/Basins Concrete Basins (includes Excavation, Backfill, and Compaction) Steel Fibergiass Plastch/IDFE Backwash Tanks/Basins Concrete Basins (includes Excavation, Backfill, and Compaction) Steel Fibergiass Plastch/IDFE Backwash Tanks/Basins Concrete Basins (includes Excavation, Backfill, and Compaction) Steel Tanks Plastch/IDFE Backwash Tanks/Basins Plastch/IDFE	3 units 3 units 3 units 3 units 0 units 0 units 0 tf 0 ff reserved - cy - cy 1 units 1 units 1 units 1 units 1 units 1 units 0	37,376 37,376 37,376 87,376 84 84 84 84 84 82,403 84,40364,403 84,40384,403 84,403 84,403 84,403 84,403 84	gal gal gal gal gal gal gal	37,376 37,3776 37,376 37,3776 37,3776 37,3776 37,3776 37,377,3776 37,37,	gal gai gai gal gai gai gai gai	Contract vendor contract vendor contract vendor contract vendor NA NA NA NA S 60,856 \$ 27,574 \$ 25,516 contract vendor NA NA NA NA NA NA NA		0 35 35 26 NA NA NA NA 40 35 25 25 25 NA NA NA NA NA NA	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
1.1 1.1 1.1.1 1.1.1 1.1.1 1.1.1 1.2 1.2	Pressure Vessels Stanless Steel Carbon Steel - Stanless Internals Carbon Steel - Phastic Internals Carbon Steel - Phastic Internals Cancorste Internals Cancorste Internals Cancorste Internals Carbon Steel - Constant Stream - Constant Steel Carbon Steel - Carbon	3 units 3 units 3 units 0 units 0 units 0 units 0 units 0 of - cy - cy 1 units 1 units 1 units 1 units 0 u	37,376 37,376 37,376 37,376 MA MA MA MA MA 22280 22280 22280 22280 22280 22280 22280 22280 22280 MA MA MA MA MA MA MA MA MA MA	gal gai gai gai gai gai gai gai	37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 32,375 32,403 22,280 20,280 20,290 20	gal gai gai gai gai gai gai gai gai gai	Contact vendor contact vendor contact vendor contact vendor MA MA MA MA MA MA MA MA MA MA MA MA MA	5 60,856 5 27,574 5 26,856 	0 35 25 NA NA NA NA 40 355 25 25 NA NA NA NA NA NA	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
1.1 1.1 1.1.1 1.1.1 1.1.1 1.2.1 1.2.2 1.2.2 1.2.2 1.2.2 1.2.4 1.2.5 1.2.6 2. 2. 2.1.1 2.1.1 2.1.1 2.2.1 2.2.1 2.2.1 2.3.1	Pressure Verseds Starless Steel Garbon Steel - Starless Internals Carbon Steel - Pastic Internals Carbon Steel - Pastic Internals Cancorsteel Internals (Underdran/Backwash System) Aluminum Railing Aluminum Railing Aluminum Railing Aluminum Railing Excevation Backfill and Compaction Tants Residuals Holding Tanks/Basins Concrete Basins (includes Excavation, Backfill, and Compaction) Steel Fiberglass Plastich/IDFE Backwash Tanks/Basins Concrete Railing Concrete Concrete Railing Concrete Con	3 units 3 units 3 units 3 units 0 units 0 units 0 units 0 or sers - cy 1 units 1 units 1 units 1 units 1 units 1 units 0 units	37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 32,403 32,403 22280 2280 2280 2280 200 2280 200 20	gal gai gai gai gai gai gai gai	37,376 37	gal gal gal gal gal gal gal gal	Conflact Viendor conflact Viendor conflact Viendor conflact Viendor NA NA NA NA S 60,856 S 27,574 \$ 25,516 conflact Viendor NA NA NA NA NA		0 35 35 26 NA NA NA NA 35 25 25 25 NA NA NA NA NA	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
1.1 1.1 1.1.1 1.1.1 1.1.1 1.2.1 1.2.2 1.2.2 1.2.3 1.2.4 1.2.5 2.1 2.1.1 2.1.1 2.1.1 2.1.1 2.2.1 2.3.1 2.3.1 3.3.1 3.3.1	Pressure Verseds Stanless Steel Carbon Steel - Stanless Internals Carbon Steel - Patic Internals Carbon Steel - Patic Internals Cancorsteel Internals (Inderdran/Backwash System) Aluminum Raling Aluminum Raling Aluminum Raling Aluminum Raling Excession Exce	3 units 3 units 3 units 3 units 0 units 0 units 0 units 0 of - cy - cy 1 units 1 units 1 units 1 units 0 u	37,376 37,376 37,376 37,376 MA MA MA MA MA MA MA MA MA MA MA MA MA	gal gai gai gai gai gai gai gai	37,376 37,276 37	gal gal gal gal gal ga ga ga	Contract vendor contract vendor contract vendor contract vendor NA NA NA NA S 60,055 S 27,574 S 22,515 Contract vendor NA NA NA NA NA NA		0 35 35 25 NA NA NA NA 40 35 25 25 25 25 NA NA NA NA NA NA	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
1.1 1.1 1.1 1.1 1.1 1.2 1.2 1.2	Pressure Vessels Stanless Steel Carbon Steel - Stanless Internals Carbon Steel - Stanless Internals Carbon Steel - Stanless Internals Carbon Steel - Stanless Internals Concrete Internals (Inderdrain/Backwash System) Aluminum Raling Aluminum Raling Concrete Basing (includes Excavation, Backfill, and Compaction) Steel Plastich/DPE Backwash Tanks/Basins Concrete Basing (includes Excavation, Backfill, and Compaction) Steel Plasticas Tanks Concrete Basing (includes Excavation, Backfill, and Compaction) Steel Plasticas Tanks Plasticas Tanks Plasticas Tanks Steel Tanks Steel Tanks Steel Tanks Steel Tanks Plasticas Tanks Steel Steel Plasticas Plasticas Steel Plasticas Stanless Steel Plasticas Plasticas Plasticas Stanless Steel Plasticas Plast	3 units 3 units 3 units 3 units 0 units 0 units 0 units 0 units 0 rerrs - cy - cy 1 units 1 units 1 units 1 units 1 units 0 units	37,376 37,376 37,376 37,376 37,376 37,376 84 84 84 84 84 84 84 84 84 84 84 84 84	gal gai gai gai gai gai gai gai	37,376 37,376 37,376 37,376 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4	gal gal gal gal gal gal gai gai	contact vendor contact vendor contact vendor contact vendor NA NA NA NA S 60,856 S 27,574 S 25,516 contact vendor NA NA NA NA NA NA NA S 60,856 S 75,54	\$ 60.856 \$ 25.516 \$ 25.516 	0 35 35 26 NA NA NA NA 40 35 25 25 NA NA NA NA NA NA NA NA	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
1.1 1.1 1.1.1 1.1.1 1.1.1 1.2.2 1.2.2 1.2.4 1.2.2 2.1 2.2.1 2.1.1 2.1.1 2.1.1 2.1.1 2.1.1 2.2.1 2.3.1 3.3.1 3.1.1	Pressure Verseds Starliess Steel Carbon Steel - Starliess Internals Carbon Steel - Patic Internals Carbon Steel - Patic Internals Cancortel Internals (Inderdran/Backwash System) Alurnium Railing Alurnium Railing Alurnium Railing Excelvation Eachdil and Compaction Eachdil and Compaction Eachdil and Compaction Steel Fiberglass Fib	3 units 3 units 3 units 3 units 0 units 0 units 0 units 0 units - cy - cy 1 units 1 units 1 units 1 units 1 units 0 units	37,376 37,376 37,376 37,376 0,32,403 0,32,403 0,22280 0,40 0,40 0,40 0,40 0,40 0,40 0,40 0,	gal gai gai gai gai gai gai gai gai	37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 32,280 34,39 34,40,40 34,40,4034,40,40 34,40,40,40,40,40,40,40,40,40,40,40,40,40	gal gal gal gal gal ga ga ga ga ga ga ga ga ga ga ga	contact vendor contact vendor contact vendor contact vendor NA NA NA NA S 60,856 S 25,516 contact vendor A A A A A A A A A A A A A A A A A A A	\$ 00,055 \$ 22,514 \$ 25,516 	0 35 35 25 NA NA NA NA NA NA NA NA NA NA NA NA NA	
1.1 1.1,1 1.1,1 1.1,1 1.1,1 1.2,1 1.2,2 1.2,3 1.2,4 1.2,5 1.2,4 2.1,1 2.2,1 2.2,1 2.2,1 2.3,1 2.3,1 3.1,1 3.1,1 3.1,1	Pressure Vessels Stanless Steel Carbon Steel - Stanless Internals Carbon Steel - Phatic Internals Carbon Steel - Phatic Internals Concrete Internals Concrete Internals Concrete Internals Compaction Atumium Railing Atumium Railing Atumium Railing Concrete Internals Concrete Inter	3 units 3 units 3 units 0 units 0 units 0 units 0 off 0 off 0 off 0 off 0 off 0 off 1 units 1 units 1 units 1 units 0 unit	37,376 37,376 37,376 37,376 0,37,376 0,40 0,40 0,40 0,220 0,403 22200 22200 0,403 22200 22200 22200 22200 0,403 22200 22200 22200 22200 22200 0,403 0,403 22200 2020 2000 200 200 200 200 200 200 200 200 200 200 200 200 200 200 200 200	gal gai gai gal gal gal gal gal gal in. diam in. diam	27,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 37,376 22,280 20,280 20,290 20	gal gai gai gal gal gai gai gai gai gai gai gai gai in. diam in. diam	Contact vendor contact vendor contact vendor contact vendor NA NA NA NA NA NA NA NA NA NA NA NA NA		0 35 35 25 25 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	
1 1 1 1 1 1 1 1 1 1 1 1 1 1	Pressure Verseds Starliess Steel Carbon Steel - Starliess Internals Carbon Steel - Paratic Internals Carbon Steel - Paratic Internals Carbon Steel - Paratic Internals Cancerte Internals (Induetrian/Backwash System) Aluminum Railing Aluminum Railing Aluminum Railing Aluminum Railing Aluminum Steel Excavation Backfill and Compaction Tanks Residuali Holding Tanks/Bacins Concerte Basins (includes Excavation, Backfill, and Compaction) Steel Fiberglass Concrete Basins (includes Excavation, Backfill, and Compaction) Steel Fiberglass Concerte Basins (includes Excavation, Backfill, and Compaction) Steel Fiberglass Fiberglass Fiberglass Farks Pathoms Fiberglass	3 units 3 units 3 units 3 units 0 units 0 units 0 lf 0 freers - cy - cy 1 units 1 units 1 units 1 units 0	37,376 37	gal gai gai gai gal gal gal gal gal gai n. diam in. diam	37,376 37,276 37,276 37,276 37,376 37,276 37,276 37,376 37,376 37,276 37,276 37,377 37,376 37,377 37,376 37,377 37,376 37,3776 37,3777776 37,3776 37,37777777777	gal gal gal gal gal ga ga ga ga ga ga n ga n	Contract vendor contract vendor contract vendor contract vendor NA NA NA NA NA S 60,856 \$ 22,516 contract vendor NA NA NA S 25,516 Contract vendor S 25,516 S 212,199 \$ 212,99 \$ 214,49 \$ 212,91 \$ 214,49 \$ 215,410 \$ 215,410\$ \$ 215,410\$	\$ 60,855 \$ 22,574 \$ 22,574 \$ 22,575 \$ 2	0 35 35 25 NA NA NA NA 40 35 25 25 NA NA NA NA NA NA NA NA NA NA NA NA NA	

4.2	Manual								
4.2.1	Inlet and outlet - Polypropylene/PVC	2 units	10 in, diam	10 in diam	\$ 1,449	5	2.898	25	- 0
4.2.1	Inlet and outlet - Stainless Steel	2 units	10 in. diam	10 in. diam	\$ 5,842	2 \$	11,684	25	0
4.2.1	Inlet and outlet - Cast Iron	2 units	10 in. diam	10 in. diam	\$ 1.980	5 5	3.972	25	0
4.2.2	Process - Polypropylene/PVC	14 units	12 in diam	12 in diam	\$ 2.28	8 8	31,967	25	0
4.2.2	Process - Stainless Steel	14 units	12 in. diam	12 in. diam	\$ 7.63	2 \$	106.847	25	0
4.2.2	Process - Cast Iron	14 units	12 in diam	12 in diam	\$ 2.874	1 \$	40.232	25	6
4.2.3	Backwash - Polypropylene/PVC	9 units	10 in. diam	10 in. diam	\$ 1.44	S	13.042	25	0
423	Backwash - Stainless Steel	9 units	10 in diam	10 in diam	\$ 5.84	s	52 578	25	6
4.2.3	Backwash - Cast Iron	9 units	10 in. diam	10 in. diam	\$ 1.980	5 5	17.872	25	0
424	Residuals - Polypropylene/PVC	0 units	NA	NA	NA			NA	
4.2.4	Residuals - Stainless Steel	0 units	NA	NA	NA			NA	
424	Residuals - Cast Iron	0 units	NA	NA	NA			NA	
425	Polymer- Polypropylene/PVC	0 units	NA	NA	NA			NA	
425	Polymer- Stainless Steel	0 units	NA	NA	NA			NA	
425	Polymer- Cast Iron	0 units	NA	NA	NA			NA	
426	Bynass - Polynronylene/PVC	0 units	NA	NA	NA			NA	
426	Bypass - Stainless Steel	0 units	NA	NA	NA			NA	
426	Bypass - Cast Iron	0 units	NA	NA	NA		-	NA	
4.3	Cherk Valves								
431	Backwash - Polypropylene/PVC	2 units	10 in diam	10 in diam	\$ 3.660	5	7 320	25	-
431	Backwash - Stainless Steel	2 units	10 in diam	10 in diam	\$ 6.64	5	13 291	25	
431	Backwash - Cast Iron	2 units	10 in diam	10 in diam	\$ 3.61	s	7 224	25	
432	Residuals - Polynronylene/PVC	1 units	10 in diam	10 in diam	\$ 3.660	s	3 660	25	- 0
432	Residuals - Stainless Steel	1 units	10 in diam	10 in diam	\$ 6.64	i s	6 645	25	-
432	Residuals - Cast Iron	1 units	10 in diam	10 in diam	\$ 3.61	s	3 612	25	-
433	Polymer - Polypropylene/PVC	0 units	NA	NA	NA		-,	NA	
433	Polymer - Stainless Steel	0 units	NA	NA	NA			NA	
4.3.3	Polymer - Cast Iron	0 units	NA	NA	NA			NA	
434	Inlet - Polypropylene/PV/C	2 units	10 in diam	10 in diam	\$ 3.660	8	7 320	25	(
434	Inlet - Stainless Steel	1 units	10 in diam	10 in diam	\$ 6.64	5 5	6 645	25	- 0
434	Inlet - Cast Iron	1 units	10 in diam	10 in diam	\$ 3.61	5	3,612	25	- 0
435	Bypass - Polypropylene/PVC	0 units	NA	NA	NA		0,012	NA	
435	Bypadd - Hyphopytonen + d Bypadd - Stainless Steel	0 units	NA	NA	NA			NA	
435	Bypass - Cast Iron	0 units	NA	NA	NA			NA	
5.	Pumps								
5.1	Booster	1 units	2.023 gpm	2.023 gpm	\$ 27.294	\$	27.294	20	1
5.2	Backwash	2 units	2.785 gpm	2.785 gpm	\$ 34,468	I S	68,935	20	1
5.3	Residuals	0 units	NA	NA	NA			NA	
5.4	Polymer Metering								
5.4.1	PVC - Motor Driven	0 units	NA	NA	NA			NA	
5.4.1	Stainless Steel - Motor Driven	0 units	NA	NA	NA			NA	
5.4.1	PVC - Electric	0 units	NA	NA	NA			NA	
5.4.1	Stainless Steel - Electric	0 units	NA	NA	NA			NA	
6.	Instrumentation								
6.1	Flow Meters - Inlet and Outlet								
6.1.1	Orifice Plate	1 units	10 in. diam	10 in. diam	\$ 5,492	2 \$	5,492	15	0
6.1.1	Propeller	1 units	10 in. diam	10 in. diam	\$ 4,290	\$	4,290	15	1
6.1.1	Venturi	1 units	10 in. diam	10 in. diam	\$ 14,097	\$	14,097	15	0
6.1.1	Magnetic	1 units	10 in. diam	10 in. diam	\$ 12,258	8 \$	12,258	15	0
6.2	Flow Meters - Process								
6.2.1	Orifice Plate	0 units	NA	NA	NA			NA	
6.2.1	Propeller	0 units	NA	NA	NA			NA	
6.2.1	Venturi	0 units	NA	NA	NA			NA	
6.2.1	Magnetic	0 units	NA	NA	NA			NA	_
6.3	Flow Meters - Backwash								
6.3.1	Orifice Plate	1 units	10 in. diam	10 in. diam	\$ 5,492	? \$	5,492	15	0
6.3.1	Propeller	1 units	10 in. diam	10 in. diam	\$ 4,290	\$	4,290	15	1
6.3.1	Venturi	1 units	10 in. diam	10 in. diam	\$ 14,097	\$	14,097	15	0
621	Magnotio	1 unite	10 in diam	10 in diam	C 12.261	2 C	12 268	16	(

6.4	Flow Meters - Residuals							
6.4.1	Orifice Plate	1 units	10 in. diam	10 in. diam	\$ 5,492	\$ 5,492	15	0
6.4.1	Propeller	1 units	10 in. diam	10 in. diam	\$ 4,290	\$ 4,290	15	1
6.4.1	Venturi	1 units	10 in. diam	10 in. diam	\$ 14,097	\$ 14,097	15	0
6.4.1	Magnetic	1 units	10 in. diam	10 in. diam	\$ 12,258	\$ 12,258	15	0
6.5	Level Switches/Alarms (for vessels)	0 units	NA	NA	NA		NA	
6.6	High/Low Alarms (for backwash tanks)	1 units	NA	NA	\$ 644	\$ 644	15	1
6.7	High/Low Alarm (for holding tanks)	0 units	NA	NA	NA		NA	
6.8	pH Meters	2 units	NA	NA	\$ 2,185	\$ 4,371	15	1
6.9	Temperature meters	2 units	NA	NA	\$ 523	\$ 1,045	15	1
6.10	Turbidity meters	3 units	NA	NA	\$ 4,929	\$ 14,787	15	1
6.11	Head loss sensors	3 units	NA	NA	\$ 2,699	\$ 8,098	15	1
6.12	Sampling Ports							
6.12.1	Stainless Steel	6 units	NA	NA	\$ 50	\$ 300	35	0
6.12.1	Carbon Steel	6 units	NA	NA	\$ 50	\$ 300	25	0
6.13	Electrical enclosure	0 units	NA	NA	NA		NA	
7.	System Controls							
7.1	PLC Units							
7.1.1	PLC racks/power supplies	0 units	NA	NA	NA		NA	
7.1.2	CPUs	0 units	NA	NA	NA		NA	
7.1.3	I/O discrete input modules	0 units	NA	NA	NA		NA	
7.1.4	I/O discrete output modules	0 units	NA	NA	NA		NA	
7.1.5	I/O combination analog modules	0 units	NA	NA	NA		NA	
7.1.6	Ethernet modules	0 units	NA	NA	NA		NA	
7.1.7	Base expansion modules	0 units	NA	NA	NA		NA	
7.1.8	Base expansion controller modules	0 units	NA	NA	NA		NA	
7.1.9	UPSs	0 units	NA	NA	NA		NA	
7.2	Operator Equipment							
7.2.1	Drive controllers	0 units	NA	NA	NA		NA	
7.2.2	Operator interface units	0 units	NA	NA	NA		NA	
7.2.3	PC Workstations	0 units	NA	NA	NA		NA	
7.2.4	Printers - laser jet	0 units	NA	NA	NA		NA	
7.2.5	Printers - dot matrix	0 units	NA	NA	NA		NA	
7.3	Controls Software							
7.3.1	Operator interface software	0 units	NA	NA	NA		NA	
7.3.2	PLC programming software	0 units	NA	NA	NA		NA	
7.3.3	PLC data collection software	0 units	NA	NA	NA		NA	
7.3.4	Plant intelligence software	0 units	NA	NA	NA		NA	
8.	Chemical Feed and Transfer							
8.1	Solids Transfer							
8.1.1	Eductors for GAC Transfer	3 units	6 in. diam	6 in. diam	\$ 14,017	\$ 42,051	45	1
8.1.2	Manual holding tank solids transfer, no equipment needed	0 units	NA	NA	NA		NA	
8.2	Dry Feeders for Residuals Coagulant							
8.2.1	Volumetric Feeder	0 units	NA	NA	NA		NA	
8.2.1	Gravimetric Feeder	0 units	NA	NA	NA		NA	
8.3	Residuals Mixers							
8.3.1	Portable	1 units	0 hp	1.0 hp	\$ 1,978	\$ 1,978	25	1
8.3.1	Mounted	0 units	NA	NA	NA		NA	
8.3.1	Impeller	0 units	NA	NA	NA		NA	

0.4	Polymer Storage Tank Mixers	0		N/4	1/2	A14		NA
0.4.1	Ponable	0	units	N/A N/A	N/A	NA NA	-	IVA NA
0.4.1	Impoller	0	unito	NA NA	N/A	NA NA		NA
0.4.7	Media and Chemicals	0	unita	MA	1VA	MA.		IVA
0.1	Initial GAC Charme	256 875	lbs	NA	NA	\$ 2.32	\$ 506.028	N/A 0
0.1	Forrio Chlorida	230,073	lbe	NA	N/A	3 2.32 NA	3 330,320	N/A U
0.2	Polymers		lbe	NA	NA	NA		N/A
10	On-site GAC Regeneration		103	100	110	110		100
10.1	Multiple Hearth Furnace System		units	NA	NA	\$	\$	NΔ
10.2	Additional Europee Canacity (Retrofit)		unite	NA	NA NA	NA NA	J	NA
10.2	Viroin GAC Storage	-	unito	114	114	104		100
10.3.1	Concrete Basins (includes Excavation, Backfill, and Compaction)		units	NA	NA	\$.	s .	NA
10 3 1	Steel Tanks	-	units	NA	NA	\$	\$.	NA
10.4	Spent GAC Storage							
10.4.1	Concrete Basins (includes Excavation, Backfill, and Compaction)		units	NA	NA	s -	s -	NA 0
10.4.1	Steel Tanks		units	NA	NA	s -	s -	NA
10.5	Regenerated GAC Storage		unito			Ű.	÷	101
10.5.1	Concrete Basins (includes Excavation, Backfill, and Compaction)		units	NA	NA	s -	s -	NA
10.5.1	Steel Tanks		units	NA	NA	s -	S -	NA
11.	Septic System						-	
11.1	Septic Tanks	1	units	33.420 gai	33.420 gai	\$ 56,220	\$ 56.220	40 1
11.2	Excavation for Septic Tanks	221	CV	NA	NA	\$ 12.70	\$ 2,803	40 0
11.3	Distribution Boxes	8	units	NA	NA	\$ 146	\$ 1 168	40 0
11.4	Distribution Pine (Perforated PVC)	5 570	lf	4 in diam	4 in diam	\$ 12.55	\$ 69.904	45 0
11.5	Drain Field Trench Excavation	3 301	CV.	NA	NA	\$ 5.50	\$ 18 154	45 0
116	Drain Eield Gravel	1 925	CV	NA	NA	\$ 35.00	\$ 67,390	45 0
12.	Solids drving pad	1,020	.,	101			0.,000	10
12.1	Solids drving pad	0) units	NA	NA	NA		NA
12	Evaporation Pond							
13.1	Excavation		cells	NA	NA	NA		NA
13.2	Backfill	-	cells	NA	NA	NA		NA
13.3	Liner		cells	NA	NA	NA		NA
13.4	Dike Construction	-	cells	NA	NA	NA		NA
14	Building Structures and HVAC							
14.1	Building 1							
14.1.1	Small Low Cost Shed	-	units	3.180 sf	3.180 sf	NA		N/A
14.1.1	Low Quality	1	units	3,180 sf	3,180 sf	\$ 64.91	\$ 206,416	40 0
14.1.1	Medium Quality	1	units	3.180 sf	3.180 sf	\$ 78.83	\$ 250.678	40 0
14.1.1	High Quality	1	units	3,180 sf	3.180 sf	\$ 105.14	\$ 334,347	40 0
14.1.2	Heating System							
14.1.2.1	Electric resistance	NA		NA	NA	NA		NA 0
14.1.2.1	Natural gas non-condensing furnace	NA		NA	NA	NA		NA 0
14.1.2.1	Natural gas condensing furnace	NA		NA	NA	NA		NA 0
14.1.2.1	Standard efficiency oil furnace	NA		NA	NA	NA		NA 0
14121	Mid-efficiency oil fumace	NA			A14	A14		N/A 0
Total of c	irect line items above:	T		NA	N/A	NA		NA U
Total of c	irect line items above: Direct cost category Process costs Building costs	Tota \$ 303,421 \$ 31,672	I Guidanc Excludes See indire	e alternate cost line items in italics, without a ct assumptions sheet to exclude buildings	NA a 1 in the "Use?" column. Includes installation	, transportation, ar		104
Total of c	irect line items above; Direct cost category Process costs Building costs Total direct costs	Tota \$ 303,421 \$ 31,672 \$ 335,093	I Guidanc Excludes See indire Total of p	e alternate cost line items in italics, without ect assumptions sheet to exclude buildings rocess and building costs	794 a 1 in the "Use?" column. Includes installation	, transportation, ar	 nd O&P	194
Total of c	irect line items above: Direct cost category Process costs Building costs Total direct costs	Tota \$ 303,421 \$ 31,672 \$ 335,093	I Guidanc Excludes See indire Total of p	NA e alternate cost line items in italics, without a saternate cost line items in italics, without a start of the solution of the solutio	IVA a 1 in the "Use?" column. Includes installation	, transportation, ar	nd O&P	
Total of c	irect line items above; Direct cost category Process costs Building costs Total direct costs Cost Detailis (See indirect assumptions sheet to exclude individual add-on iten	Tota \$ 303,421 \$ 31,672 \$ 335,093	I Guidanc Excludes See indire Total of p	NA alternate cost line items in italics, without a alternate cost line items in italics, without a rocess and building costs	rva a 1 in the "Use?" column. Includes installation	, transportation, ar	nd O&P	
Total of c	irect line items above: Direct cost category Process costs Building costs Total direct costs Cost Details (See indirect assumptions sheet to exclude individual add-on iter Add-on Line Item	Tota \$ 303,421 \$ 31,672 \$ 335,093 ms) Tota	I Guidanc Excludes See indire Total of p	NA aternate cost line items in italics, without a aternate cost line items in italics, without a sect assumptions sheet to exclude buildings rocess and building costs	rva a 1 in the "Use?" column. Includes installation	, transportation, ar	nd O&P	
Total of c	Irect line items above; Direct cost category Process costs Building costs Total direct costs Cost Details (See indirect assumptions sheet to exclude individual add-on iten Add-on Line Item Permits	Tota \$ 303,421 \$ 31,672 \$ 335,093 ms) Tota \$ 2,355	I Guidanc Excludes See indiru Total of p	NA alternate cost line items in italics, without a alternate cost line items in italics, without a rocess and building costs	rva a 1 in the "Use?" column. Includes installation	, transportation, ar	nd O&P	
Total of c	Irect line items above; Direct cost category Process costs Building costs Total direct costs Cost Details (See indirect assumptions sheet to exclude individual add-on iter Add-on Line Item Permits Plot Study	Tota \$ 303,421 \$ 31,672 \$ 335,093 ms) Tota \$ 2,355 \$ -	I Guidanc Excludes See indiru Total of p	NA aternate cost line items in italics, without ect assumptions sheet to exclude buildings rocess and building costs	rva	, transportation, ar	nd O&P	
Total of c	Irect line items above: Direct cost category Process costs Building costs Cost Details (See indirect assumptions sheet to exclude individual add-on iten Add-on Line Item Permits Plot Study Land Cost	Tota \$ 303,421 \$ 31,672 \$ 335,093 ms) Tota \$ 2,355 \$ - \$ - \$ -	I Guidanc Excludes See indire Total of p	NA alternate cost line items in italics, without a alternate cost line items in italics, without a aternate to exclude buildings rocess and building costs acres	rva a 1 in the "Use?" column. Includes installation	, transportation, ar		
Total of c	Irect line items above: Direct cost category Process costs Building costs Total direct costs Cost Details (See indirect assumptions sheet to exclude individual add-on iter Add-on Line item Permits Pior Study Land Cost Total add-on costs	Tota \$ 303,421 \$ 31,672 \$ 335,093 ms) Tota \$ 2,355 \$ - \$ - \$ - \$ - \$ - \$	I Guidanc Excludes See indiru Total of p	NA Atemate cost line items in italics, without a cost set of exclude buildings rocess and building costs acres	rva a 1 in the "Use?" column. Includes installation	, transportation, ar		
Total of c	Irect line items above: Direct cost category Process costs Building costs Cost Details (See indirect assumptions sheet to exclude individual add-on iter Add-on line item Piot Study Land Cost Total add-on costs	Tota \$ 303,421 \$ 31,672 \$ 335,093 ns) Tota \$ 2,365 \$ - \$ - \$ 2,355	I Guidanc Excludes See indiri Total of p I Guidanc	NA Identified the set of	rva a 1 in the "Use?" column. Includes installation	transportation, ar		
Total of c	Irect line items above; Direct cost category Process costs Building costs Total direct costs Cost Details (See indirect assumptions sheet to exclude individual add-on item Add-on Line item Permits Pilot Study Land Cost Total add-on costs	Tota \$ 303,421 \$ 31,672 \$ 335,093 ns) Tota \$ 2,355 \$ - \$ 2,355	I Guidanc Excludes See indiri Total of p I Guidanc	NA Attended to the items in italics, without a casumptions sheet to exclude buildings rocess and building costs acres	rva a 1 in the "Use?" column. Includes installation	, transportation, ar	id O&P	
Total of c Add-on	Inect line items above: Direct cost category Process costs Building costs Cost Details (See indirect assumptions sheet to exclude individual add-on iter Add-on Line item Permits Piert Study Land Cost Total add-on costs Capital Cost Details (See indirect assumptions sheet to exclude individual)	Tota \$ 303,421 \$ 31672 \$ 335,093 ns) Tota \$ 2,355 \$ 2,355 ndirect items)	I Guidanc Excludes See indiri Total of p	NA atemate cost line items in italics, without atemate cost line items in italics, without ect assumptions sheet to exclude buildings rocess and building costs	rva a 1 in the "Use?" column. Includes installation	, transportation, ar	id O&P	
Total of c Add-on	Irect line items above; Direct cost category Process costs Building costs Cost Details (See indirect assumptions sheet to exclude individual add-on iter Add-on Line item Plets Study Land Cost Cost Details (See indirect assumptions sheet to exclude individual, Indirect Line item	Tota \$ 303.421 \$ 31.672 \$ 335,093 ms) Tota \$ 2,355 \$ - \$ - \$ 2,355 mdirect items) Total	I Guidanc Excludes See indiri Total of p I Guidanc For 2.07 :		1 in the "Use?" column. Includes installation	, transportation, ar	id O&P	
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Add-on	Irect line items above; Direct cost category Process costs Building costs Cost Details (See indirect assumptions sheet to exclude individual add-on iter Add-on Line item Permits Permits Permits Part Sudy Land Cost Total add-on costs Capital Cost Details (See indirect assumptions sheet to exclude individual i Indirect Line item Mobilization and Demobilization Archiectural Fess for Treatment Building	Tota \$ 303,421 \$ 31,672 \$ 335,093 ms) Tota \$ 2,355 \$ 2,355 \$ 2,355 address \$ 61,321	I Guidanc Excludes See indiri Total of p I Guidanc For 2.07 Percen 49 9.09	e alternate cost line items in italics, without a cet assumptions shee to exclude buildings roccess and building costs acres tt Guidance t Guidance E Excluded for pre-engineered packages E Excluded for small systems	1 in the "Use?" column. Includes installation	, transportation, ar	nd O&P	
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Equations used for NF process design

The effects of a nanofiltration membrane on the water being treated are determined as

such.

The mass of water in the permeate stream is equal to the mass of water in the feed stream multiplied by the recovery rate. The recovery rate was determined experimentally(Schaefer,

2005). The mass of water in the retentate stream is equal to the mass of water in the feed stream multiplied by one minus the recovery rate.

$$P_{H2O} = F_{H2O} \times Rec$$

 $R_{H2O} = F_{H2O} \times (1 - Rec)$
 $R_{H2O} + P_{H2O} = F_{H2O}$

Where P_{H2O} is the mass flow rate of water in the permeate,

 F_{H2O} is the mass flow rate of water in the feed,

 $R_{\rm H2O}$ is the mass flow rate of water in the retentate,

and Rec is the recovery of the membrane, which was found to be 70% in the cases present in these processes.

The mass of other species in the permeate, such as the two PFAS species, and the various ionic species, is determined based on the rejection rate. The rejection rate for ionic species by the NF90 membranes was found to be 93%(Krieg, 2005), and 99.8% for the two PFAS species (Soriano, 2019).

$$P_A = F_A x (1 - r_A)$$
$$R_A = F_A x r_A$$
$$R_A + P_A = F_A$$

where

P_A is the mass flow rate of species A in the permeate,

R_A is the mass flow rate of species A in the retentate,

 F_A is the mass flow rate of species A in the feed,

and r_A is the rejection rate of species A for the NF90 membrane.

Calculation of the mass of salt precipitating from NF process

Salt precipitation was calculated based on solubility values provided by The Engineering Toolbox (Engineering Toolbox, 2017). First, it was determined that the mixture would reach the solubility level during the duration of the retentate's settling period. Based on work done by Dr. Taher Rabizadeh, a solution with a lower concentration of calcium salts was found to precipitate fully and reach the point of solubility in four hours (Rabizadeh, 2016). Since the rate of nucleation increases as the extent of supersaturation increases, it can be predicted that solubility will be reached in fewer than four hours.

Of the available salt species, CaF_2 was found to be the least soluble, with a solubility of 0.0016pph, and so it was predicted that this would precipitate first. The mass of fluoride was found to be the limiting factor, since the mass of calcium was far greater. At this point of solubility, the concentration of fluoride remaining in the water was calculated such that:

$$C_{\text{sat, F-}} = C_{\text{sat, CaF2}} \times (2 \times Mw_{\text{F-}})/(Mw_{\text{CaF2}})$$

Where $C_{sat, F}$ is the concentration of fluoride in the water after the solution reaches the point of saturation,

 $C_{\text{sat, CaF2}}$ is the solubility of calcium fluoride in water,

 Mw_{F-} is the molar mass of a fluoride ion,

And Mw_{CaF2} is the molar mass of calcium fluoride.

Following this precipitation, a precipitation of calcium sulfate was predicted, since it had the second lowest solubility among present species. Engineering Toolbox gave a solubility of 0.205 pph for calcium sulfate in water. The final concentration of sulfate, after the precipitation,

was calculated such that:

$$C_{sat, SO4,2-} = C_{sat, CaSO4} \times (2 \times Mw_{SO4,2-})/(Mw_{CaSO4})$$

Where $C_{sat, SO4,2}$ is the concentration of sulfate in the water after the solution reaches the point of saturation,

 $C_{\mbox{\scriptsize sat, CaSO4}}$ is the solubility of calcium sulfate in water,

 $Mw_{SO4,2-}$ is the molar mass of a sulfate ion,

And $Mw_{\mbox{\tiny CaSO4}}$ is the molar mass of calcium sulfate.

Equipment Costing Spreadsheet

Bare Module Cost Ar	nalysis Worksheet									
Instructions (Read Carefully Bet	fore Using!!!)									
 Input the CE cost index below 	that corresponds to the date	when you want t	he cost estimate (e.g	. a 2018 CE v	vill provide 20	18 costs for	equipment) . Th	ne CE index will a	utomatically update each p	age accordingly.
Select the link below for the	appropriate unit operation. Li	nks provided at t	he top of each worksh	neet will retu	rn back to this	s title page.				
Enter all data into the yellow	boxes ONLY. For a process in	volving multiple	sizes of the same type	e unit operat	ions, use a di	fferent line t	o input the spec	s (up to 5 provide	d)	
	Input									
4. The Bare Module Cost of the	Unit Operation is calculated a	and shown in red.								
	Bare Module Cost									
5. If you are extrapolating the o	ost correlations, the spreadsh	eet will warn you	. Consult the textboo	k for valid ra	nges of the e	quations, and	l use outside the	se ranges very c	arefully.	
6. Below are the individual unit	bare module costs and comp	iled tables of eac	h type of unit operation	on, summariz	ing the differ	ent propertie	25.			
7. Total Bare Module Cost for a	Il types of all equipment is als	o displayed below	N.							
All costing from:										
Product and Process Design Prin	nciples									
4th Edition	© Seider, Lewin, Seader, W	idagdo, Gani, Ng,	2017							
Worksheet prepared by Prof. R	ussell Dunn, Department of C	hemical and Bion	olecular Engineering	, Vanderbilt l	Jniversity					
Revised by Prof. Bruce Vrana, D	epartment of Chemical and E	Biomolecular Engi	neering, University of	f Pennsylvan	ia					
CE Cost Index for this Estimate	800									
Equipment	Total Cbm For each Unit Op		Total Bare module Co	st= \$	1,210,429					
Electric Motors	\$ -									
Centrifugal Pumps	\$ 427,589									
External Gear Pumps	\$ -									
Reciprocating Plunger Pumps	\$ 148,608	Warning - extra	polation in cost estimation	ate, refer to	textbook for v	alid range				
Fans	\$ -									
Centrifugal (turbo) Blower	\$ -									
Rotary Straight Lobe Blower	\$ -									
Compressors	\$ 187,315									
Shell and Tube Heat Exchanger	\$ 343,088	1								
Double Pipe Heat Exchanger	\$ -	T								
Fired Heaters	\$ -									
Pressure Vessel	\$ -									
Packed Column	\$ -									

Packed Column	\$						
Tray Column	\$						
Storage Tanks	\$ 103,829	Warning - extra	apolation in cost	estimate, ref	er to textbook for v	alid range	
		-	İ				
Electric Motors	Q (gal/min)	H (ft)	FT	Pb (hp)	Cbm		
		0 0	0.00	0.00	0		
		0 0	0.00	0.00	0		
		0 0	0.00	0.00	0		
		0 0	0.00	0.00	0		
		0 0	0.00	0.00	0		
		-					
Centrifugal Pumps	Q (gal/min)	H (ft)	Ft	Fm	Cbm		
Stage1	160	0 500	2	1.35	192964		
Stage 2	12	5 500	1.7	1.35	53007		
Stage 3	14	6 500	1.7	1.35	54991		
P-302	41	2 150	1	1	27158		
P-301	161	5 150	2	1	99469		
External Gear Pumps	Q (gal/min)	Fm	Cbm				
		0 0	0				
		0 0	0				
		0 0	0				
		0 0	0				
		0 0	0				
Reciprocating Plunger Pumps	Q (gal/min)	H (ft)	Fm	Pb (hp)	Cbm		
Stage 4	4	4 540	1.00	6.66	27644		
Stage 5	13	2 540	1.00	2.00	16204		
P-300	7	5 50	1.00	0.11	9970	Warning - e	extrapolation in cost estimate, refer to textbook for valid range
P-303		4 150	1.00	0.17	9963	Warning - e	extrapolation in cost estimate, refer to textbook for valid range
Cleaning Pump	4	0 85	6.60	0.95	84826	Warning - e	extrapolation in cost estimate, refer to textbook for valid range

Fans	Type of Fan	Q (ACFM)	CBM						
		0 0	0 0						
		0 0	0 0						
		0 0	0 0	Warning - ex	trapolation in cost	estimate, refe	er to textbook for	valid range	
		0 0	0 0	Warning - ex	trapolation in cost	estimate, refe	er to textbook for	valid range	
		0 0	0 0	Warning - ex	trapolation in cost	estimate, refe	er to textbook for	valid range	
Centrifugal Blower	Qi (cuft/min)	Pi (lbf/in2)	Po (lbf/in2)	Pc	Cbm				
		0 0	0 0	0.00	0				
		0 0	0 0	0.00	0				
		0 0	0 0	0.00	0				
		0 0	0 0	0.00	0				
		0 0	0 0	0.00	0				
Rotary Straight-Lobe Blowers	Qi (ft^3/min)	Pi (lbf/in^2)	Po(lbf/in^2)	Pc (hp)	Cbm				
		0 0	0	0.00	0				
		0 0	0 0	0.00	0				
		0 0	0 0	0.00	0				
		0 0	0 0	0.00	0				
		0 0	0 0	0.00	0				
Compressor	Туре	Pc (hp)	CBM						
C-300	Screw Compressor	46.52	187315						
		0 0	0 0						
		0 0	0 0						
		0 0	0 0						
		0 0	0 0						
Shell and Tube Heat Exchanger	s Heat Exchanger Design	Surface Area	f Pressure (psig)	CBM					
HX-1	Fixed Head	1300	20	343088					
		0 0	0 0	0					
		0 0	0 0	0					
		0 0	0 0	0					
		0 0	0 0	0					

		1					
Double Pipe Heat Exchanger	Surface Area (ft ²)	Pressure (psig)	CBM				
	0	0	0				
	0	C	0				
	0	0	0				
	0	C	0				
	0	0	0				
Fired Heaters	Q (BTU/hr)	Pressure (psig)	Fm	Cbm			
	0.00E+00	C	0	C)		
	0.00E+00	0	0	C)		
	0.00E+00	C	0	C)		
	0.00E+00	C	0	C)		
	0.00E+00	0	0	C	1		
Pressure vessel	Type	Di	L	Pressure	Weight	Cbm	
	0	0	0	C	0		0
	0	C	0	C	0		0
	0	0	0	C	0		0
	0	C	0	C	0		0
	0	0	0	C	0		0
Packed Column	Di (ft)	L (ft)	Pressure (psig)	Vp (ft^3)	Cbm		
	0	C	0	C	0		
	0	C	0	C	0		
	0	C	0	C	0		
	0	0	0	C	0		
	0	C	0	C	0		
Tray Column	Di (ft)	L(ft)	Pressure (psig)	Nt	Ftt	Cbm	
•	0	0	0	c	0		0
	0	0	0	0	0		0
	0	0	0	0	0		0
	0	0	0	0	0		0
	1 0	0	0				0
	- 0						<u> </u>

Storage Tanks	V (gal)	Cbm					
	581.2	67573	Warning - extrapolation in	ost estimate, refer t	o textbook fo	or valid range	
	500	36256	Warning - extrapolation in	ost estimate, refer t	o textbook fo	or valid range	
	0	0					
	0	0					
	C	C					

Field 3.3 CE 800 FT FT P P P P P P P Stage 1600 900 977 13-80 CE FT P	Centrifugal P	umps							Summary pag	e						
Name Q H S GB FT FM CP CP GBM CM CM <thcm< th=""> CM CM CM<!--</th--><th>FBM =</th><th>3.3</th><th></th><th>CE =</th><th>800</th><th></th><th></th><th></th><th></th><th></th><th></th><th></th><th></th><th></th><th></th><th></th></thcm<>	FBM =	3.3		CE =	800											
Name Q H S GB CB CP CB CB </th <th></th>																
	Name	Q	Н	S	CB	FT	FM	CP	CP	CBM						
Singel 1000 5000 3777 1338 2 136 4143 3474 13294 Singel 105 2000 2795 44961 1.7 1.35 11384 16663 53007 -<		(gal/min)	(ft)	(gpm)(ft)^.5	\$ (CE=567)	Table 22.20	Table 22.21	\$ (CE=567)	\$ (Given CE)	\$ (Given CE)						
Stage 2 158 500 279 490 1.7 1.35 1184 1600 5000 1.0 1.0 1.00 Stage 3 146 500 320 516 1.7 1.35 1181 1660 5900 1.1 1.00 P-302 412 150 500 5930 1.0 1.2 2136 3014 9940 7.0 7.0 7.0 Stage 3 Staft 1 1.0 1.0 2.0 2.0 1.0 2.0 2.0 1.0 Staft 1.0 Type 3/2 Staft 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1 3.600 HSC Staft 1.0 Staft 1.0 1.0 1.0 1.0 1.0 1 3.600 HSC Staft 1.0 Staft 1.0 1.0 1.0 1.0 1 3.600 HSC Staft 1.0 3.00 1.0 3.0 3.0 3.0 2 3.600 HSC Staft 1.0 3.00 3.00 1.0 3.0 3.0 3.0 2 3.600 HSC Staft 1.0 3.0 3.0 3.0 3.0 3.0 3.0 3.0 3.0 <th>Stage1</th> <th>1600</th> <th>500</th> <th>35777</th> <th>15349</th> <th>2</th> <th>1.35</th> <th>41443</th> <th>58474</th> <th>192964</th> <th></th> <th></th> <th></th> <th></th> <th></th> <th></th>	Stage1	1600	500	35777	15349	2	1.35	41443	58474	192964						
Stage 146 500 3265 51.64 1.7 1.35 1181 1664 5491 1 <th>Stage 2</th> <th>125</th> <th>500</th> <th>2795</th> <th>4961</th> <th>1.7</th> <th>1.35</th> <th>11384</th> <th>16063</th> <th>53007</th> <th></th> <th></th> <th></th> <th></th> <th></th> <th></th>	Stage 2	125	500	2795	4961	1.7	1.35	11384	16063	53007						
P-302 412 504 583 1 1 5833 8230 27158 1 1 6833 6120 27158 1 1 6833 6120 27158 1 <th1< th=""> 1 <th1< th=""> <th1< th=""></th1<></th1<></th1<>	Stage 3	146	500	3265	5146	1.7	1.35	11811	16664	54991						
P-30. 1.00 1.00 1.00.0	P-302	412	150	5046	5933	1	1	5933	8230	27159						
P-301 1615 150 19780 10662 2 2 2 2 2 9969 Image	F-302	412	150	5040	5655	-	-	3833	0250	2/150						
Table 16.20 Types of France Types of Criticity Particity Partity Particity Particity Particity Partity Partity Particity Partici	P-301	1615	150	19780	10682	2	1	21363	30142	99469						
Table 16.20 Table 16.21 Ta											-		1			
No. of Stages Case Split Shaft rpm Flow Rate Orientation Prop Head Range(gm) Maximum Range(f) Type Factor (F Bd,(16.15) Material a Construction Material Factor (F_{M-} in Eq. (16.15)) 1 3.600 VSC 50-300 50-400 75 1.00 Cast steel 1.15 1 3.600 HSC 100-1,500 100-450 150 1.70 Cast steel 1.35 2 3.600 HSC 250-500 50-500 250 2.00 Branze 1.90 2 3.600 HSC 100-1,500 650-3,200 1.450 8.90 Morel 3.30 2 3.600 HSC 100-1,500 650-3,200 1.450 8.90 Morel 3.30 7 PM Sage statistical 2.00 1.450 8.90 Morel 3.30 8 VSC 50-300 50-300 50-300 1.450 8.90 Morel 3.30 8 HSC 100-1,500 650-3,200 1.450 8.90 Morel 3.30 8 Gien OL Marci Sage statistical	Table 16.20	Typical Types	s of Radial (Centrifugal Pump	os and $F_{\rm T}$ Fact	ors					Table 16.21 Pumps	Materials of	Construction	Factors, F_M , fo	Centrifuga	ıl –
Stages Shaft rpm Orientation Range(f) Motor Hp Eq. (6.15) Matchina to Cossuducion Matchina to Cossuducion Matchina to Cossuducion 1 3.600 VSC 50-900 50-400 7.5 1.00 Cast ion 1.00 1 3.000 HSC 100-1,500 100-450 150 1.70 Cast ion 1.35 1.00 Matchina VSC 50-100 200 1.50 2.00 1.00 Stainless steel 2.20 2.4 3.600 HSC 100-1,500 650-3.200 1.450 8.90 Nickel 3.30 1.4 1.00 2.00 1.450 8.90 Nickel 3.30 1.4 1.00 1.00 2.00 1.450 8.37 Titaniur 9.70 Reciprocentary Purser FM 6 6 9.97 Nickel 3.30 Stage 4 64 540 8.32 0.9 6.66 9.97 8.37 7.644 1.00 1.00 1.00 <td>No. of</td> <td></td> <td></td> <td>Case-Split</td> <td>Flow Ra</td> <td>ite</td> <td>Pump Head</td> <td>Maxi</td> <td>num</td> <td>Type Factor [F</td> <td>Motorial of (</td> <td>Construction</td> <td>Mate</td> <td>arial Easter [E</td> <td>in Eq. (16</td> <td>15)1</td>	No. of			Case-Split	Flow Ra	ite	Pump Head	Maxi	num	Type Factor [F	Motorial of (Construction	Mate	arial Easter [E	in Eq. (16	15)1
1 3.600 VSC \$0-900 75 1.00 Cast iron 1.00 1 1.800 VSC \$0-3500 \$0-200 200 1.50 Ductili iron 1.15 1.3.600 HSC 100-1,500 100-450 150 1.70 Brouze 1.90 2.3.600 HSC 20-5,000 \$0-500 250 2.00 Stainles steel 2.00 2.4 3.600 HSC \$0-1,100 300-1,100 250 2.70 Haselby C 2.95 2.4 3.600 HSC 100-1,500 650-3,200 1,450 8.99 Morel 3.30 1.15 CE 800 - - - Nickel 3.50 1.16 CE 800 - - Nickel 3.50 Name Q H P	Stages	Shaft rpm	(Drientation	Range (g	pm)	Range(ft)	Moto	r Hp	Eq. (16.15)	Wraterial of v	Construction	wiate	erial Factor [r _M	, III Eq. (10	.15)]
1 1.800 VSC 50-300 50-200 200 1.50 Dictite from 1.15 1 3.600 HSC 100-1500 100-450 150 170 Cast stell 1.35 1 1.800 HSC 250-5000 50-500 250 200 Stainless stell 2.000 2 3.600 HSC 50-1,100 300-1,100 250 2.07 Hastelby C 2.95 2+ 3.600 HSC 100-1,500 650-3,200 1.45 5.90 Model 3.30 Recipaced and the state of th	1	3,600		VSC	50-900)	50-400		75	1.00	Cast iron			1.00		
1 3,600 HSC 100-1,500 100-4,50 150 1,70 Case seed 1,33 2 3,600 HSC 250-1,100 300-1,100 250 2,00 Snoze 2,00 2,4 3,600 HSC 500-1,000 650-3,200 1,450 8,90 Histelloy C 2,25 2,4 3,600 HSC 100-1,500 650-3,200 1,450 8,90 Histelloy C 2,35 1 1 1 1 1 1 1 3,30 Siniflexs stelloy C 3,30 1 1 1 1 1 1 1 3,30 Siniflexs stelloy C 3,30 1 1 1 1 1 1 1 1 3,00 Siniflexs stelloy C 3,00 1	1	1,800		VSC	50-3,5	00	50-200	2	00	1.50	Ductile iron			1.15		
1 1,800 HSC 250-500 50-500 250 2,00 Buines 1,800 1,800 2 3,600 HSC 50-1,000 300-1,100 250 2,70 Buines stell 2,00 2+ 3,600 HSC 100-1,500 650-3,200 1,450 8,90 Nickel 3,30	1	3,600		HSC	100-1,5	00	100-450	1	50	1.70	Cast steel			1.55		
2 3.600 HSC 500-1,100 300-1,100 250 2.70 Hastelloy C 2.95 2+ 3.600 HSC 100-1,500 650-3,200 1,450 8.90 Monel 3.30 1 1 1 1 1 1 1 Nickel 3.50 1 1 1 1 1 1 1 Nickel 3.50 1 1 1 1 1 1 1 Nickel 3.50 1 <td< td=""><td>1</td><td>1,800</td><td></td><td>HSC</td><td>250-5,0</td><td>00</td><td>50-500</td><td>2</td><td>50</td><td>2.00</td><td>Stainless ste</td><td>el</td><td></td><td>2.00</td><td></td><td></td></td<>	1	1,800		HSC	250-5,0	00	50-500	2	50	2.00	Stainless ste	el		2.00		
2+ 3,600 HSC 100-1,500 650-3,200 1,450 8.90 Monel 3,30 Nickel 3,50 3,50 3,50 3,50 3,50 3,50 Nickel 3,50 Nickel 3,50 Nickel 3,50 Reciprocating Pumper Pumper Timinum 9,70 Reciprocating (gal/min) (f1) p <t< td=""><td>2</td><td>3,600</td><td></td><td>HSC</td><td>50-1,1</td><td>00</td><td>300-1,100</td><td>2</td><td>50</td><td>2.70</td><td>Hastellov C</td><td></td><td></td><td>2.00</td><td></td><td></td></t<>	2	3,600		HSC	50-1,1	00	300-1,100	2	50	2.70	Hastellov C			2.00		
Image: Participant of the second of the	2+	3,600		HSC	100-1,5	00	650–3,200	1,4	50	8.90	Monel			3.30		
Image: barrier											Nickel			3.50		
Summary page FBM 3.3 CE = 800 Summary page C Given Q, H, p Name Q H p np P8 CB FM CP CP CB Stage 4 44 540 8.32 0.9 6.66 5937 1.00 5937 8377 27644 Stage 4 44 540 8.32 0.9 0.11 2141 1.00 2141 3021 9970 Warning - extrapolation in cost estimate, refer to textbook for valid range P-300 7.5 50 8.32 0.9 0.17 2140 1.00 2141 3021 9970 Warning - extrapolation in cost estimate, refer to textbook for valid range P-303 4 150 8.32 0.9 0.17 2140 1.00 2140 3019 9963 Warning - extrapolation in cost estimate, refer to textbook for valid range Beaning Pumj 40 85 8.32 0.9 0.95 2760 6.60 18218 25705 84826 Warning - extrapolation in cost estimate, refer to textbook for valid range Stage 4 Cm											Titanium			9.70		
Reciprocessing Functional processing from the second proces in the second processing from the second processing																
FBM 3.3 CE = 800 CE 1 <t< td=""><td>Reciprocating</td><td>Plunger Pumps</td><td></td><td></td><td></td><td></td><td></td><td>Summary p</td><td>age</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></t<>	Reciprocating	Plunger Pumps						Summary p	age							
Given Q, H, p Q H p np	FBM	3.3		CE =	800											
Name Q H p np PB CB FM CP CP CB CB <th< td=""><td>Given O. H. o</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></th<>	Given O. H. o															
(gd/min) (ft) (lb/gd) (hbp) \$ (CE=567) Sec below \$ (CE=567) \$ (Given CE) \$	Name	Q	н	ρ	ηp I	РВ СВ	FM	СР	CP	CBM						
Stage 4 44 540 8.32 0.9 6.66 5937 1.00 5937 2764 Component of the second		(gal/min)	(ft)	(lb/gal)	()	hp) \$ (CE=	567) See belo	ow \$ (CE=56	7) \$ (Given CE)	\$ (Given CE)						
Stage 5 13.2 540 8.32 0.9 2.00 3480 1.00 3480 4910 16204 <td>Stage 4</td> <td>44</td> <td>540</td> <td>8.32</td> <td>0.9 6</td> <td>.66 593</td> <td>37 <u>1.00</u></td> <td>5937</td> <td>8377</td> <td>27644</td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td>	Stage 4	44	540	8.32	0.9 6	.66 593	37 <u>1.00</u>	5937	8377	27644						
P-300 7.5 50 8.32 0.9 0.11 2141 1.00 2141 3021 9970 Warning - extrapolation in cost estimate, refer to textbook for valid range P-303 4 150 8.32 0.9 0.17 2140 1.00 2141 3021 9970 Warning - extrapolation in cost estimate, refer to textbook for valid range Baning Pum; 40 85 8.32 0.9 0.95 2760 6.60 18218 25705 84826 Warning - extrapolation in cost estimate, refer to textbook for valid range Given PB 98 996 Warning - extrapolation in cost estimate, refer to textbook for valid range 9970 Warning - extrapolation in cost estimate, refer to textbook for valid range Stage 4 98 9963 Warning - extrapolation in cost estimate, refer to textbook for valid range P-300 98	Stage 5	13.2	540	8.32	0.9 2	.00 348	30 1.00	3480	4910	16204						
P-300 7.5 50 8.32 0.9 0.11 2141 1.00 2141 3021 9970 Warning - extrapolation in cost estimate, refer to textbook for valid range P-303 4 150 8.32 0.9 0.17 2140 1.00 2141 3019 9963 Warning - extrapolation in cost estimate, refer to textbook for valid range Baning Pumy 40 85 8.32 0.9 0.95 2760 6.60 18218 25705 84826 Warning - extrapolation in cost estimate, refer to textbook for valid range Given PB . . Ductile iron $F_M = 1.00$. .																
P-303 4 150 8.32 0.9 0.17 2140 1.00 2140 3019 9963 Warning - extrapolation in cost estimate, refer to textbook for valid range Jeaning Purp 40 85 8.32 0.9 0.95 2760 6.60 18218 25705 84826 Warning - extrapolation in cost estimate, refer to textbook for valid range Given PB 98 0.9 0.95 2760 6.60 18218 25705 84826 Warning - extrapolation in cost estimate, refer to textbook for valid range Given PB 98 0.9 0.95 2760 6.60 18218 25705 84826 Warning - extrapolation in cost estimate, refer to textbook for valid range Mame PB 99 0.95 2760 6.60 18218 25705 84826 Warning - extrapolation in cost estimate, refer to textbook for valid range Stage 3 99 99 99 99 99 84826 Warning - extrapolation in cost estimate, refer to textbook for valid range Stage 5 98 98 98 98 98 98 98 98 98 98 98 98	P-300	7.5	50	8.32	0.9 0	.11 214	1 1.00	2141	3021	9970	Warning - ext	rapolation in co	st estimate, r	efer to textbook	for valid rar	nge
learning Pum; 40 85 8.32 0.9 0.95 2760 6.60 18218 25705 84826 Warning - extrapolation in cost estimate, refer to textbook for valid range Given PB	P-303	4	150	8.32	0.9 0	.17 214	1.00	2140	3019	9963	Warning - ext	rapolation in co	st estimate, r	efer to textbook	for valid rar	nge
Given PB Mane PB Ductile inno $F_M = 1.0$ Mane <	Cleaning Pump	40	85	8.32	0.9 0	.95 276	60 6.60	18218	25705	84826	Warning - ext	rapolation in co	st estimate, r	efer to textbook	for valid rar	nge
Name PB Ductie ion $F_M = 1.0^{\circ}$ (hp) Ni-Al-Bronz $F_M = 1.5^{\circ}$ Ni-Al-Bronz $F_M = 1.5^{\circ}$ Stage 4 Stamesisted $F_M = 1.5^{\circ}$ Ni-Al-Bronz $F_M = 1.5^{\circ}$ Stage 5 Stamesisted $F_M = 1.5^{\circ}$ Ni-Al-Bronz $F_M = 1.5^{\circ}$ P-303 Ni-Al-Bronz $F_M = 1.5^{\circ}$ Ni-Al-Bronz Ni-Al-Bronz P-303 Ni-Al-Bronz Ni-Al-Bronz Ni-Al-Bronz Ni-Al-Bronz Ni-Al-Bronz Ni-Al-Bronz Ni-Al-Bronz Ni-Al-Bronz Ni-Al-Bronz P-303 Ni-Al-Bronz Ni-Al-Bronz Ni-Al-Bronz Ni-Al-Bronz Ni-Al-Bronz Ni-Al-Bronz Ni-Al-Bronz Ni-Al-Bronz Ni-Al-Bronz Ni-Al-Bronz Ni-Al-Bronz P-303 Ni-Al-Bronz Ni-Al-Bronz Ni-Al-Bronz Ni-Al-Bronz Ni-Al-Bronz Ni-Al-Bronz Ni-Al-Bronz Ni-Al-Bronz <td>Given PB</td> <td></td>	Given PB															
(hp) Ni-Al-Branze $M = 1.5$ Stage 4 Carbon steel $F_M = 1.50$ Image: Carbon steel $F_M = 2.20$ Stage 5 Stage 6 Stainless steel $F_M = 2.20$ Image: Carbon steel $F_M = 0.20$ P-300 Image: Carbon steel $F_M = 0.20$ Image: Carbon steel $F_M = 0.20$ Image: Carbon steel $F_M = 0.20$ P-300 Image: Carbon steel $F_M = 0.20$ Image: Carbon steel Image: Carbon steele Image: Carbon steele <td< td=""><td>Name</td><td>PB</td><td></td><td></td><td></td><td>Du</td><td>actile iron F</td><td>M = 1.00</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></td<>	Name	PB				Du	actile iron F	M = 1.00								
Stage 4 Stage 4 Stage 5 Stage 5 Stage 5 Stage 6 Stage 6 Stage 7		(hp)				Ni	-Al-Bronze F	M = 1.15								
Stage 5 Stage 5 Stage 6 Stage 6 Stage 7	Stage 4					Ca	ainless steel F	M = 1.50 M = 2.20								
P-300 Image: Control of the control	Stage 5						anness steer 7 j	M = 2.20								
P-303 Image: Constraint of the const	Stage 5															
P-303 Leaning Pump	P-300															
Jeaning Pump	P-303															
Jeaning Pump																
	Ileaning Pump															

Tube Heat E	Exchangers							Sumr	nary pa	age			
FBM =	3.17		CE =	800									
Name	Heat Exchanger Design	Surface Area	СВ	а	b	FM	Pressi	ure	Fp	FL	Ср	Ср	CBM
Hume	neut Exchanger Besign	ft^2	\$ (CE=567)	Table 22.25	Table 22.25		nsio	7	10	See below	\$ (CE=567)	Ś(Given CF)	Ś (Given CF)
HY-1	Fixed Head	1300	19371	2 7	0.07	3 89667449	20	,	1	1 01625	76708	108230	343088
11/1	Tixed field	1500	15571	2.7	0.07	5.05007445	20		-	1.01025	/0/00	100250	343000
			0			0			1		0	0	0
											-		
			0			0			1		0	0	0
			0			0			1		0	0	0
			0			0			1		0	0	0
		Table 16.25 N	Materials of C	onstruction Fa	ctors, $F_{\rm M}$, for								
		Shell-and-Tube	e Heat Exchan	agers				1	Гube	Length (ft)	F_L		
		Materials of Co	onstruction	(a in	<i>b</i> in					1.05		
		Shell/Tube		Eq.	(16.44)	Eq. (16.44)				8	1.25		
		Carbon steel/a	when steel	(0.00	0.00				12	1.12		
		Carbon steel/ca	arbon steel	(0.00	0.00				16	1.05	ა	
		Carbon steel/bl	niploss steel	1	75	5 0.05 –				20	1.00	J	
		Carbon steel/M	Innel) 1	0.13							
		Carbon steel/ti	tanium	4	5.2	0.13 0.16 0.05 0.07							
		Carbon steel/C	r-Mo steel	-	55								
		Cr-Mo steel/Cr	-Mo steel	1	.70								
		Stainless steel/	stainless steel	2	2.70	0.07							
		Monel/Monel		3	3.3	0.08							
		Titanium/titani	um	ç	0.6	0.06							
	Storage Tanks								Su	immary page			
	FBM =	4		CE =	80	0							
	Neme	Time	N/	<u>(</u>	CT								
	Name	Type	V IIS and	CP			om CEl						
		Eloating root	581 2	11973	168	93 67	573 N	Warning -	extran	plation in cost es	timate refer	to textbook fo	r valid range
		i louting root	501.2	110/1	. 100				cherapt				vana range
		Cone roof	500	6424	906	4 362	256	Warning -	extrapo	plation in cost es	timate, refer	to textbook fo	r valid range
				0	0	()						
				0	0)						
				0	0	()						
Note	e: Carbon steel only												
M	ax pressure 3 psig												
See text	t for open roof, spheres												
Cone roof fo	r low vapor pressure, requ	ires vent system	n										
Floating ro	of to prevent evaporation												
		1											

ASPEN Plus Report for Distillation Column within IX Alternatives Analysis

+ + + + ASPEN PLUS CALCULATION REPORT + + + + + + + + ASPEN PLUS IS A TRADEMARK OF HOTLINE: ASPEN TECHNOLOGY, INC. U.S.A. 888/996-7100 781/221-6400 EUROPE (44) 1189-226555 PLATFORM: WIN-X64 FEBRUARY 21, 2022

VERSION: 39.0 Build 116 MONDAY INSTALLATION: 10:15:15 P.M. ▲ ASPEN PLUS PLAT: WIN-X64 VER: 39.0 02/21/2022 PAGE

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BLOCK: B1 MODEL: DSTWU	4

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RUN CONTROL SECTION

RUN CONTROL INFORMATION

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TYPE OF RUN: EDIT

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INPUT FILE NAME: _3325znf.inm

INPUT PROBLEM DATA FILE NAME : _3325znf
OUTPUT PROBLEM DATA FILE NAME: _1510xhf
LOCATED IN:

PDF SIZE USED FOR INPUT TRANSLATION: NUMBER OF FILE RECORDS (PSIZE) = 0 NUMBER OF IN-CORE RECORDS = 256 PSIZE NEEDED FOR SIMULATION = 1

CALLING PROGRAM NAME: apmain LOCATED IN: C:\Program Files\AspenTech\Aspen Plus V12.1\Engine\\xeq

SIMULATION REQUESTED FOR ENTIRE FLOWSHEET♠ ASPEN PLUSPLAT: WIN-X64VER: 39.002/21/2022PAGE 2

FLOWSHEET SECTION

FLOWSHEET CONNECTIVITY BY STREAMS

STREAM	SOURCE	DEST	STREAM	SOURCE	DEST
FEED		B1	DISTILAT	B1	
BOTTOMS	B1				

FLOWSHEET CONNECTIVITY BY BLOCKS

BLOCK	INLETS	OUTLE	ТS
DLUCK		UUILL	Ι.

B1 FEED

COMPUTATIONAL SEQUENCE

SEQUENCE USED WAS:

B1

OVERALL FLOWSHEET BALANCE

***	MASS AND ENERGY BA	LANCE ***	
	IN	OUT	RELATIVE DIFF.
CONVENTIONAL COMPONENTS	5 (KMOL/HR)		
METHANOL	1200.00	1200.00	0.00000
WATER	13800.0	13800.0	0.00000
TOTAL BALANCE			
MOLE(KMOL/HR)	15000.0	15000.0	0.00000
MASS(KG/HR)	287061.	287061.	0.00000
ENTHALPY(CAL/SEC)	-0.279756E+09	-0.275069E+09	-0.167545E-01
***		MADV ***	

	*** CO2	EQUIVALENT	SUMMARY ***		
	FEED STREAMS CO2E	0.00000	KG/HR		
	PRODUCT STREAMS CO2E	0.00000	KG/HR		
	NET STREAMS CO2E PRODUCTION	0.00000	KG/HR		
	UTILITIES CO2E PRODUCTION	0.00000	KG/HR		
	TOTAL CO2E PRODUCTION	0.00000	KG/HR		
♠	ASPEN PLUS PLAT: WIN-X64	VER: 39.0		02/21/2022	PAGE 3

PHYSICAL PROPERTIES SECTION

COMPONENTS

	ID	TYPE	ALIAS	NAME		
	METHANOL	. С	CH40	METHANOL		
	WATER	С	H20	WATER		
♠	ASPEN PLU	JS F	PLAT: WIN-X64	VER: 39.0	02/21/2022	PAGE 4

U-O-S BLOCK SECTION

BLOCK:	B1	MODEL:	DSTWU			
INLET	STREAM:		FEED			
CONDEN	NSER OUTLI	ET:	DISTILAT			
REBOII	_ER OUTLE	Г:	BOTTOMS			
PROPE	RTY OPTIO	N SET:	WILSON	WILSON	/ IDEAL	GAS

***	MASS AND ENERGY BA	LANCE ***	
	IN	OUT	RELATIVE DIFF.
TOTAL BALANCE			
MOLE(KMOL/HR)	15000.0	15000.0	0.00000
MASS(KG/HR)	287061.	287061.	0.00000
ENTHALPY(CAL/SEC)	-0.279756E+09	-0.275069E+09	-0.167545E-01
***		MADV ***	
EEED STREAMS CODE			
PEED STREAMS COZE	0.00000		
NET STREAMS COSE DRODU	0.00000 CTTON 0 00000		
	TON 0.00000		
TOTAL COZE PRODUCTION	0.00000	KG/HK	
	*** INPUT DATA **	*	
HEAVY KEY COMPONENT			WATER
RECOVERY FOR HEAVY KEY			0.022000
LIGHT KEY COMPONENT			METHANOL
RECOVERY FOR LIGHT KEY			0.99000
TOP STAGE PRESSURE (BA	R)		1.01325
BOTTOM STAGE PRESSURE	(BAR)		1.01325
REFLUX RATIO	、		3.00000
DISTILLATE VAPOR FRACT	ION		0.0
	*** RESULTS ***		
DISTILLATE TEMP. (C)	6	/./158
BOITOM TEMP. (C)	9	9.8434
MINIMUM REFLUX RATIO			1.72296
ACTUAL REFLUX RATIO			3.00000
MINIMUM STAGES			4.88833
ACTUAL EQUILIBRIUM STA	GES		7.82063
NUMBER OF ACTUAL STAGE	S ABOVE FEED		4.23964
DIST. VS FEED			0.099440
CONDENSER COOLING REQU	IRED (CAL/SEC)		0.146560+08
NET CONDENSER DUTY (CA	L/SEC)		0.146560+08
REBOILER HEATING REQUI	RED (CAL/SEC)		0.193432+08
NET REBOILER DUTY (CAL	/SEC)		0.193432+08
▲ ASPEN PLUS PLAT: WIN-X	64 VER: 39.0	02	2/21/2022 PAGE 5

STREAM SECTION

BOTTOMS DISTILAT FEED

STREA	M ID	BOTTOMS	DISTILAT	FEED
FROM	:	B1	B1	
то	:			B1

SUBSTREAM: MIXED				
PHASE:	LIQUID	LIQUID	LIQUID	
COMPONENTS: KMOL/HR				
METHANOL	12.0000	1188.0000	1200.0000	
WATER	1.3496+04	303.6000	1.3800+04	
TOTAL FLOW:				
KMOL/HR	1.3508+04	1491.6000	1.5000+04	
KG/HR	2.4353+05	4.3536+04	2.8706+05	
L/MIN	4421.3291	956.5917	5069.5789	
STATE VARIABLES:				
TEMP C	99.8434	67.7158	40.0000	
PRES BAR	1.0133	1.0133	1.0133	
VFRAC	0.0	0.0	0.0	
LFRAC	1.0000	1.0000	1.0000	
SFRAC	0.0	0.0	0.0	
ENTHALPY:				
CAL/MOL	-6.6865+04	-5.8335+04	-6.7142+04	
CAL/GM	-3708.9985	-1998.6409	-3508.3882	
CAL/SEC	-2.5090+08	-2.4170+07	-2.7976+08	
ENTROPY:				
CAL/MOL-K	-34.8597	-50.0749	-39.2722	
CAL/GM-K	-1.9337	-1.7157	-2.0521	
DENSITY:				
MOL/CC	5.0921-02	2.5988-02	4.9314-02	
GM/CC	0.9180	0.7585	0.9437	
AVG MW	18.0277	29.1871	19.1374	
▲ ASPEN PLUS PLAT:	WIN-X64 V	ER: 39.0		02/21/2022

PROBLEM STATUS SECTION

BLOCK STATUS

PAGE 6

-----* * * Calculations were completed normally * * * All Unit Operation blocks were completed normally * * * * All streams were flashed normally * * *

ASPEN Plus Report for HX-1 Design

+ + + + ASPEN PLUS CALCULATION REPORT + + + + + + + + ASPEN PLUS IS A TRADEMARK OF HOTLINE: ASPEN TECHNOLOGY, INC. U.S.A. 888/996-7100 781/221-6400 EUROPE (44) 1189-226555 PLATFORM: WIN-X64 MARCH 28, 2022

VERSION: 39.0 Build 116 MONDAY INSTALLATION: 5:15:13 P.M.

▲ ASPEN PLUS PLAT: WIN-X64 VER: 39.0

03/28/2022 PAGE I

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BLOCK: HX-ER MODEL: HEATX	4

♠

	HEATX	COLD-TQCU HX-ER	TQCURV INLET.	6	
	HEATX	HOT-TQCUR HX-ER	TQCURV INLET.	7	
	STREAM SEC	TION		8	
	COLDI	N COLDOUT HOTIN HO	TOUT	8	
	PROBLEM ST	ATUS SECTION			
	BLOCK	STATUS	•••••		
♠	ASPEN PLUS PLAT: W	IIN-X64 VER: 39.0)	03/28/2022	PAGE 1

RUN CONTROL SECTION

RUN CONTROL INFORMATION

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TYPE OF RUN: EDIT

INPUT FILE NAME: _4600uph.inm

INPUT PROBLEM DATA FILE NAME : _4600uph OUTPUT PROBLEM DATA FILE NAME: _5552eok LOCATED IN:

PDF SIZE USED FOR INPUT TRANSLATION: NUMBER OF FILE RECORDS (PSIZE) = 0 NUMBER OF IN-CORE RECORDS = 256 PSIZE NEEDED FOR SIMULATION = 1

CALLING PROGRAM NAME: apmain LOCATED IN: C:\Program Files\AspenTech\Aspen Plus V12.1\Engine\\xeq

SIMULATION REQUESTED FOR ENTIRE FLOWSHEET♠ ASPEN PLUSPLAT: WIN-X64VER: 39.003/28/2022PAGE 2

FLOWSHEET SECTION

FLOWSHEET CONNECTIVITY BY STREAMS

STREAM	SOURCE	DEST	STREAM	SOURCE	DEST
COLDIN		HX-ER	HOTIN		HX-ER
HOTOUT	HX-ER		COLDOUT	HX-ER	

FLOWSHEET CONNECTIVITY BY BLOCKS

BLOCK INLETS HX-ER HOTIN COLDIN		OUTLETS HOTOUT COLDOU	OUTLETS HOTOUT COLDOUT	
COMPUTATION	AL SEQUENCE			
SEQUENCE USE HX-ER OVERALL FLOM	ED WAS: NSHEET BALANCE			
	*** MA	SS AND ENERGY BAI IN	LANCE *** OUT	RELATIVE DIFF.
CONVENTIO	ONAL COMPONENTS (KMOL/HR)		
WATER		21864.0	21864.0	0.00000
MOLE() MOLE() MASS()	_ANCE (MOL/HR) (G/HR)	21864.0 393887.	21864.0 393887.	0.00000 0.00000
ENTHAI	_PY(CAL/SEC)	-0.415006E+09	-0.415006E+09	0.00000
FEED STRF PRODUCT S NET STREA UTILITIES TOTAL CO2 ▲ ASPEN PLUS	*** CO EAMS CO2E STREAMS CO2E AMS CO2E PRODUCTION S CO2E PRODUCTION 2E PRODUCTION PLAT: WIN-X64	2 EQUIVALENT SUM 0.00000 0.00000 0.00000 0.00000 VER: 39.0	MARY *** KG/HR KG/HR KG/HR KG/HR	03/28/2022 PAGE 3
	PHY	SICAL PROPERTIES	SECTION	
COMPONENTS				
ID T WATER (♠ ASPEN PLUS	YPE ALIAS C H2O PLAT: WIN-X64	NAME WATER VER: 39.0	e	03/28/2022 PAGE 4
		U-O-S BLOCK SEC	TION	
BLOCK: HX-	ER MODEL: HEAT	х		
THIS BLOCH HOT SIDE:	K RUNS WITH ASPEN	- EDR 38.0 WITH A	ADVANCED METHOD) FOR SHELL&TUBE
INLET STRE OUTLET STR	EAM: REAM:	HOTIN HOTOUT		

PROPERTY OPTION SET: IDEAL IDEAL LIQUID / IDEAL GAS COLD SIDE: -----INLET STREAM: COLDIN OUTLET STREAM: COLDOUT PROPERTY OPTION SET: IDEAL IDEAL LIQUID / IDEAL GAS *** MASS AND ENERGY BALANCE *** IΝ OUT RELATIVE DIFF. TOTAL BALANCE 21864.0 MOLE(KMOL/HR) 21864.0 0.00000 393887. 0.00000 MASS(KG/HR) 393887. ENTHALPY(CAL/SEC) -0.415006E+09 -0.415006E+09 0.00000 *** CO2 EQUIVALENT SUMMARY *** FEED STREAMS CO2E 0.00000 KG/HR PRODUCT STREAMS CO2E 0.00000 KG/HR NET STREAMS CO2E PRODUCTION 0.00000 KG/HR UTILITIES CO2E PRODUCTION 0.00000 KG/HR TOTAL CO2E PRODUCTION 0.00000 KG/HR *** INPUT DATA *** FLASH SPECS FOR HOT SIDE: THREE PHASE FLASH MAXIMUM NO. ITERATIONS 30 CONVERGENCE TOLERANCE 0.000100000 FLASH SPECS FOR COLD SIDE: THREE PHASE FLASH MAXIMUM NO. ITERATIONS 30 CONVERGENCE TOLERANCE 0.000100000 SHELL&TUBE INPUT FILE NAME HX-ER 1.EDR SHELL&TUBE PROGRAM MODE SIMULATION HEAT CURVE GENERATION ASPEN PLUS HOT HEAT CURVE GENERATED BY COLD HEAT CURVE GENERATED BY ASPEN PLUS *** OVERALL RESULTS *** ▲ ASPEN PLUS PLAT: WIN-X64 VER: 39.0 03/28/2022 PAGE 5 **U-O-S BLOCK SECTION** MODEL: HEATX (CONTINUED) BLOCK: HX-ER STREAMS:

1			I	
HOTIN> T= 4.0400D+01 P= 1.0132D+00 V= 0.0000D+00	НОТ	(SHELL)	> HOTO T= P= V=	OUT 1.9896D+01 9.1271D-01 0.0000D+00
COLDOUT < T= 2.1389D+01 P= 2.2727D+00 V= 0.0000D+00	COL	D (TUBE)	< COLI T= P= V=	DIN 1.5000D+01 2.3922D+00 0.0000D+00
UNIT RESULTS: CALCULATED HEAT CALCULATED (REQ ACTUAL EXCHANGE % OVER (UNDER) AVERAGE COEFFIC UA LMTD (CORRECTED LMTD CORRECTION NUMBER OF SHELL NUMBER OF SHELL HIGH RHOV2 INDI VIBRATION INDIC	DUTY DUIRED) AREA R AREA DESIGN CIENT) I FACTOR S IN SERIES S IN PARALLEL CATION	CAL/SEC SQM SQM CAL/SEC-SQCM-K CAL/SEC-K C	522758.7761 120.8156 120.6878 -0.1058 0.0414 50072.0146 10.4401 1.0034 1 1 NO NO	
SHELLSIDE RESULTS MEAN SHELL META TOTAL PRESSURE WINDOW PRESSURE CROSSFLOW PRESS BULK FILM COEFF WALL FILM COEFF THERMAL RESISTA FOULING RESISTA CROSSFLOW VELOCI WINDOW VELOCITY MIDPOINT VELOCI SHELL ENTRANCE SHELL EXIT RHOW BUNDLE ENTRANCE BUNDLE EXIT RHOW FOULING % OF OV FILM % OF OVERA FRICTIONAL PRES	S: AL TEMPERATURE DROP DROP DROP SURE DROP SICIENT SICIENT NCE NCE SITY TY RHOV^2 (^2 E RHOV^2 V^2 VA2 VA2 VA2 VA2 VA2 VA2 VA2 VA	C BAR BAR CAL/SEC-SQCM-K CAL/SEC-SQCM-K CAL/SEC-SQCM-K/CAL SEC-SQCM-K/CAL M/SEC M/SEC M/SEC KG/M-SQSEC KG/M-SQSEC KG/M-SQSEC KG/M-SQSEC E BAR	27 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	.7892 .1005 .0164 .0588 .1127 .1127 .8745 .0000 .3727 .3344 .3535 .3123 .0959 .1389 .0033 .0000 .7805 .1006
TUBESIDE RESULTS: MEAN TUBE METAL TOTAL PRESSURE BULK FILM COEFF	. TEMPERATURE DROP ICIENT	C BAR CAL/SEC-SQCM-K	22 0	.9083 .1195 .0985

	WALL FILM COEFFICIENT	CAL/SEC-SQCM-K	0.098	35
	THERMAL RESISTANCE	SEC-SQCM-K/CAL	10.15	37
	FOULING RESISTANCE	SEC-SQCM-K/CAL	0.000	90
	INPUT VELOCITY	M/SEC	1.19	51
	OUTLET VELOCITY	M/SEC	1.202	24
	FOULING % OF OVERALL RESISTANCE		0.000	90
	FILM % OF OVERALL RESISTANCE		42.082	20
	FRICTIONAL PRESSURE DROP	BAR	0.119	94
♠	ASPEN PLUS PLAT: WIN-X64 VER: 3	9.0	03/28/2022	PAGE 6

U-O-S BLOCK SECTION

HEATX COLD-TQCU HX-ER TQCURV INLET PRESSURE PROFILE: CONSTANT2 PRESSURE DROP: -0.1195 BAR PROPERTY OPTION SET: IDEAL IDEAL LIQUID / IDEAL GAS

								_
!	DUTY	ļ	PRES	!	TEMP	!	VFRAC	ļ
!		!		!		!		ļ
!		!		!		!		ļ
!		!		!		!		ļ
!	CAL/SEC	!	BAR	!	С	!		ļ
!		!		!		!		ļ
!=	=======================================	:!=		! =		! =	==================	ļ
!	0.0	!	2.3922	!	21.3891	!	0.0	ļ
!	2.4893+04	!	2.3922	ļ	21.0856	!	0.0	ļ
!	4.9787+04	!	2.3922	!	20.7820	!	0.0	ļ
!	7.4680+04	!	2.3922	!	20.4784	!	0.0	ļ
!	9.9573+04	!	2.3922	!	20.1746	!	0.0	ļ
! -		+-		+ -		+-		ļ
!	1.2447+05	!	2.3922	!	19.8708	!	0.0	ļ
!	1.4936+05	!	2.3922	!	19.5670	!	0.0	ļ
!	1.7425+05	!	2.3922	!	19.2630	!	0.0	ļ
!	1.9915+05	!	2.3922	!	18.9590	!	0.0	ļ
!	2.2404+05	!	2.3922	!	18.6549	!	0.0	ļ
! -		+-		+ -		+-		ļ
!	2.4893+05	!	2.3922	!	18.3507	!	0.0	ļ
!	2.7383+05	!	2.3922	!	18.0465	!	0.0	ļ
!	2.9872+05	!	2.3922	!	17.7422	!	0.0	ļ
!	3.2361+05	!	2.3922	!	17.4378	!	0.0	ļ
!	3.4851+05	!	2.3922	!	17.1333	!	0.0	ļ
! -		+-		+ -		+-		ļ
!	3.7340+05	!	2.3922	!	16.8288	!	0.0	ļ
!	3.9829+05	!	2.3922	!	16.5241	!	0.0	ļ
!	4.2319+05	!	2.3922	!	16.2195	!	0.0	ļ
!	4.4808+05	!	2.3922	!	15.9147	!	0.0	ļ
!	4.7297+05	!	2.3922	!	15.6099	!	0.0	ļ

<u> </u>		++	+		ļ	
!	4.9787+05	! 2.3922 !	15.3050 !	0.0	!	
!	5.2276+05	! 2.3922 !	15.0000 !	0.0	!	
 ∧	ASPEN PLUS	PLAT: WIN-X64	VER: 39.0		- 03/28/2022	PAGE 7

U-O-S BLOCK SECTION

HEATX HOT-TQCUR HX-ER	TQCURV 1	
PRESSURE PROFILE:	CONSTANT	T2
PRESSURE DROP:	0.0	BAR
PROPERTY OPTION SET:	IDEAL	IDEAL LIQUID / IDEAL GAS

! DUTY	! PRES	ТЕМР	VFRAC !
! !	• !		 ! ! ! !
! CAL/SEC !	! BAR !	C	! ! ! !
!===========	!======	========	!=====!
! 0.0	! 1.0133	40.4000	! 0.0 !
! 2.4893+04	! 1.0133	39.4329	! 0.0 !
! 4.9787+04	! 1.0133	38.4648	! 0.0 !
! 7.4680+04	1.0133	37.4957	! 0.0 !
! 9.9573+04	! 1.0133	36.5257	! 0.0 !
! 1.2447+05	! 1.0133	35.5547	! 0.0 !
! 1.4936+05	! 1.0133	34.5827	! 0.0 !
! 1.7425+05	! 1.0133	33.6098	! 0.0 !
! 1.9915+05	1.0133	32.6360	! 0.0 !
! 2.2404+05	! 1.0133	31.6613	! 0.0 !
! 2.4893+05	! 1.0133	30.6856	! 0.0 !
! 2.7383+05	1.0133	29.7091	! 0.0 !
! 2.9872+05	! 1.0133	28.7316	! 0.0 !
! 3.2361+05	1.0133	27.7532	! 0.0 !
! 3.4851+05	! 1.0133	26.7740	! 0.0 !
! 3.7340+05	! 1.0133	25.7939	! 0.0 !
! 3.9829+05	! 1.0133	24.8130	! 0.0 !
! 4.2319+05	1.0133	23.8312	! 0.0 !
! 4.4808+05	1.0133	22.8486	! 0.0 !
! 4.7297+05	! 1.0133	21.8652	! 0.0 !
· 4.9787+05	! 1.0133	20.8809	! 0.0 !
! 5.2276+05	! 1.0133	19.8958	! 0.0 !

STREAM SECTION

COLDIN COLDOUT HOTIN HOTOUT

	STREAM ID	COLDIN	COLDOUT	HOTIN	HOTOUT	
	TO :	HX-ER	HX-EK 	HX-ER	HX-EK 	
	CURSTREAM. MTYED					
	DHASE					
	COMPONENTS · KMOL/HR	LIQUID	LIQUID	LIQUID	LIQUID	
	WATER	1 6712+04	1 6712+04	5152 3546	5152 3546	
		1.0/12/04	1.0712.04	5152.55+0	5152.5540	
	KMOL/HR	1.6712+04	1.6712+04	5152.3546	5152.3546	
	KG/HR	3.0107+05	3.0107+05	9.2821+04	9.2821+04	
	L/MIN	5000.0000	5030.6722	1580.2420	1548.7730	
	STATE VARIABLES:					
	TEMP C	15.0000	21.3892	40.4000	19.8958	
	PRES BAR	2.3922	2.2727	1.0133	0.9127	
	VFRAC	0.0	0.0	0.0	0.0	
	LFRAC	1.0000	1.0000	1.0000	1.0000	
	SFRAC	0.0	0.0	0.0	0.0	
	ENTHALPY:					
	CAL/MOL	-6.8439+04	-6.8326+04	-6.7987+04	-6.8352+04	
	CAL/GM	-3798.9261	-3792.6752	-3773.8642	-3794.1390	
	CAL/SEC	-3.1770+08	-3.1718+08	-9.7304+07	-9.7827+07	
	ENTROPY:					
	CAL/MOL-K	-39.5644	-39.1799	-38.0695	-39.2692	
	CAL/GM-K	-2.1962	-2.1748	-2.1132	-2.1798	
	DENSITY:					
	MOL/CC	5.5706-02	5.5366-02	5.4341-02	5.5446-02	
	GM/CC	1.0036	0.9974	0.9790	0.9989	
	AVG MW	18.0153	18.0153	18.0153	18.0153	
1	▲ ASPEN PLUS PLAT:	WIN-X64 V	EK: 39.0		03/28/2022	PAGE 9

PROBLEM STATUS SECTION

 Appendix C: Safety Data Sheets

The following section includes the following material safety data sheets, in the order given:

- Water
- Delrin FG100 plastic
- PFOS
- PFOA
- Argon
- HCl
- GAC
- Tungsten
- Calcium Fluoride
- Calcium Sulfate



Water Safety Data Sheet according to Federal Register / Vol. 77, No. 58 / Monday, March 26, 2012 / Rules and Regulations

according to Federal Re Issue date: 11/15/2013

Revision date: 06/26/2020

Supersedes: 06/12/2018

Version: 1.4

SECTION 1: Identification				
1.1. Identification				
Product form :	Substance			
Substance name :	Water			
CAS-No.	7732-18-5			
Product code :	LC26750			
Formula :	H2O			
1.2. Recommended use and restrictions of	n use			
Use of the substance/mixture :	For laboratory and manuf	acturing use only.		
Recommended use :	Laboratory chemicals			
Restrictions on use :	Not for food, drug or hous	ehold use		
1.3. Supplier				
LabChem, Inc.				
1010 Jackson's Pointe Ct.				
Zelienople, PA 16063 - USA				
T 412-826-5230 - F 724-473-0647				
info@labchem.com - www.labchem.com				
1.4. Emergency telephone number				
Emergency number :	CHEMTREC: 1-800-424-9	9300 or +1-703-741-59	970	
SECTION 2: Hazard(s) identification				
2.1. Classification of the substance or mix	ture			
GHS US classification				
Not classified				
2.2. GHS Label elements, including precau	utionary statements			
Not classified as a hazardous chemical.				
Other hazards not contributing to the classification :	None.			
2.4. Unknown acute toxicity (GHS US)				
Not applicable				
SECTION 3: Composition/Information	on ingredients			
3.1. Substances				
Substance type :	Mono-constituent			
Name		Product identifier	%	GHS US classification
Water (Main constituent)		(CAS-No.) 7732-18-5	100	Not classified
Full text of hazard classes and H-statements : see	section 16			·]
3.2. Mixtures				
Not applicable				
SECTION 4: First-aid measures				
4.1. Description of first aid measures				
First-aid measures general : If you feel unwell, seek medical advice (show the label where possible).				
First-aid measures after inhalation : Allow affected person to breathe fresh air. Allow the victim to rest. Adverse effects not expected from this product				
First-aid measures after skin contact	Adverse effects not expect	cted from this product.	Take off contaminat	ed clothing.
First-aid measures after eye contact	Adverse effects not expect	ted from this product.		-
First-aid measures after ingestion : Do NOT induce vomiting. Adverse effects not expected from this product.				

according to Federal Register / Vol. 77, No. 58 / Monday	/, March 26, 2012 / Rules and Regulations			
4.2. Most important symptoms and effe	cts (acute and delayed)			
Potential Adverse human health effects and symptoms	: Based on available data, the classification criteria are not met.			
Symptoms/effects	: Not expected to present a significant hazard under anticipated conditions of normal use.			
4.3. Immediate medical attention and su	pecial treatment, if necessary			
Treat symptomatically.	······································			
SECTION 5: Fire-fighting measures				
5.1 Suitable (and unsuitable) extinguis	hing media			
Suitable extinguishing media	· Foam Dry powder, Carbon dioxide, Water spray, Sand			
5.0 Crecific hererels crising from the c				
5.2. Specific nazaros arising from the c	Not flammable			
5.3. Special protective equipment and p	precautions for fire-fighters			
Firefighting instructions	: Use water spray of tog for cooling exposed containers. Exercise caution when fighting any chemical fire.			
Protection during firefighting	: Do not enter fire area without proper protective equipment, including respiratory protection.			
SECTION 6: Accidental release mea	isures			
6.1. Personal precautions, protective ed	quipment and emergency procedures			
6.1.1. For non-emergency personnel				
Emergency procedures	: Evacuate unnecessary personnel.			
612 For omorgonou responders				
Protective equipment	Equip cleanup crew with proper protection			
Emergency procedures	· Ventilate area			
6.2. Environmental precautions Prevent entry to sewers and public waters. Noti	fy authorities if liquid enters sewers or public waters.			
6.3. Methods and material for containm	ent and cleaning up			
Methods for cleaning up	: Soak up spills with inert solids, such as clay or diatomaceous earth as soon as possible.			
6.4. Reference to other sections				
See Heading 8. Exposure controls and persona	I protection.			
SECTION 7: Handling and storage				
SECTION 7. Handling and storage				
7.1. Precautions for safe handling	· Week hands and other expanded areas with mild seen and water before esting drinking or			
Frecautions for sale nationing	smoking and when leaving work.			
7.2. Conditions for safe storage, includ	ing any incompatibilities			
Storage conditions	: Keep container closed when not in use.			
Incompatible products	: Metallic sodium.			
Incompatible materials	: Sources of ignition. Direct sunlight.			
SECTION 8: Exposure controls/personal protection				
8.1. Control parameters				
control parametero				
Water (7732-18-5)				
No additional information available				
8.2. Appropriate engineering controls				
Appropriate engineering controls	: Provide adequate general and local exhaust ventilation.			
	1 3			

8.3. Individual protection measures/Personal protective equipment

Personal protective equipment:

Safety glasses.

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Water

Safety Data Sheet

Water

Safety Data Sheet

according to Federal Register / Vol. 77, No. 58 / Monday, March 26, 2012 / Rules and Regulations

Eye protection:

Chemical goggles or safety glasses

Respiratory protection:

None necessary.

Personal protective equipment symbol(s):



Other information:

Do not eat, drink or smoke during use.

SECTION 9: Physical and chemical p	roperties				
9.1. Information on basic physical and cl	9.1. Information on basic physical and chemical properties				
Physical state	: Liquid				
Color	: Colorless				
Odor	: None.				
Odor threshold	: No data available				
pH	: 7				
Melting point	: 0°C				
Freezing point	: No data available				
Boiling point	: 100 °C				
Critical temperature	: 374.1 °C				
Critical pressure	: 218.3 atm				
Flash point	: No data available				
Relative evaporation rate (butyl acetate=1)	: No data available				
Flammability (solid, gas)	: Non flammable.				
Vapor pressure	: 17.535 mm Hg				
Vapor pressure at 50 °C	: 92.51 mm Hg				
Relative vapor density at 20 °C	: No data available				
Relative density	: 1				
Specific gravity / density	: 0.99823 g/ml				
Molecular mass	: 18 g/mol				
Solubility	 Soluble in acetic acid. Soluble in acetone. Soluble in ammonia. Soluble in ammonium chloride. Soluble in ethanol. Soluble in glycerol. Soluble in hydrochloric acid. Soluble in methanol. Soluble in nitric acid. Soluble in sulfuric acid. Soluble in sodium hydroxide solution. Soluble in propylene glycol. 				
Log Pow	: No data available				
Auto-ignition temperature	: No data available				
Decomposition temperature	: No data available				
Viscosity, kinematic	: 1.004 mm²/s				
Viscosity, dynamic	: 1.002 cP				
Explosion limits	: No data available				
Explosive properties	: Not applicable.				
Oxidizing properties	: None.				
9.2. Other information					
VOC content	: 0%				
SECTION 10: Stability and reactivity					
10.1. Reactivity					

No additional information available

Water

Safety Data Sheet

according to Federal Register / Vol. 77, No. 58 / Monday, March 26, 2012 / Rules and Regulations

10.2. Chemical stability	
Stable under normal conditions.	
10.3. Possibility of hazardous reactions	
Not established.	
10.4. Conditions to avoid	
Extremely high or low temperatures.	
10.5. Incompatible materials	
Metallic sodium.	
10.6. Hazardous decomposition products	
Hydrogen. oxygen.	
SECTION 11: Toxicological information	n
11.1. Information on toxicological effects	
Acute toxicity (oral)	Not classified
Acute toxicity (dermal)	Not classified
Acute toxicity (inhalation)	Not classified
Water (7732-18-5)	
LD50 oral rat	≥ 90000 mg/kg
ATE US (oral)	90000 mg/kg body weight
Skin corrosion/irritation	Not classified
	pH: 7
Serious eye damage/irritation	Not classified
Peopirotony or akin consitization	pH: 7
Carcinogenicity	Not classified (Based on available data, the classification criteria are not met)
Poproductive toxicity	
STOT-single exposure	Not classified
STOT-repeated exposure	Not classified
Aspiration hazard	Not classified
Viscosity, kinematic	1.004 mm²/s
Likely routes of exposure	Skin and eye contact.
Potential Adverse human health effects and	Based on available data, the classification criteria are not met.
symptoms	
Symptoms/effects	Not expected to present a significant nazard under anticipated conditions of normal USE.

SECTION 12: Ecological information 12.1. Toxicity

No additional information available

12.2. Persistence and degradability	
Water (7732-18-5)	
Persistence and degradability	Not established.
12.3 Bioaccumulative potential	
Water (7722 19 5)	
Water (1152-10-5)	
Bioaccumulative potential	Not established.
12.4. Mobility in soil	
No additional information available	

12.5. Other adverse effects

Water

Safety Data Sheet

according to Federal Register / Vol. 77, No. 58 / Monday, March 26, 2012 / Rules and Regulations

Other information

: No other effects known.

SECTION 13: Disposal considerations

13.1. Disposal methods

Waste disposal recommendations

: Dispose in a safe manner in accordance with local/national regulations.

SECTION 14: Transport information

Department of Transportation (DOT)

In accordance with DOT

Not regulated

Transport by sea

Not regulated

Air transport

Not regulated

SECTION 15: Regulatory information

15.1. US Federal regulations

Water (7732-18-5)

Listed on the United States TSCA (Toxic Substances Control Act) inventory

All components of this product are listed, or excluded from listing, on the United States Environmental Protection Agency Toxic Substances Control Act (TSCA) inventory

15.2. International regulations

CANADA Water (7732-18-5) Listed on the Canadian DSL (Domestic Substances List) EU-Regulations No additional information available National regulations No additional information available 15.3. US State regulations

California Proposition 65 - This product does not contain any substances known to the state of California to cause cancer, developmental and/or reproductive harm

SECTION 16: Other information

according to Federal Register / Vol. 77, No. 58 / Monday, March 26, 2012 / Rules and Regulations

Revision date	: 06/26/2020
Other information	: None.
NFPA health hazard	: 0 - Materials that, under emergency conditions, would offer no hazard beyond that of ordinary combustible materials.
NFPA fire hazard	: 0 - Materials that will not burn under typical fire conditions, including intrinsically noncombustible materials such as concrete, stone, and sand.
NFPA reactivity	: 0 - Material that in themselves are normally stable, even under fire conditions.

Water Safety Data Sheet

according to Federal Register / Vol. 77, No. 58 / Monday, March 26, 2012 / Rules and Regulations

Hazard Rating	
Health	: 0 Minimal Hazard - No significant risk to health
Flammability	: 0 Minimal Hazard - Materials that will not burn
Physical	: 0 Minimal Hazard - Materials that are normally stable, even under fire conditions, and will NOT react with water, polymerize, decompose, condense, or self-react. Non-Explosives.
Personal protection	: A
	A - Safety glasses

SDS US LabChem

Information in this SDS is from available published sources and is believed to be accurate. No warranty, express or implied, is made and LabChem Inc assumes no liability resulting from the use of this SDS. The user must determine suitability of this information for his application.

US

Safety Data Sheet acc. to OSHA HCS

Printing date 03/23/2019

Version Number 2

Reviewed on 03/23/2019

Product i	dentifier
Trade na	me: Perfluorooctanoic Acid (PFOA)
Part num CAS Nun 335-67-1 EC numb 206-397-9	ber: N-1588 nber: er:
Index nui 607-704-0 Application	nber: 10-2 on of the substance / the mixture Reagents and Standards for Analytical Chemical Laboratory Us
Details of Manufact Agilent Te 5301 Stev Santa Clar	the supplier of the safety data sheet turer/Supplier: echnologies, Inc. ens Creek Blvd. ra, CA 95051 USA
Informati Telephone e-mail: po Emergeno	on department: :: 800-227-9770 il-msds_author@agilent.com cy telephone number: CHEMTREC®: 1-800-424-9300
Hazard	(s) identification
Classifica	tion of the substance or mixture GHS08 Health hazard

Repr. 1BH360May damage fertility or the unborn child.STOT RE 1H372Causes damage to the liver through prolonged or repeated exposure.

GHS05 Corrosion

Eye Dam. 1 H318 Causes serious eye damage.

GHS07

Acute Tox. 4 H302 Harmful if swallowed. Acute Tox. 4 H332 Harmful if inhaled.

· Label elements

• GHS label elements The substance is classified and labeled according to the Globally Harmonized System (GHS). (Contd. on page 2)

Safety Data Sheet acc. to OSHA HCS

Reviewed on 03/23/2019

Version Number 2

Trade name: Perfluorooctanoic Acid (PFOA)

(Contd. of page 1) · Hazard pictograms GHS05 GHS07 GHS08 · Signal word Danger · Hazard-determining components of labeling: perfluorooctanoic acid (PFOA) · Hazard statements Harmful if swallowed or if inhaled. Causes serious eye damage. Suspected of causing cancer. May damage fertility or the unborn child. Causes damage to the liver through prolonged or repeated exposure. **Precautionary statements** Obtain special instructions before use. Do not handle until all safety precautions have been read and understood. Do not breathe dust/fume/gas/mist/vapors/spray. Wash thoroughly after handling. Do not eat, drink or smoke when using this product. Use only outdoors or in a well-ventilated area. Wear protective gloves/protective clothing/eye protection/face protection. If swallowed: Call a poison center/doctor if you feel unwell. Rinse mouth. IF INHALED: Remove person to fresh air and keep comfortable for breathing. If in eyes: Rinse cautiously with water for several minutes. Remove contact lenses, if present and easy to do. Continue rinsing. Immediately call a poison center/doctor. IF exposed or concerned: Get medical advice/attention. Get medical advice/attention if you feel unwell. Store locked up. Dispose of contents/container in accordance with local/regional/national/international regulations. · Classification system: · NFPA ratings (scale 0 - 4) Health = 3Fire = 0Reactivity = 0· HMIS-ratings (scale 0 - 4) HEALTH *3 Health = *3FIRF 0 Fire = 0Reactivity = 0**REACTIVITY** 0

- · Other hazards
- · Results of PBT and vPvB assessment
- **PBT:** Not applicable.

(Contd. on page 3)

US



Printing date 03/23/2019

Safety Data Sheet acc. to OSHA HCS

Reviewed on 03/23/2019

Trade name: Perfluorooctanoic Acid (PFOA)

(Contd. of page 2)

• **vPvB:** Not applicable.

3 Composition/information on ingredients

· Chemical characterization: Substances

- · CAS No. Description
- 335-67-1 perfluorooctanoic acid (PFOA)
- · Identification number(s)
- EC number: 206-397-9
- · Index number: 607-704-00-2

4 First-aid measures

 \cdot Description of first aid measures

· General information:

Symptoms of poisoning may even occur after several hours; therefore medical observation for at least 48 hours after the accident.

· After inhalation:

Supply fresh air. If required, provide artificial respiration. Keep patient warm. Consult doctor if symptoms persist. In case of unconsciousness place patient stably in side position for transportation.

- After skin contact: Generally the product does not irritate the skin.
- · After eye contact: Rinse opened eye for several minutes under running water. Then consult a doctor.
- After swallowing: Immediately call a doctor.
- · Information for doctor:
- · Most important symptoms and effects, both acute and delayed No further relevant information available.
- · Indication of any immediate medical attention and special treatment needed
- No further relevant information available.

5 Fire-fighting measures

- · Extinguishing media
- Suitable extinguishing agents: Use fire fighting measures that suit the environment.
- · Special hazards arising from the substance or mixture
- During heating or in case of fire poisonous gases are produced.
- · Advice for firefighters
- · Protective equipment: Mouth respiratory protective device.

6 Accidental release measures

- **Personal precautions, protective equipment and emergency procedures** Mount respiratory protective device. Wear protective equipment. Keep unprotected persons away.
- Environmental precautions: Do not allow to enter sewers/ surface or ground water.
- Methods and material for containment and cleaning up: Use neutralizing agent.

Dispose contaminated material as waste according to item 13. Ensure adequate ventilation.

(Contd. on page 4)



Version Number 2

Printing date 03/23/2019

US
Reviewed on 03/23/2019

Trade name: Perfluorooctanoic Acid (PFOA)

(Contd. of page 3)

· Reference to other sections

See Section 7 for information on safe handling.

See Section 8 for information on personal protection equipment.

See Section 13 for disposal information.

· Protective Action Criteria for Chemicals

PAC-1:	
	1.1 mg/m³
· PAC-2:	
	12 mg/m ³
· PAC-3:	
	75 mg/m ³

7 Handling and storage

· Handling:

· Precautions for safe handling

Thorough dedusting.

Ensure good ventilation/exhaustion at the workplace.

Open and handle receptacle with care.

· Information about protection against explosions and fires: Keep respiratory protective device available.

· Conditions for safe storage, including any incompatibilities

· Storage:

• Requirements to be met by storerooms and receptacles: No special requirements.

· Information about storage in one common storage facility: Not required.

• Further information about storage conditions: Keep receptacle tightly sealed.

• Specific end use(s) No further relevant information available.

*

8 Exposure controls/personal protection

• Additional information about design of technical systems: No further data; see item 7.

- · Control parameters
- Components with limit values that require monitoring at the workplace: Not required.
- · Additional information: The lists that were valid during the creation were used as basis.
- · Exposure controls
- · Personal protective equipment:
- · General protective and hygienic measures:
- Keep away from foodstuffs, beverages and feed.

Immediately remove all soiled and contaminated clothing.

Wash hands before breaks and at the end of work.

Store protective clothing separately.

Avoid contact with the eyes.

Avoid contact with the eyes and skin.

[•] Breathing equipment:

When used as intended with Agilent instruments, the use of the product under normal laboratory conditions and with standard practices does not result in significant airborne exposures and therefore respiratory protection is not needed.

Under an emergency condition where a respirator is deemed necessary, use a NIOSH or equivalent approved device/equipment with appropriate organic or acid gas cartridge.



Printing date 03/23/2019

Reviewed on 03/23/2019

Trade name: Perfluorooctanoic Acid (PFOA)

(Contd. of page 4)

• **Protection of hands:** Although not recommended for constant contact with the chemicals or for clean-up, nitrile gloves 11-13 mil thickness are recommended for normal use. The breakthrough time is 1 hr. For cleaning a spill where there is direct contact of the chemical, butyl rubber gloves are recommended 12-15 mil thickness with breakthrough times exceeding 4 hrs. Supplier recommendations should be followed.

· Material of gloves

For normal use: nitrile rubber, 11-13 mil thickness

For direct contact with the chemical: butyl rubber, 12-15 mil thickness

The selection of the suitable gloves does not only depend on the material, but also on further marks of quality and varies from manufacturer to manufacturer.

· Penetration time of glove material

- For normal use: nitrile rubber: 1 hour
- For direct contact with the chemical: butyl rubber: >4 hours
- Eye protection:



Tightly sealed goggles

Information on basic physical and c	chemical properties	
General Information		
Appearance:	0.171	
Form: Calary	Solid National	
Color: Odor:	Not determined.	
Odor threshold:	Not determined.	
pH-value:	Not applicable.	
Change in condition		
Melting point/Melting range:	55-56 °C (131-132.8 °F)	
Boiling point/Boiling range:	190 °C (374 °F)	
Flash point:	Not applicable.	
Flammability (solid, gaseous):	Product is not flammable.	
Decomposition temperature:	Not determined.	
Auto igniting:	Not determined.	
Danger of explosion:	Product does not present an explosion hazard.	
Explosion limits:		
Lower:	Not determined.	
Upper:	Not determined.	
Vapor pressure at 20 °C (68 °F):	0.69 hPa (0.5 mm Hg)	
Density at 20 °C (68 °F):	0.9 g/cm ³ (7.5105 lbs/gal)	
Relative density	Not determined.	
Vapor density	Not applicable.	



Printing date 03/23/2019

Reviewed on 03/23/2019

Trade name: Perfluorooctanoic Acid (PFOA)

		(Contd. of page
• Evaporation rate	Not applicable.	
Solubility in / Miscibility with Water at 20 °C (68 °F):	3.4 g/l	
Partition coefficient (n-octanol/wa	ter): Not determined.	
Viscosity:		
Dynamic:	Not applicable.	
Kinematic:	Not applicable.	
VOC content:	0.00 %	
	0.0 g/l / 0.00 lb/gal	
Solids content:	100.0 %	
Other information	No further relevant information available.	

10 Stability and reactivity

· Reactivity No further relevant information available.

- · Chemical stability
- Thermal decomposition / conditions to be avoided: No decomposition if used according to specifications.
- · Possibility of hazardous reactions No dangerous reactions known.
- · Conditions to avoid No further relevant information available.
- · Incompatible materials: No further relevant information available.
- · Hazardous decomposition products: No dangerous decomposition products known.

11 Toxicological information

· Information on toxicological effects

• Acute toxicity:

· LD/LC50 values that are relevant for classification:

ATE (Acute Toxicity Estimate)

Oral	LD50	500 mg/kg
------	------	-----------

Inhalative LC50/4 h 1.5 mg/L

Primary irritant effect:

- on the skin: No irritant effect.
- on the eye: Strong irritant with the danger of severe eye injury.
- · Sensitization: No sensitizing effects known.

· Additional toxicological information:

· Carcinogenic categories

· IARC (International Agency for Research on Cancer)

· NTP (National Toxicology Program)

Substance is not listed.

(Contd. on page 7)

2B



Printing date 03/23/2019

Version Number 2

Reviewed on 03/23/2019

Trade name: Perfluorooctanoic Acid (PFOA)

· OSHA-Ca (Occupational Safety & Health Administration)

Substance is not listed.

Printing date 03/23/2019

12 Ecological information

· Toxicity

- · Aquatic toxicity: No further relevant information available.
- · Persistence and degradability No further relevant information available.
- · Behavior in environmental systems:
- · Bioaccumulative potential No further relevant information available.
- · Mobility in soil No further relevant information available.
- · Additional ecological information:

· General notes:

Water hazard class 2 (Assessment by list): hazardous for water

Do not allow product to reach ground water, water course or sewage system. Must not reach bodies of water or drainage ditch undiluted or unneutralized.

Danger to drinking water if even small quantities leak into the ground.

- · Results of PBT and vPvB assessment
- **PBT:** Not applicable.
- **vPvB:** Not applicable.
- · Other adverse effects No further relevant information available.

13 Disposal considerations

· Waste treatment methods

· Recommendation:

Must not be disposed of together with household garbage. Do not allow product to reach sewage system.

· Uncleaned packagings:

· Recommendation: Disposal must be made according to official regulations.

UN-Number	
DOT, IMDG, IATA	UN3261
UN proper shipping name	
DOT	Corrosive solid, acidic, organic, n.o.s. (perfluorooctanoic acid (PFOA))
IMDG, IATA	CORROSIVE SOLID, ACIDIC, ORGANIC, N.O.S.
	(perfluorooctanoic acid (PFOA))



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Reviewed on 03/23/2019

Printing date 03/23/2019

Version Number 2

Trade name:	Perfluorooctanoic Acid	(PFOA))
		(-)	

	(Contd. of page 7
· Transport hazard class(es)	
·IATA	
· Class	8 Corrosive substances
· Label	8
· Environmental hazards:	Not applicable.
· Special precautions for user	Warning: Corrosive substances
· Danger code (Kemler):	80
· EMS Number:	F-A,S-B
· Segregation groups	Acids
• Transport in bulk according to Annex I MARPOL73/78 and the IBC Code	II of Not applicable.
· Transport/Additional information:	
· Quantity limitations	On passenger aircraft/rail: 25 kg
	On cargo aircraft only: 100 kg
·IMDG	
· Limited quantities (LO)	5 kg
· Excepted quantities (EQ)	Code: E1
	Maximum net quantity per inner packaging: 30 g
	Maximum net quantity per outer packaging: 1000 g
· UN "Model Regulation":	UN 3261 CORROSIVE SOLID, ACIDIC, ORGANIC, N.O.S. (PERFLUOROOCTANOIC ACID (PFOA)), 8, III

15 Regulatory information

· Safety, health and environmental regulations/legislation specific for the substance or mixture · Sara

· Section 355 (extremely hazardous substances): Substance is not listed. · Section 313 (Specific toxic chemical listings): Substance is not listed. · TSCA (Toxic Substances Control Act): Substance is listed. · Proposition 65 · Chemicals known to cause cancer: Substance is not listed. · Chemicals known to cause reproductive toxicity for females: Substance is not listed. (Contd. on page 9) US



Version Number 2

Reviewed on 03/23/2019

Trade name: Perfluorooctanoic Acid (PFOA)

· Chemicals known to cause reproductive toxicity for males:

Substance is not listed.

· Chemicals known to cause developmental toxicity:

Substance is listed.

Printing date 03/23/2019

· Carcinogenic categories

· EPA (Environmental Protection Agency)

· TLV (Threshold Limit Value established by ACGIH)

Substance is not listed.

Substance is not listed.

· NIOSH-Ca (National Institute for Occupational Safety and Health)

Substance is not listed.

· Chemical safety assessment: A Chemical Safety Assessment has not been carried out.

16 Other information

The information contained in this document is based on Agilent's state of knowledge at the time of preparation. No warranty as to its accurateness, completeness or suitability for a particular purpose is expressed or implied.

· Date of preparation / last revision 03/23/2019 / 1

· Abbreviations and acronyms:

ADR: Accord européen sur le transport des marchandises dangereuses par Route (European Agreement concerning the International Carriage of Dangerous Goods by Road) IMDG: International Maritime Code for Dangerous Goods

DOT: US Department of Transportation

IATA: International Air Transport Association

ACGIH: American Conference of Governmental Industrial Hygienists

EINECS: European Inventory of Existing Commercial Chemical Substances CAS: Chemical Abstracts Service (division of the American Chemical Society)

NFPA: National Fire Protection Association (USA)

HMIS: Hazardous Materials Identification System (USA)

VOC: Volatile Organic Compounds (USA, EU)

LC50: Lethal concentration, 50 percent

- LD50: Lethal dose, 50 percent
- PBT: Persistent, Bioaccumulative and Toxic

vPvB: very Persistent and very Bioaccumulative

NIOSH: National Institute for Occupational Safety

OSHA: Occupational Safety & Health

TLV: Threshold Limit Value

PEL: Permissible Exposure Limit

REL: Recommended Exposure Limit Acute Tox. 4: Acute toxicity – Category 4

Eye Dam. 1: Serious eye damage/eye irritation – Category 1

Carc. 2: Carcinogenicity – Category 2

Repr. 1B: Reproductive toxicity – Category 1B

STOT RE 1: Specific target organ toxicity (repeated exposure) - Category 1

* Data compared to the previous version altered.



(Contd. of page 8)

Printing date 04/01/2019

qilent

Version Number 2

Reviewed on 04/01/2019

1 Identification

- · Product identifier
- · Trade name: PFOA/PFOS Standard (1X1 mL)
- · Part number: PFM-100-1
- · Application of the substance / the mixture Reagents and Standards for Analytical Chemical Laboratory Use
- · Details of the supplier of the safety data sheet

• Manufacturer/Supplier: Agilent Technologies, Inc. 5301 Stevens Creek Blvd. Santa Clara, CA 95051 USA

· Information department:

Telephone: 800-227-9770 e-mail: pdl-msds_author@agilent.com • Emergency telephone number: CHEMTREC®: 1-800-424-9300

2 Hazard(s) identification

· Classification of the substance or mixture

GHS02 Flame

Flam. Liq. 2 H225 Highly flammable liquid and vapor.

GHS06 Skull and crossbones

Acute Tox. 3 H331 Toxic if inhaled.

GHS08 Health hazard

Carc. 2 H351 Suspected of causing cancer.

Repr. 1B H360 May damage fertility or the unborn child.

STOT SE 1 H370 Causes damage to organs.

· Label elements

• GHS label elements The product is classified and labeled according to the Globally Harmonized System (GHS). • Hazard pictograms



· Signal word Danger

• **Hazard-determining components of labeling:** methanol perfluorooctanoic acid (PFOA) perfluorooctane sulfonic acid (PFOS)

(Contd. on page 2)

Reviewed on 04/01/2019

Trade name: PFOA/PFOS Standard (1X1 mL)

(Contd. of page 1) · Hazard statements Highly flammable liquid and vapor. Toxic if inhaled. Suspected of causing cancer. May damage fertility or the unborn child. Causes damage to organs. **Precautionary statements** Obtain special instructions before use. Do not handle until all safety precautions have been read and understood. Keep away from heat/sparks/open flames/hot surfaces. - No smoking. Ground/bond container and receiving equipment. Use explosion-proof electrical/ventilating/lighting/equipment. Use only non-sparking tools. Take precautionary measures against static discharge. Do not breathe dust/fume/gas/mist/vapors/spray. Wash thoroughly after handling. Do not eat, drink or smoke when using this product. Use only outdoors or in a well-ventilated area. Wear protective gloves/protective clothing/eye protection/face protection. If on skin (or hair): Take off immediately all contaminated clothing. Rinse skin with water/shower. IF INHALED: Remove person to fresh air and keep comfortable for breathing. IF exposed or concerned: Get medical advice/attention. Specific treatment (see on this label). In case of fire: Use for extinction: CO2, powder or water spray. Store in a well-ventilated place. Keep container tightly closed. Store in a well-ventilated place. Keep cool. Store locked up. Dispose of contents/container in accordance with local/regional/national/international regulations. · Classification system: • NFPA ratings (scale 0 - 4) Health = 1Fire = 3Reactivity = 0· HMIS-ratings (scale 0 - 4) HEALTH ^{*1} Health = *1FIRE 3 Fire = 3**REACTIVITY** Reactivity = 0· Other hazards · Results of PBT and vPvB assessment • **PBT:** Not applicable. • **vPvB**: Not applicable.

3 Composition/information on ingredients

· Chemical characterization: Mixtures

• Description: Mixture of the substances listed below with nonhazardous additions.

(Contd. on page 3)

US

Printing date 04/01/2019

Agilent

Reviewed on 04/01/2019

Trade name: PFOA/PFOS Standard (1X1 mL)

	(Con	td. of page 2)
· Dangerous	s components:	
67-56-1	methanol	99.747%
335-67-1	perfluorooctanoic acid (PFOA)	0.126%
1763-23-1	perfluorooctane sulfonic acid (PFOS)	0.126%

4 First-aid measures

· Description of first aid measures

• General information:

Immediately remove any clothing soiled by the product.

Remove breathing apparatus only after contaminated clothing have been completely removed.

In case of irregular breathing or respiratory arrest provide artificial respiration.

· After inhalation:

Supply fresh air or oxygen; call for doctor.

In case of unconsciousness place patient stably in side position for transportation.

- After skin contact: Immediately wash with water and soap and rinse thoroughly.
- After eye contact: Rinse opened eye for several minutes under running water. Then consult a doctor.
- After swallowing: If symptoms persist consult doctor.

· Information for doctor:

• Most important symptoms and effects, both acute and delayed No further relevant information available.

Indication of any immediate medical attention and special treatment needed

No further relevant information available.

5 Fire-fighting measures

- · Extinguishing media
- · Suitable extinguishing agents:

CO2, extinguishing powder or water spray. Fight larger fires with water spray or alcohol resistant foam.

- For safety reasons unsuitable extinguishing agents: Water with full jet
- Special hazards arising from the substance or mixture
- During heating or in case of fire poisonous gases are produced.
- · Advice for firefighters
- · Protective equipment: Mouth respiratory protective device.

6 Accidental release measures

- **Personal precautions, protective equipment and emergency procedures** Mount respiratory protective device. Wear protective equipment. Keep unprotected persons away.
- Environmental precautions: Do not allow to enter sewers/ surface or ground water.
- Methods and material for containment and cleaning up: Absorb with liquid-binding material (sand, diatomite, acid binders, universal binders, sawdust). Dispose contaminated material as waste according to item 13. Ensure adequate ventilation.
- Reference to other sections

See Section 7 for information on safe handling.

See Section 8 for information on personal protection equipment.

See Section 13 for disposal information.

(Contd. on page 4)



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Printing date 04/01/2019

Reviewed on 04/01/2019

Trade name: PFOA/PFOS Standard (1X1 mL)

Printing date 04/01/2019

· Protectiv	e Action Criteria for Chemicals	(Contd. of page 3)
· PAC-1:		
67-56-1	methanol	530 ppm
335-67-1	perfluorooctanoic acid (PFOA)	1.1 mg/m ³
· PAC-2:		
67-56-1	methanol	2,100 ppm
335-67-1	perfluorooctanoic acid (PFOA)	12 mg/m ³
· PAC-3:		
67-56-1	methanol	7200* ppm
335-67-1	perfluorooctanoic acid (PFOA)	75 mg/m ³

7 Handling and storage

· Handling:

- · Precautions for safe handling
- Ensure good ventilation/exhaustion at the workplace. Open and handle receptacle with care.
- Prevent formation of aerosols.
- · Information about protection against explosions and fires: Keep ignition sources away - Do not smoke. Protect against electrostatic charges. Keep respiratory protective device available.
- · Conditions for safe storage, including any incompatibilities
- · Storage:
- Requirements to be met by storerooms and receptacles: Store in a cool location.
- Information about storage in one common storage facility: Not required.
- · Further information about storage conditions:
- Keep receptacle tightly sealed.
- Store in cool, dry conditions in well sealed receptacles.
- Specific end use(s) No further relevant information available.

8 Exposure controls/personal protection

• Additional information about design of technical systems: No further data; see item 7.

· Control parameters

DEL		
PEL	Long-term value: 260 mg/m ³ , 200 ppm	
REL	Short-term value: 325 mg/m ³ , 250 ppm	
	Long-term value: 260 mg/m ³ , 200 ppm	
	Skin	
TLV	Short-term value: 328 mg/m ³ , 250 ppm	
	Long-term value: 262 mg/m ³ , 200 ppm	
	Skin ⁻ BEI	



Reviewed on 04/01/2019

Agilent

Printing date 04/01/2019

Version Number 2

Trade name: PFOA/PFOS Standard (1X1 mL)

Ingre	edients with biological limit values:
67-50	5-1 methanol
BEI	15 mg/L
	Medium: urine
	Time: end of shift
	Parameter: Methanol (background, nonspecific)
Addi	tional information: The lists that were valid during the creation were used as basis.
Expo	osure controls
Perso	onal protective equipment:
Gene	eral protective and hygienic measures:
Keep	away from foodstuffs, beverages and feed.
Imme	ediately remove all soiled and contaminated clothing.
Wash	hands before breaks and at the end of work.
Store	protective clothing separately.
Brea	thing equipment:
When	n used as intended with Agilent instruments, the use of the product under normal laboratory conditions and
with	standard practices does not result in significant airborne exposures and therefore respiratory protection is n
neede	su. In an amarganay condition where a requireter is deemed necessary, use a NIOSU or equivalent entroyed.
daria	an emergency condition where a respirator is deemed necessary, use a NIOSH of equivalent approved
Drote	e/equipment with appropriate organic of actu gas cartiluge.
Altho	with not recommended for constant contact with the chemicals or for clean-up, nitrile gloves 11-13 mil
thick	ness are recommended for normal use. The breakthrough time is 1 hr. For cleaning a spill where there is
direct	t contact of the chemical butyl rubber gloves are recommended 12-15 mil thickness with breakthrough tim
excer	eding 4 hrs Supplier recommendations should be followed
Mate	rial of gloves
For n	ormal use: nitrile rubber, 11-13 mil thickness
For d	lirect contact with the chemical: butyl rubber, 12-15 mil thickness
Pene	tration time of glove material
For n	ormal use: nitrile rubber: 1 hour
For d	lirect contact with the chemical: butyl rubber: >4 hours
Eye ı	protection:
	Tightly seeled goggles
5	

9 Physical and chemical properties • Information on basic physical and chemical properties • General Information • Appearance: • Form: Fluid Color: Colorless • Odor: Alcohol-like • Odor threshold: Not determined.

Reviewed on 04/01/2019

Printing date 04/01/2019

Version Number 2

Trade name:	PFOA/PFOS	Standard	(1X1 mL))
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	(Contd. of page 5)
 Change in condition Melting point/Melting range: Boiling point/Boiling range: 	-98 °C (-144.4 °F) 64.7 °C (148.5 °F)
· Flash point:	9 °C (48.2 °F)
· Flammability (solid, gaseous):	Not applicable.
· Ignition temperature:	455 °C (851 °F)
• Decomposition temperature:	Not determined.
· Auto igniting:	Product is not selfigniting.
Danger of explosion:	Product is not explosive. However, formation of explosive air/vapor mixtures are possible.
· Explosion limits: Lower: Upper:	5.5 Vol % 44 Vol %
· Vapor pressure at 20 °C (68 °F):	100 hPa (75 mm Hg)
Density at 20 °C (68 °F): Relative density Vapor density Evaporation rate	0.8007 g/cm ³ (6.68184 lbs/gal) Not determined. Not determined. Not determined.
· Solubility in / Miscibility with Water:	Not miscible or difficult to mix.
· Partition coefficient (n-octanol/water	r): Not determined.
· Viscosity: Dynamic: Kinematic:	Not determined. Not determined.
• Solvent content: Organic solvents: VOC content:	99.7 % 99.75 % 798.7 g/l / 6.67 lb/gal
Solids content: Other information	0.3 % No further relevant information available.

10 Stability and reactivity

- · Reactivity No further relevant information available.
- Chemical stability
- Thermal decomposition / conditions to be avoided: No decomposition if used according to specifications.
- Possibility of hazardous reactions No dangerous reactions known.
- · Conditions to avoid No further relevant information available.
- · Incompatible materials: No further relevant information available.
- · Hazardous decomposition products: No dangerous decomposition products known.

(Contd. on page 7)

US



Reviewed on 04/01/2019

Trade name: PFOA/PFOS Standard (1X1 mL)

11 Toxicological information

· Information on toxicological effects

· Acute toxicity:

Printing date 04/01/2019

· LD/LC50 values that are relevant for classification:

ATE (Acute Toxicity Estimate)

Inhalative LC50/4 h 3.01 mg/L

67-56-1 methanol

Oral	LD50	5,628 mg/kg (rat)
------	------	-------------------

Dermal LD50 15,800 mg/kg (rabbit)

1763-23-1 perfluorooctane sulfonic acid (PFOS)

Oral LD50 154 mg/kg (rat)

Primary irritant effect:

- on the skin: No irritant effect.
- on the eye: No irritating effect.
- Sensitization: No sensitizing effects known.
- · Additional toxicological information:

The product shows the following dangers according to internally approved calculation methods for preparations: Toxic

· Carcinogenic categories

· IARC (International Agency for Research on Cancer)

335-67-1 perfluorooctanoic acid (PFOA)

· NTP (National Toxicology Program)

None of the ingredients is listed.

OSHA-Ca (Occupational Safety & Health Administration)

None of the ingredients is listed.

12 Ecological information

· Toxicity

- Aquatic toxicity: No further relevant information available.
- · Persistence and degradability No further relevant information available.
- · Behavior in environmental systems:
- · Bioaccumulative potential No further relevant information available.
- Mobility in soil No further relevant information available.
- Additional ecological information:

· General notes:

Water hazard class 2 (Self-assessment): hazardous for water

Do not allow product to reach ground water, water course or sewage system.

Danger to drinking water if even small quantities leak into the ground.

- · Results of PBT and vPvB assessment
- **PBT:** Not applicable.
- **vPvB:** Not applicable.



Version Number 2

(Contd. of page 6)

2B

Version Number 2

Reviewed on 04/01/2019

Trade name: PFOA/PFOS Standard (1X1 mL)

• Other adverse effects No further relevant information available.

13 Disposal considerations

· Waste treatment methods

· Recommendation:

Printing date 04/01/2019

Must not be disposed of together with household garbage. Do not allow product to reach sewage system.

- · Uncleaned packagings:
- Recommendation: Disposal must be made according to official regulations.

Not Regulated, De minimus Quant	ities -	
· UN-Number · DOT, IMDG, IATA	UN1230	
· UN proper shipping name · DOT · IMDG, IATA	Methanol solution METHANOL solution	
· Transport hazard class(es)		
DOT		
· Class · Label	3 Flammable liquids 3, 6.1	
· IMDG		
Class	3 Flammable liquids	
· Label	3/6.1	
Class	3 Flammable liquids	
· Label	3 (6.1)	
Packing group DOT, IMDG, IATA	Π	
Fnvironmental hazards.	Not applicable	



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(Contd. of page 7)

Reviewed on 04/01/2019

Trade name: PFOA/PFOS Standard (1X1 mL)

	(Contd. of page 8)
· Special precautions for user	Warning: Flammable liquids
Danger code (Kemler):	336
EMS Number:	F-E,S-D
 Stowage Category 	В
· Stowage Code	SW2 Clear of living quarters.
· Transport in bulk according to Annex II	of
MARPOL73/78 and the IBC Code	Not applicable.
· Transport/Additional information:	
DOT	
 Quantity limitations 	On passenger aircraft/rail: 1 L
	On cargo aircraft only: 60 L
·IMDG	
· Limited quantities (LQ)	1L
 Excepted quantities (EQ) 	Code: E2
	Maximum net quantity per inner packaging: 30 ml
	Maximum net quantity per outer packaging: 500 ml
· UN "Model Regulation":	UN 1230 METHANOL SOLUTION, 3 (6.1), II

15 Regulatory information

· Safety, health and environmental regulations/legislation specific for the substance or mixture · Sara

· Section 355 (extremely hazardous substances):

None of the ingredients is listed.

· Section 313 (Specific toxic chemical listings):

67-56-1 methanol

• TSCA (Toxic Substances Control Act):

All ingredients are listed.

TSCA new (21st Century Act): (Substances not listed)

1763-23-1 perfluorooctane sulfonic acid (PFOS)

· Proposition 65

· Chemicals known to cause cancer:

None of the ingredients is listed.

· Chemicals known to cause reproductive toxicity for females:

None of the ingredients is listed.

· Chemicals known to cause reproductive toxicity for males:

None of the ingredients is listed.

· Chemicals known to cause developmental toxicity:

All ingredients are listed.

(Contd. on page 10)

US



Printing date 04/01/2019

Reviewed on 04/01/2019

Trade name: PFOA/PFOS Standard (1X1 mL)

(Contd. of page 9)

· Carcinogenic categories

· EPA (Environmental Protection Agency)

None of the ingredients is listed.

• TLV (Threshold Limit Value established by ACGIH)

None of the ingredients is listed.

· NIOSH-Ca (National Institute for Occupational Safety and Health)

None of the ingredients is listed.

Chemical safety assessment: A Chemical Safety Assessment has not been carried out.

16 Other information

The information contained in this document is based on Agilent's state of knowledge at the time of preparation. No warranty as to its accurateness, completeness or suitability for a particular purpose is expressed or implied.

· Date of preparation / last revision 04/01/2019 / 1

· Abbreviations and acronyms: ADR: Accord européen sur le transport des marchandises dangereuses par Route (European Agreement concerning the International Carriage of Dangerous Goods by Road) IMDG: International Maritime Code for Dangerous Goods DOT: US Department of Transportation IATA: International Air Transport Association ACGIH: American Conference of Governmental Industrial Hygienists EINECS: European Inventory of Existing Commercial Chemical Substances ELINCS: European List of Notified Chemical Substances CAS: Chemical Abstracts Service (division of the American Chemical Society) NFPA: National Fire Protection Association (USA) HMIS: Hazardous Materials Identification System (USA) VOC: Volatile Organic Compounds (USA, EU) LC50: Lethal concentration, 50 percent LD50: Lethal dose, 50 percent PBT: Persistent, Bioaccumulative and Toxic vPvB: very Persistent and very Bioaccumulative NIOSH: National Institute for Occupational Safety OSHA: Occupational Safety & Health TLV: Threshold Limit Value PEL: Permissible Exposure Limit REL: Recommended Exposure Limit BEI: Biological Exposure Limit Flam. Liq. 2: Flammable liquids - Category 2 Acute Tox. 3: Acute toxicity - Category 3 Carc. 2: Carcinogenicity - Category 2 Repr. 1B: Reproductive toxicity - Category 1B STOT SE 1: Specific target organ toxicity (single exposure) - Category 1 * * Data compared to the previous version altered.



Printing date 04/01/2019

SAFETY DATA SHEET



Argon

Section 1. Identification

GHS product identifier	: Argon
Chemical name	: Argon
Other means of identification	: Argon-40; Argon, isotope of mass 40; 40Ar; ARGON; Argon,Welding Quality; ARGON, COMPRESSED
Product type	: Gas.
Product use	: Synthetic/Analytical chemistry.
Synonym	: Argon-40; Argon, isotope of mass 40; 40Ar; ARGON; Argon, Welding Quality; ARGON, COMPRESSED
SDS #	: 001004
Supplier's details	: Airgas USA, LLC and its affiliates 259 North Radnor-Chester Road Suite 100 Radnor, PA 19087-5283 1-610-687-5253
24-hour telephone	: 1-866-734-3438

Section 2. Hazards identification

OSHA/HCS status	: This material is considered hazardous by the OSHA Hazard Communication Standard (29 CFR 1910.1200).
Classification of the substance or mixture	: GASES UNDER PRESSURE - Compressed gas SIMPLE ASPHYXIANTS
GHS label elements	
Hazard pictograms	
Signal word	: Warning
Hazard statements	: Contains gas under pressure; may explode if heated. May displace oxygen and cause rapid suffocation.
Precautionary statements	
General	: Read and follow all Safety Data Sheets (SDS'S) before use. Read label before use. Keep out of reach of children. If medical advice is needed, have product container or label at hand. Close valve after each use and when empty. Use equipment rated for cylinder pressure. Do not open valve until connected to equipment prepared for use. Use a back flow preventative device in the piping. Use only equipment of compatible materials of construction.
Prevention	: Not applicable.
Response	: Not applicable.
Storage	: Protect from sunlight. Store in a well-ventilated place.
Disposal	: Not applicable.
Supplemental label elements	: Keep container tightly closed. Use only with adequate ventilation. Do not enter storage areas and confined spaces unless adequately ventilated.
Hazards not otherwise classified	: In addition to any other important health or physical hazards, this product may displace oxygen and cause rapid suffocation.

Section 3. Composition/information on ingredients

Substance/mixture	Substance
Chemical name	Argon
Other means of identification	Argon-40; Argon, isotope of mass 40; 40Ar; ARGON; Argon,Welding Quality; ARGON, COMPRESSED
Product code	001004

CAS number/other identifiers

Argon

CAS number	: 7440-37-1

Ingredient name	%	CAS number
Argon	100	7440-37-1

Any concentration shown as a range is to protect confidentiality or is due to batch variation.

There are no additional ingredients present which, within the current knowledge of the supplier and in the concentrations applicable, are classified as hazardous to health or the environment and hence require reporting in this section.

Occupational exposure limits, if available, are listed in Section 8.

Section 4. First aid measures

Description of necessary first aid measures		
Eye contact	:	Immediately flush eyes with plenty of water, occasionally lifting the upper and lower eyelids. Check for and remove any contact lenses. Continue to rinse for at least 10 minutes. Get medical attention if irritation occurs.
Inhalation	:	Remove victim to fresh air and keep at rest in a position comfortable for breathing. If it is suspected that fumes are still present, the rescuer should wear an appropriate mask or self-contained breathing apparatus. If not breathing, if breathing is irregular or if respiratory arrest occurs, provide artificial respiration or oxygen by trained personnel. It may be dangerous to the person providing aid to give mouth-to-mouth resuscitation. Get medical attention if adverse health effects persist or are severe. If unconscious, place in recovery position and get medical attention immediately. Maintain an open airway. Loosen tight clothing such as a collar, tie, belt or waistband.
Skin contact	:	Flush contaminated skin with plenty of water. Remove contaminated clothing and shoes. Get medical attention if symptoms occur. Wash clothing before reuse. Clean shoes thoroughly before reuse.
Ingestion	:	As this product is a gas, refer to the inhalation section.

Most important symptoms/effects, acute and delayed

Potential acute health effects Eve contact : C

Eye contact	: Contact with rapidly expanding gas may cause burns or frostbite.
Inhalation	: No known significant effects or critical hazards. Acts as a simple asphyxiant.
Skin contact	: Contact with rapidly expanding gas may cause burns or frostbite.
Frostbite	: Try to warm up the frozen tissues and seek medical attention.
Ingestion	: As this product is a gas, refer to the inhalation section.
Over-exposure signs/sy	<u>mptoms</u>
Eye contact	: No specific data.
Inhalation	: No specific data.
Skin contact	: No specific data.
Ingestion	: No specific data.
Indication of immediate r	nedical attention and special treatment needed, if necessary
Notes to physician	: Treat symptomatically. Contact poison treatment specialist immediately if large quantities have been ingested or inhaled.
Specific treatments	: No specific treatment.

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Section 4. First aid measures

Protection of first-aiders

: No action shall be taken involving any personal risk or without suitable training. If it is suspected that fumes are still present, the rescuer should wear an appropriate mask or self-contained breathing apparatus. It may be dangerous to the person providing aid to give mouth-to-mouth resuscitation.

See toxicological information (Section 11)

Section 5. Fire-fighting measures		
Extinguishing media		
Suitable extinguishing media	: Use an extinguishing agent suitable for the surrounding fire.	
Unsuitable extinguishing media	: None known.	
Specific hazards arising from the chemical	: Contains gas under pressure. In a fire or if heated, a pressure increase will occur and the container may burst or explode.	
Hazardous thermal decomposition products	: No specific data.	
Special protective actions for fire-fighters	: Promptly isolate the scene by removing all persons from the vicinity of the incident if there is a fire. No action shall be taken involving any personal risk or without suitable training. Contact supplier immediately for specialist advice. Move containers from fire area if this can be done without risk. Use water spray to keep fire-exposed containers cool.	
Special protective equipment for fire-fighters	: Fire-fighters should wear appropriate protective equipment and self-contained breathing apparatus (SCBA) with a full face-piece operated in positive pressure mode.	

Section 6. Accidental release measures

Personal precautions, protec	tiv	e equipment and emergency procedures
For non-emergency personnel	:	No action shall be taken involving any personal risk or without suitable training. Evacuate surrounding areas. Keep unnecessary and unprotected personnel from entering. Avoid breathing gas. Provide adequate ventilation. Wear appropriate respirator when ventilation is inadequate. Put on appropriate personal protective equipment.
For emergency responders	:	If specialized clothing is required to deal with the spillage, take note of any information in Section 8 on suitable and unsuitable materials. See also the information in "For non-emergency personnel".
Environmental precautions	:	Ensure emergency procedures to deal with accidental gas releases are in place to avoid contamination of the environment. Inform the relevant authorities if the product has caused environmental pollution (sewers, waterways, soil or air).
Methods and materials for co	ont	ainment and cleaning up
Small spill	:	Immediately contact emergency personnel. Stop leak if without risk.
Large spill	:	Immediately contact emergency personnel. Stop leak if without risk. Note: see Section 1 for emergency contact information and Section 13 for waste disposal.

Section 7. Handling and storage

Precautions for safe handling

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Section 7. Handling and storage

Protective measures	: Put on appropriate personal protective equipment (see Section 8). Contains gas under pressure. Avoid breathing gas. Use only with adequate ventilation. Wear appropriate respirator when ventilation is inadequate. Do not puncture or incinerate container. Use equipment rated for cylinder pressure. Close valve after each use and when empty. Protect cylinders from physical damage; do not drag, roll, slide, or drop. Use a suitable hand truck for cylinder movement. Avoid contact with eyes, skin and clothing. Empty containers retain product residue and can be hazardous.
Advice on general occupational hygiene	: Eating, drinking and smoking should be prohibited in areas where this material is handled, stored and processed. Workers should wash hands and face before eating, drinking and smoking. Remove contaminated clothing and protective equipment before entering eating areas. See also Section 8 for additional information on hygiene measures.
Conditions for safe storage, including any incompatibilities	: Store in accordance with local regulations. Store in a segregated and approved area. Store away from direct sunlight in a dry, cool and well-ventilated area, away from incompatible materials (see Section 10). Cylinders should be stored upright, with valve protection cap in place, and firmly secured to prevent falling or being knocked over. Cylinder temperatures should not exceed 52 °C (125 °F). Keep container tightly closed and sealed until ready for use. See Section 10 for incompatible materials before handling or use.

Section 8. Exposure controls/personal protection

Control parameters

Occupational exposure limits

Ingredient name	Exposure limits
Argon	ACGIH TLV (United States, 3/2017). Oxygen Depletion [Asphyxiant].

Appropriate engineering controls	:	Use only with adequate ventilation. Use process enclosures, local exhaust ventilation or other engineering controls to keep worker exposure to airborne contaminants below any recommended or statutory limits.		
Environmental exposure controls	:	Emissions from ventilation or work process equipment should be checked to ensure they comply with the requirements of environmental protection legislation. In some cases, fume scrubbers, filters or engineering modifications to the process equipment will be necessary to reduce emissions to acceptable levels.		
Individual protection measure	ures			
Hygiene measures	:	Wash hands, forearms and face thoroughly after handling chemical products, before eating, smoking and using the lavatory and at the end of the working period. Appropriate techniques should be used to remove potentially contaminated clothing. Wash contaminated clothing before reusing. Ensure that eyewash stations and safety showers are close to the workstation location.		
Eye/face protection	:	Safety eyewear complying with an approved standard should be used when a risk assessment indicates this is necessary to avoid exposure to liquid splashes, mists, gases or dusts. If contact is possible, the following protection should be worn, unless the assessment indicates a higher degree of protection: safety glasses with side-shields.		
Skin protection				
Hand protection	:	Chemical-resistant, impervious gloves complying with an approved standard should be worn at all times when handling chemical products if a risk assessment indicates this is necessary. Considering the parameters specified by the glove manufacturer, check during use that the gloves are still retaining their protective properties. It should be noted that the time to breakthrough for any glove material may be different for different glove manufacturers. In the case of mixtures, consisting of several substances, the protection time of the gloves cannot be accurately estimated.		

Section 8. Exposure controls/personal protection

Body protection	: Personal protective equipment for the body should be selected based on the task being performed and the risks involved and should be approved by a specialist before handling this product.
Other skin protection	: Appropriate footwear and any additional skin protection measures should be selected based on the task being performed and the risks involved and should be approved by a specialist before handling this product.
Respiratory protection	: The gas can cause asphyxiation without warning by replacing the oxygen in the air. Based on the hazard and potential for exposure, select a respirator that meets the appropriate standard or certification. If operating conditions cause high gas concentrations to be produced or any recommended or statutory exposure limit is exceeded, use an air-fed respirator or self-contained breathing apparatus. Respirators must be used according to a respiratory protection program to ensure proper fitting, training, and other important aspects of use. Respirator selection must be based on known or anticipated exposure levels, the hazards of the product and the safe working limits of the selected respirator.

Section 9. Physical and chemical properties

<u>Appearance</u>		
Physical state	:	Gas.
Color	:	Colorless.
Odor	:	Odorless.
Odor threshold	:	Not available.
рН	:	Not available.
Melting point	:	-189.2°C (-308.6°F)
Boiling point	:	-185.9°C (-302.6°F)
Critical temperature	:	-122.4°C (-188.3°F)
Flash point	:	[Product does not sustain combustion.]
Evaporation rate	:	Not available.
Flammability (solid, gas)	:	Not available.
Lower and upper explosive (flammable) limits	:	Not available.
Vapor pressure	:	Not available.
Vapor density	4	1.66 (Air = 1)
Specific Volume (ft ³ /lb)	:	9.7087
Gas Density (Ib/ft ³)	:	0.103
Relative density	:	Not applicable.
Solubility	:	Not available.
Solubility in water	:	Not available.
Partition coefficient: n- octanol/water	:	0.74
Auto-ignition temperature	:	Not available.
Decomposition temperature	:	Not available.
Viscosity	:	Not applicable.
Flow time (ISO 2431)	:	Not available.
Molecular weight	1	39.95 g/mole

Section	10.	Stability	and	reactivity
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Reactivity	: No specific test data related to reactivity available for this product or its ingredients.
Chemical stability	: The product is stable.
Possibility of hazardous reactions	: Under normal conditions of storage and use, hazardous reactions will not occur.
Conditions to avoid	: Do not allow gas to accumulate in low or confined areas.
Incompatible materials	: No specific data.
Hazardous decomposition products	: Under normal conditions of storage and use, hazardous decomposition products should not be produced.

Hazardous polymerization : Under normal conditions of storage and use, hazardous polymerization will not occur.

Section 11. Toxicological information

Information on toxicological effects

Acute toxicity

Not available.

Irritation/Corrosion

Not available.

Sensitization

Not available.

Mutagenicity

Not available.

Carcinogenicity

Not available.

Reproductive toxicity

Not available.

Teratogenicity

Not available.

Specific target organ toxicity (single exposure)

Not available.

Specific target organ toxicity (repeated exposure)

Not available.

Aspiration hazard

Not available.

Information on the likely : Not available.

routes of exposure Potential acute health effects Eye contact : Contact with rapidly expanding gas may cause burns or frostbite. Inhalation : No known significant effects or critical hazards. Acts as a simple asphyxiant. **Skin contact** : Contact with rapidly expanding gas may cause burns or frostbite. Date of issue/Date of revision : 1/5/2021 : 8/25/2020 Version : 1.05 Date of previous issue

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Argon	
Section 11. Toxico	ological information
Ingestion	: As this product is a gas, refer to the inhalation section.
Symptoms related to the phy	vsical, chemical and toxicological characteristics
Eye contact	: No specific data.
Inhalation	: No specific data.
Skin contact	: No specific data.
Ingestion	: No specific data.
Delayed and immediate effe	cts and also chronic effects from short and long term exposure
Short term exposure	
Potential immediate effects	: Not available.
Potential delayed effects	: Not available.
Long term exposure	
Potential immediate effects	: Not available.
Potential delayed effects	: Not available.
Potential chronic health eff	ects
Not available.	
General	: No known significant effects or critical hazards.
Carcinogenicity	: No known significant effects or critical hazards.
Mutagenicity	: No known significant effects or critical hazards.
Teratogenicity	: No known significant effects or critical hazards.
Developmental effects	: No known significant effects or critical hazards.
Fertility effects	: No known significant effects or critical hazards.

Numerical measures of toxicity

Acute toxicity estimates

Not available.

Section 12. Ecological information

Toxicity

Not available.

Persistence and degradability

Not available.

Bioaccumulative potential

Product/ingredient name	LogPow	BCF		Potential	
Argon	0.74	-		low	
Mobility in soil Soil/water partition coefficient (Koc)	: Not avail	able.			
Other adverse effects	: No know	n significant effects or crit	ical hazards.		
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Section 13. Disposal considerations

Disposal methods

: The generation of waste should be avoided or minimized wherever possible. Disposal of this product, solutions and any by-products should at all times comply with the requirements of environmental protection and waste disposal legislation and any regional local authority requirements. Dispose of surplus and non-recyclable products via a licensed waste disposal contractor. Waste should not be disposed of untreated to the sewer unless fully compliant with the requirements of all authorities with jurisdiction. Empty Airgas-owned pressure vessels should be returned to Airgas. Waste packaging should be recycled. Incineration or landfill should only be considered when recycling is not feasible. This material and its container must be disposed of in a safe way. Empty containers or liners may retain some product residues. Do not puncture or incinerate container.

Section 14. Transport information

	DOT	TDG	Mexico	IMDG	ΙΑΤΑ
UN number	UN1006	UN1006	UN1006	UN1006	UN1006
UN proper shipping name	ARGON, COMPRESSED	ARGON, COMPRESSED	ARGON, COMPRESSED	ARGON, COMPRESSED	ARGON, COMPRESSED
Transport hazard class(es)	2.2	2.2	2.2	2.2	2.2
Packing group	-	-	-	-	-
Environmental hazards	No.	No.	No.	No.	No.

"Refer to CFR 49 (or authority having jurisdiction) to determine the information required for shipment of the product."

Additional information

DOT Classification	:	<u>Limited quantity</u> No
TDG Classification	:	Product classified as per the following sections of the Transportation of Dangerous Goods Regulations: 2.13-2.17 (Class 2). Explosive Limit and Limited Quantity Index 0.125 Passenger Carrying Road or Rail Index 75 Special provisions 42
ΙΑΤΑ	:	Quantity limitation No
Special precautions for user	:	Transport within user's premises: always transport in closed containers that are upright and secure. Ensure that persons transporting the product know what to do in the event of an accident or spillage.
Transport in bulk according to IMO instruments	:	Not available.

Section 15. Regulatory information

U.S. Federal regulations : TSCA 8(a) CDR Exempt/Partial exemption: This material is listed or exempted.

Clean Air Act Section 112 : Not listed (b) Hazardous Air Pollutants (HAPs)

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Section 15.	Regulatory	information

Argon

Clean Air Act Section 602 Class I Substances	: Not listed
Clean Air Act Section 602 Class II Substances	: Not listed
DEA List I Chemicals (Precursor Chemicals)	: Not listed
DEA List II Chemicals (Essential Chemicals)	: Not listed
<u>SARA 302/304</u>	
Composition/information	on ingredients
No products were found.	
SARA 304 RQ	: Not applicable.
SARA 311/312	
Classification	: Refer to Section 2: Hazards Identification of this SDS for classification of substance.
State regulations	
Massachusotte	. This material is listed
New York	This material is not listed
New Jersev	This material is listed
Pennsylvania	: This material is listed.
International regulations	
Chemical Weapon Conve	ntion List Schedules I, II & III Chemicals
Not listed.	
Montroal Protocol	
Not listed	
Stockholm Convention or Not listed.	<u>i Persistent Organic Pollutants</u>
Rotterdam Convention or	Prior Informed Consent (PIC)
Not listed.	
UNECE Aarhus Protocol o	on POPs and Heavy Metals
Not listed.	
Inventory list	
Australia	: This material is listed or exempted.
Canada	: This material is listed or exempted.
China	: This material is listed or exempted.
Europe	: This material is listed or exempted.
Japan	: Japan inventory (ENCS): Not determined. Japan inventory (ISHL): Not determined.
New Zealand	: This material is listed or exempted.
Philippines	: This material is listed or exempted.
Republic of Korea	: This material is listed or exempted.
Taiwan	: This material is listed or exempted.
Thailand	: Not determined.
Turkey	: Not determined.
United States	: This material is listed or exempted.
Viet Nam	: Not determined.

Section 16. Other information

Hazardous Material Information System (U.S.A.)



Caution: HMIS® ratings are based on a 0-4 rating scale, with 0 representing minimal hazards or risks, and 4 representing significant hazards or risks. Although HMIS® ratings and the associated label are not required on SDSs or products leaving a facility under 29 CFR 1910.1200, the preparer may choose to provide them. HMIS® ratings are to be used with a fully implemented HMIS® program. HMIS® is a registered trademark and service mark of the American Coatings Association, Inc.

The customer is responsible for determining the PPE code for this material. For more information on HMIS® Personal Protective Equipment (PPE) codes, consult the HMIS® Implementation Manual.

National Fire Protection Association (U.S.A.)



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Copyright ©2001, National Fire Protection Association, Quincy, MA 02269. This warning system is intended to be interpreted and applied only by properly trained individuals to identify fire, health and reactivity hazards of chemicals. The user is referred to certain limited number of chemicals with recommended classifications in NFPA 49 and NFPA 325, which would be used as a guideline only. Whether the chemicals are classified by NFPA or not, anyone using the 704 systems to classify chemicals does so at their own risk.

Classification **Justification** GASES UNDER PRESSURE - Compressed gas Expert judgment SIMPLE ASPHYXIANTS Expert judgment **History Date of printing** : 1/5/2021 Date of issue/Date of : 1/5/2021 revision Date of previous issue : 8/25/2020 Version 1.05 Key to abbreviations : ATE = Acute Toxicity Estimate BCF = Bioconcentration Factor GHS = Globally Harmonized System of Classification and Labelling of Chemicals IATA = International Air Transport Association IBC = Intermediate Bulk Container IMDG = International Maritime Dangerous Goods LogPow = logarithm of the octanol/water partition coefficient MARPOL = International Convention for the Prevention of Pollution From Ships, 1973 as modified by the Protocol of 1978. ("Marpol" = marine pollution) UN = United Nations : Not available. References Notice to reader

Procedure used to derive the classification

Section 16. Other information

To the best of our knowledge, the information contained herein is accurate. However, neither the above-named supplier, nor any of its subsidiaries, assumes any liability whatsoever for the accuracy or completeness of the information contained herein.

Final determination of suitability of any material is the sole responsibility of the user. All materials may present unknown hazards and should be used with caution. Although certain hazards are described herein, we cannot guarantee that these are the only hazards that exist.



SAFETY DATA SHEET

Prepared to U.S. OSHA, CMA, ANSI and Canadian WHMIS Standards . This Material Safety Data Sheet is offered pursuant to OSHA's Hazard Communication Standard (29 CFR 1910.1200). Other government regulations must be reviewed for applicability to these products. WARNING: PRODUCT COMPONENTS PRESENT HEALTH AND SAFETY HAZARDS. READ AND UNDERSTAND THIS SAFETY DATA SHEET (S.DS.). ALSO, FOLLOW YOUR EMPLOYER'S SAFETY PRACTICES. This product may contain Chromium and/or Nickel which are listed by OSHA, NTP, or IARC as being a carcinogen or potential carcinogen. Use of this product may expose you or others to fumes and gases at levels exceeding those established by the American Conference of Governmental Industrial Hygienists (ACGIH) or the Occupational Safety and Health Administration (OSHA) The information contained herein relates only to the specific product. If the product is combined with other materials, all component properties must be considered. BE SURE TO CONSULT THE LATEST VERSION OF THE SDS. Safety Data Sheets are available from Midwest Tungsten Service at www.midwesttungsten.com

STATEMENT OF LIABILITY-DISCLAIMER

To the best of Midwest Tungsten Service's knowledge, the information and recommendations contained in this publication are reliable and accurate as of the date prepared. However, accuracy, suitability, or completeness are not guaranteed, and no warranty, guarantee, or representation, expressed or implied, is made by Midwest Tungsten Service. as to the absolute correctness or sufficiency of any representation contained in this and other publications; Midwest Tungsten Service assumes no responsibility in connection therewith; nor can it be assumed that all acceptable safety measures are contained in this and other publications, or that other or additional measures may not be required under particular or exceptional conditions or circumstances. Data may be changed from time to time.

PART I What is the material and what do I need to know in an emergency

TRADE NAME (AS LABELED): CHEMICAL NAME/CLASS: SYNONYMS: PRODUCT USE: DOCUMENT NUMBER: SUPPLIER/MANUFACTURER'S NAME:

1. PRODUCT IDENTIFICATION *Weld*True Tugsten Electrodes Tungsten; Element Wolfram Welding; Metal-Working Operations 0001 AME: Midwest Tungsten Service

540 Executive Drive, Willowbrook, IL 60527 (800) 626-0226 July 27, 2015

Emergency PHONE: DATE OF PREPARATION:

2. COMPOSITION and INFORMATION ON INGREDIENTS							
	NOMINAL COMPOSITION WEIGHT % ELECTRODES						
TRADE NAME	w	CeO ₂	La ₂ O ₃	ThO₂	ZrO ₂	Other Oxides or Elements Total	
Pure Tungsten	99.5					0.5	
1% Thoriated Tungsten	98.3			0.8-1.2		0.5	
2% Thoriated Tungsten	97.3			1.7-2.2		0.5	
1% Lanthanated Tungsten	98.3		0.8-1.2			0.5	
1.5% Lanthanated Tungsten	97.8		1.3-1.7			0.5	
2% Lanthanated Tungsten	97.3		1.8-2.2			0.5	
Ceriated Tungsten	97.3	1.8-2.2				0.5	
Zirconiated Tungsten	99.1				0.15-0.40	0.5	

2. COMPOSITION and INFORMATION ON INGREDIENTS (Continued)

CHEMICAL NAME	CAS #	% w/w	EXPOSURE LIMITS IN AIR					
			ACGIH-TLV		OSHA-PEL			OTHER
			TWA	STEL	TWA	STEL	IDLH	
			mg/m ³	mg/m ³	mg/m ³	mg/m ³	mg/m ³	mg/m ³
Tungsten The exposure limits provided are for "Tungsten and Insoluble Compounds"	7440-33-7	97.3-99.5 See Table in Previous Page	5	10	5 (Vacated 1989 PEL)	10 (Vacated 1989 PEL)	NE	NIOSH RELs TWA = 5 STEL = 10
Lanthanum Oxide (La ₂ O ₃)	1312-81-8	See Table in Previous Page	NE	NE	NE	NE	NE	NE
Cerium Oxide (CeO ₂)	1306-38-3	See Table in Previous Page	NE	NE	NE	NE	NE	NE
Thorium Oxide (ThO ₂)	1314-20-1	See Table in Previous Page	NE	NE	NE	NE	NE	Carcinogenicity: IARC-1
Zirconium Oxide (ZrO ₂) The exposure limits provided are for "Zirconium Compounds, as Zr" (CAS # 7440-67-7)	1314-23-4	See Table in Previous Page	5, A4 (Not Classifiable as a Human Carcinogen)	10, A4 (Not Classifiable as a Human Carcinogen)	5	10 (Vacated 1989 PEL)	50 (as Zr)	NIOSH RELS TWA = 5 STEL = 10 DFG MAKS: TWA = 5 (MAK measured as the inhalable fraction of the aerosol) PEAK = 10 MAK 30 min., average value Carcinogenicity: TLV-A4
Other components each present in less than 1 percent concentration (0.1% concentration for potential carcinogens, reproductive toxins, respiratory tract sensitizers, and mutagens).			None of the concentrations provided in this Health Adminis Canadian Wor the applicable 0	other compon present in thes s document, per stration Standard kplace Hazardou Council Directives	ents contrib e products. the requirem d (29 CFR 1 is Materials is of the Europ	ute significa All pertine nents of the F 910.1200), L dentification ean Commun	ant additic nt hazard Federal Oc J.S. State System Sta hity.	onal hazards at the information has been ccupational Safety and equivalent Standards; andards (CPR 4); and

NE = Not Established. See Section 16 for Definitions of Terms Used.

NOTE (1): The ACGIH has an established exposure limit for Welding Fumes, Not Otherwise Classified. The Threshold Limit Value is 5 mg/m³. NIOSH classifies welding fumes as carcinogens.

NOTE (2): ALL WHMIS required information is included in appropriate sections based on the ANSI Z400.1-1998 format. These products has been classified in accordance with the hazard criteria of the CPR and the SDS contains all the information required by the CPR.

3. HAZARD IDENTIFICATION

EMERGENCY OVERVIEW: These products are hard, brittle, silvery-gray metal electrodes. The chief health hazard associated with these products would be the inhalation of fumes generated by welding or dusts and powdered, formed if grinding operations are performed on the product. Those electrodes that contain Thorium Oxide have a special hazard if dusts or powders are produced and inhaled during use or grinding of tips of the electrodes, as thorium compounds are suspected of being cancer-causing compounds. When exposed to extremely high temperatures, these products will produce irritating oxides of cerium, thorium, tungsten and zirconium. These electrodes present no significant fire hazard; however finely divided metal powder which may be generated during grinding of the tips of electrodes, is highly flammable (especially when exposed to oxidizing compounds at elevated temperatures). In some circumstances, powdered tungsten can be spontaneously flammable. Emergency responders must wear the proper personal protective equipment (and have appropriate fire-extinguishing protection) suitable for the situation to which the are responding.

3. HAZARD IDENTIFICATION (Continued)

SYMPTOMS OF OVER-EXPOSURE BY ROUTE OF EXPOSURE:

The most significant routes of over-exposure to these products is inhalation of fumes generated during welding operations or of dusts generated by grinding operations.

INHALATION: Inhalation is not a significant route of overexposure to the electrodes. Inhalation of fumes generated from welding operations and to powders generated by grinding of the electrode tips, can cause irritation of the nose, throat, and respiratory system. Symptoms of such over-exposure can include sneezing, coughing, and a sore throat. Inhalation of Tungsten fumes has the potential for causing transient or permanent lung damage. Additionally, short-term over-exposure to welding fumes may result in discomfort, dizziness, nausea, and irritation of the eyes, nose, and throat. Chronic inhalation of large amounts of particulates generated by these products during metal processing operations can result in pneumoconiosis (a disease of the lungs).

CONTACT WITH SKIN or EYES: Contact with skin and eyes can be irritating, especially areas which have been over-exposed to Tungsten powders. Symptoms of skin contact include irritation and redness; prolonged or repeated skin over-exposures to Tungsten powders can lead to dermatitis. Symptoms of eye contact include pain, redness, irritation, and tearing.

SKIN ABSORPTION: Skin absorption is not a significant route of over-exposure for these products, or their components.

INGESTION: Not applicable.

INJECTION: Not applicable.

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OTHER HEALTH EFFECTS: Some of these products contain

Thorium Oxide, which is a low-level radioactive material. Studies performed by the International Institute of Welding have shown that these electrodes do not present any radiation risks during normal use, storage, welding or disposal of residues of these products. However, during grinding of electrode tips there is

generation of radioactive dusts, which present a hazard through inhalation.

HEALTH EFFECTS OR RISKS FROM EXPOSURE: An Explanation in Lav Terms.

ACUTE: The chief health hazard associated with these products would be inhalation of fumes generated during welding, or inhalation of powders generated during grinding of electrode tips. Symptoms of acute inhalation of fumes generated during welding include irritation of the nose, throat, and respiratory system.

CHRONIC: Chronic inhalation of large amounts of particulates generated by these products during metal processing operations can result in pneumoconiosis (a disease of the lungs). Prolonged or repeated skin over-exposures to Tungsten powders can lead to dermatitis. Inhalation of Tungsten fumes during welding operations has the potential for causing transient or permanent lung damage. A component of some of these electrodes contain Thorium Oxide, which is a known human carcinogen, and which is a low-level radioactive emitter. If dusts from these electrodes are generated and inhalation, there is risk of long-term effects. See Section 11, Toxicological Information, for further information.

TARGET ORGANS: ACUTE: Skin and eyes, respiratory system. CHRONIC: Respiratory system, skin.

PART II What should I do if a ha	azardous situation occurs?
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4. FIRST-AID MEASURES

Victims of chemical exposure must be taken for medical attention. Rescuers should be taken for medical attention, if necessary. Take a copy of label and SDS to health professional with victim.

SKIN EXPOSURE: If dusts or powders from these products contaminates the skin, immediately begin decontamination with running water if any adverse effect occurs. Remove exposed or contaminated clothing, taking care not to contaminate eyes. Victim must seek medical attention if any adverse reaction occurs..

EYE EXPOSURE: If the powder or particulates from these products enter the eyes, open victim's eyes while under gentle running water. Use sufficient force to open evelids. Have victim "roll" eves. Minimum flushing is for 15 minutes.

HAZARDOUS MATERIAL IDENTIFICATION SYSTEM					
HEAL	HEALTH (BLUE) 1				
FLAM	MABILI	ΓΥ	RED)	0	
REACTIVITY (YELLOW) 0					
PROTECTIVE EQUIPMENT B					
EYES	RESPIRATORY	HANDS	ВС	DDY	
	See Section 8		See Secti	on 8	
For routine industrial applications					

See Section 16 for Definition of Ratings

4. FIRST-AID MEASURES (continued)

INHALATION: If powders generated from grinding of the tips of these electrodes are inhaled, remove victim to fresh air. If necessary, use artificial respiration to support vital functions. Remove or cover gross contamination to avoid exposure to rescuers.

INGESTION: If swallowed call physician immediately! Do not induce vomiting unless directed by medical personnel. Rinse mouth with water if person is conscious. Never give fluids or induce vomiting if person is unconscious, having convulsions, or not breathing.

MEDICAL CONDITIONS AGGRAVATED BY EXPOSURE: Skin disorders may be aggravated by prolonged overexposures to fumes generated during welding or to powders generated during grinding of tips of the electrodes. Chronic over-exposure to Tungsten powders via inhalation can aggravate lung disorders.

RECOMMENDATIONS TO PHYSICIANS: When personnel have chronic exposure to dusts from electrodes that contain Thorium Oxide, monitoring of personnel for early symptoms and changes such as abnormal leukocytes in the blood smear may be of value. In cases of chronic or acute exposure, the determination of thorium in the urine or the use of whole body radiation counts & breath radon are useful methods of monitoring the exposure dose and excretion rates.

5. FIRE-FIGHTING MEASURES

FLASH POINT: Not flammable. AUTOIGNITION TEMPERATURE: Not flammable. FLAMMABLE LIMITS (in air by volume, %):

Lower (LEL): Not applicable. Upper (UEL): Not applicable.

FIRE EXTINGUISHING MATERIALS:

For Electrode: Not flammable. Use the extinguishing media appropriate for HEALTH the fire.

Water Spray: YES	Carbon Dioxide: YES
Foam: YES	Dry Chemical: YES
<u>Halon</u> : YES	Other: Any "ABC" Class.

For Powders of Tungsten: Powders of Tungsten are considered to be a

Class D Fires. Use Soda-Ash, Lime, DRY Sand (Purple K, if available).

UNUSUAL FIRE AND EXPLOSION HAZARDS: When Thorium Oxidecontaining electrodes are involved in a fire, incipient fire-fighters must wear a

respirator approved for radionuclides. When exposed to extremely high temperatures, these products will produce irritating oxides of cesium, thorium, tungsten and zirconium (depending on composition - see Section 2, Composition and Information on Ingredients). These electrodes present no significant fire hazard. Finely-divided tungsten powder, however, is highly flammable (especially when exposed to oxidizing compounds at elevated temperatures).

Explosion Sensitivity to Mechanical Impact: Not sensitive.

Explosion Sensitivity to Static Discharge: The finely divided powders of these products may ignite if exposed to static electrical discharge.

SPECIAL FIRE-FIGHTING PROCEDURES: Not applicable.

6. ACCIDENTAL RELEASE MEASURES

SPILL AND LEAK RESPONSE: Not applicable.

PART III How can I prevent hazardous situations from occurring

7. HANDLING and STORAGE

WORK PRACTICES AND HYGIENE PRACTICES: After the end of work shift, hands and other exposed skin should be thoroughly washed. Do not eat or drink during use of these products. Use ventilation and other engineering controls to minimize potential exposure to fumes during welding operations or to dusts if tips of electrodes are ground. Follow good house-keeping practices to ensure powders or dusts from grinding operations do not accumulate, which can be highly flammable and can pose special health hazards if from thorium-containing electrodes. Tungsten-Thorium Oxide alloys are generally safe to handle during use and almost all normal conditions and environments. **Special precautions must be taken during the grinding or machining of tips of electrodes that contain Thorium Oxide to avoid the generation and subsequent inhalation of dusts from these operations. Any dusts generated during these operations may be considered as "Source Material", as defined by the Nuclear Regulatory Commission, and therefore be subject to the requirements of 10 CFR, Parts 20 and 40. Routine wet-mopping or vacuuming with an explosion-proof vacuum, fitted with a HEPA filter may be considered to reduce accumulation of dusts.**



See Section 16 for Definition of Ratings

7. HANDLING and STORAGE (Continued)

STORAGE AND HANDLING PRACTICES: All employees who handle these materials should be trained to handle it safely. Avoid breathing dusts or powders generated during grinding of electrode tips. Open packages and containers of these products slowly, on a stable surface. Packages and containers of these products must be properly labeled.

When these products are used during welding operations, follow the requirements of the Federal Occupational Safety and Health Welding and Cutting Standard (29 CFR 1910 Subpart Q) and the safety standards of the American National Standards Institute for welding and cutting (ANSI Z49.1). Empty containers, which held these products, may still contain dusts from the products; therefore, such containers should be handled with care.

PROTECTIVE PRACTICES DURING MAINTENANCE OF CONTAMINATED EQUIPMENT: Not applicable.

8. EXPOSURE CONTROLS - PERSONAL PROTECTION

VENTILATION AND ENGINEERING CONTROLS: Use with adequate ventilation to ensure exposure limits are below those provided in Section 2 (Composition and Information on Ingredients). Use a mechanical fan or vent area to outside. Prudent practice is to ensure eyewash/safety shower stations are available near areas where these products is used.

RESPIRATORY PROTECTION: Maintain airborne contaminant concentrations below exposure limits listed in Section 2 (Composition and Information on Ingredients). If respiratory protection is needed (i.e. a Weld Fume Respirator, or Air-Line Respirator for welding in confined spaces), U.S. Federal OSHA Standard (29 CFR 1910.134), applicable U.S. State regulations, or the Canadian CSA Standard Z94.4-93 and applicable standards of Canadian Provinces. Respiratory Protection is recommended to be worn during welding operations. Oxygen levels below 19.5% are considered IDLH by OSHA. In such atmospheres, use of a full-facepiece pressure/demand SCBA or a full facepiece, supplied air respirator with auxiliary self-contained air supply is required under OSHA's Respiratory Protection Standard (1910.134-1998). The following are NIOSH Guidelines for respirator selection for Welding Fumes.

CONCENTRATION RESPIRATORY PROTECTION EQUIPMENT

At Concentrations above the NIOSH REL, or where there is no REL, at any Detectable Concentration: Any self-contained breathing apparatus that has a full facepiece and is operated in a pressure-demand or other positive-pressure mode, or any supplied-air respirator that has a full facepiece and is operated in a pressure-demand or other positive-pressure mode in combination with an auxiliary self-contained breathing apparatus operated in pressure-demand or other positive-pressure mode.

Escape:

Any air-purifying, full-facepiece respirator (gas mask) with a chin-style, front- or back-mounted organic vapor canister having a high-efficiency particulate filter, or any appropriate escape-type, self-contained breathing apparatus

In addition, in areas in which electrodes which contain Thorium-Oxide are involved in operations such as grinding of tips or other metal working operations are performed and dusts are generated, the use of an appropriate NIOSH approved respirator, equipped with radionuclide filters should be used.

EYE PROTECTION: Safety glasses. When used in conjunction with welding, wear safety glasses, goggles or face-shield with filter lens of appropriate shade number (per ANSI Z49.1-1988, "Safety in Welding and Cutting"), as necessary.

HAND PROTECTION: Wear gloves for routine industrial use When used in conjunction with welding, wear gloves that protect from sparks and flame (per ANSI Z49.1-1988, "Safety in Welding and Cutting"), as necessary.

BODY PROTECTION: Use body protection appropriate for task.

9. PHYSICAL and CHEMICAL PROPERTIES

RELATIVE VAPOR DENSITY (air = 1): Not applicable. SPECIFIC GRAVITY (water = 1): 19.3 SOLUBILITY IN WATER: Insoluble. VAPOR PRESSURE, mm Hg @ 20°C: Approximately 0. **ODOR THRESHOLD:** Not available. COEFFICIENT OF OIL/WATER DISTRIBUTION (PARTITION COEFFICIENT): Not applicable.

EVAPORATION RATE (nBuAc = 1): Not applicable. FREEZING/MELTING POINT: 3410°C (6170°F) **BOILING POINT:** 5927°C (10701°F) pH: Not applicable.

APPEARANCE AND COLOR: These products are a hard, brittle, silvery-gray metal electrodes.

HOW TO DETECT THIS SUBSTANCE (warning properties): The appearance is a distinctive characteristic of these product in event of accidental release.

10. STABILITY and REACTIVITY

STABILITY: Normally stable. Thorium Oxide, which is a component of some of these products, will undergo spontaneous radioactive decay.

DECOMPOSITION PRODUCTS: Exposure to elevated temperatures and oxidizers will lead to the production of tungsten oxide compounds.

MATERIALS WITH WHICH SUBSTANCE IS INCOMPATIBLE: Tungsten is not compatible with halogens and strong oxidizers (i.e. sulfuric acid, nitric acid).

HAZARDOUS POLYMERIZATION: Will not occur.

CONDITIONS TO AVOID: Avoid exposure to extreme temperatures and incompatible chemicals.

PART IV Is there any other useful information about this material?

11. TOXICOLOGICAL INFORMATION

TOXICITY DATA: Presented below are human toxicological data available for the components of these products present in concentration greater than 1%. Other data for animals are available for the components of these products, but are not presented in this Material Safety Data Sheet.

CESIUM OXIDE:

No human data currently available.

LANTHANUM OXIDE:

No human data currently available.

THORIUM OXIDE:

- TDLo (Parenteral-Woman) 1 gm/kg: Tumorigenic: Carcinogenic by RTECS criteria: Liver: tumors
- TDLo (Unreported-Human) 2880 mg/kg: Tumorigenic: neoplastic by RTECS criteria; Liver: tumors
- TDLo (Intraarterial-Human) 490 mg/kg: Tumorigenic: Carcinogenic by RTECS criteria, tumors at site of application
- TD (Parenteral-Human) 700 mg/kg: Tumorigenic: neoplastic by RTECS criteria; Liver: angiosarcoma; Blood: tumors

THORIUM OXIDE (continued):

- TD (Parenteral-Human) 1260 mg/kg: Tumorigenic: neoplastic by RTECS criteria; Liver: angiosarcoma; Blood: tumors
- TD (Parenteral-Woman) 2350 mg/kg: Tumorigenic: Carcinogenic by RTECS criteria; Kidney, Ureter, Bladder: Kidney tumors
- TD (Intraarterial-Man) 1190 mg/kg: Tumorigenic: Carcinogenic by RTECS criteria; Liver: tumors; Blood: lymphoma, including Hodgkin's disease

THORIUM OXIDE (continued):

- TD (Intraarterial-Woman) 2 gm/kg: Tumorigenic: Carcinogenic by RTECS criteria, tumors at site of application
- TD (Intraarterial-Human) 1302 mg/kg: Tumorigenic: Carcinogenic by RTECS criteria; Liver: tumors, angiosarcoma

TUNGSTEN:

No human data currently available.

ZIRCONIUM OXIDE:

No human data currently available.

SUSPECTED CANCER AGENT: The components of these products are listed as follows:

THORIUM OXIDE, a component of some of these products, is listed by IARC as a Group 1 compound (Carcinogenic to Humans - Sufficient Evidence of Carcinogenicity).

The other components of these products are not found on the following lists: FEDERAL OSHA Z LIST, NTP, IARC, CAL/OSHA and is therefore not considered to be, nor suspected to be, a cancer-causing agent by these agencies.

IRRITANCY OF PRODUCT: Dusts or powders of these products can be irritating to contaminated skin, eyes, and respiratory system.

SENSITIZATION TO THE PRODUCT: The components of these products are not known to be skin or respiratory sensitizers.

REPRODUCTIVE TOXICITY INFORMATION: Listed below is information concerning the effects of these products and their components on the human reproductive system.

Mutagenicity: These products are not reported to produce mutagenic effects in humans.

<u>Embryotoxicity</u>: These products are not reported to produce embryotoxic effects in humans. Refer to the following paragraph for additional information.

<u>Teratogenicity</u>: These products are not reported to cause teratogenic effects in humans. Clinical studies on test animals exposed to relatively high doses of Tungsten (a component of these products) during pregnancy indicate teratogenic effects.

<u>Reproductive Toxicity</u>: These products are not reported to cause reproductive effects in humans. Clinical studies on test animals exposed to relatively high doses of Tungsten (a component of these products) during pregnancy indicate adverse reproductive effects.

A <u>mutagen</u> is a chemical, which causes permanent changes to genetic material (DNA) such that the changes will propagate through generational lines. An <u>embryotoxin</u> is a chemical, which causes damage to a developing embryo (i.e. within the first eight weeks of pregnancy in humans), but the damage does not propagate across generational lines. A <u>teratogen</u> is a chemical, which causes damage to a developing fetus, but the damage does not propagate across generational lines. A <u>teratogen</u> is a chemical, which causes damage to a developing fetus, but the damage does not propagate across generational lines. A <u>reproductive toxin</u> is any substance, which interferes in any way with the reproductive process.

BIOLOGICAL EXPOSURE INDICES: Currently there are no Biological Exposure Indices (BEIs) determined for the components of these products.

12. ECOLOGICAL INFORMATION

ALL WORK PRACTICES MUST BE AIMED AT ELIMINATING ENVIRONMENTAL CONTAMINATION.

ENVIRONMENTAL STABILITY: Tungsten will slowly react with water, oxygen, and other compounds to form a wide variety of tungsten compounds.

EFFECT OF MATERIAL ON PLANTS or ANIMALS: Due to the product size and the product's form, no unusual environmental effects are expected from these products; however, large releases of Tungsten may be harmful to contaminated plants and animals.

EFFECT OF CHEMICAL ON AQUATIC LIFE: Due to the product size and the product's form, these products are not anticipated to cause adverse effects on aquatic life; however, large releases of Tungsten into a body of water may be harmful to aquatic plants and animals.

13. DISPOSAL CONSIDERATIONS

PREPARING WASTES FOR DISPOSAL: Waste disposal must be in accordance with appropriate Federal, State, and local regulations. These products, if unaltered by use, may be disposed of by treatment at a permitted facility or as advised by your local hazardous waste regulatory authority.

EPA WASTE NUMBER: Not applicable to wastes consisting only of these products.

14. TRANSPORTATION INFORMATION

THIS MATERIAL IS NOT HAZARDOUS (Per 49 CFR 172.101) BY THE U.S. DEPARTMENT OF TRANSPORTATION.

PROPER SHIPPING NAME: HAZARD CLASS NUMBER and DESCRIPTION: UN IDENTIFICATION NUMBER: PACKING GROUP: DOT LABEL(S) REQUIRED:

Not applicable. Not applicable. Not applicable. Not applicable. Not applicable.

NORTH AMERICAN EMERGENCY RESPONSE GUIDEBOOK NUMBER, 2000: Not applicable.

MARINE POLLUTANT: No component of these products is designated as a marine pollutant by the Department of Transportation (49 CFR 172.101, Appendix B).

TRANSPORT CANADA TRANSPORTATION OF DANGEROUS GOODS REGULATIONS: These materials are not considered as dangerous goods, per regulations of Transport Canada.

15. REGULATORY INFORMATION

ADDITIONAL U.S. REGULATIONS:

U.S. SARA REPORTING REQUIREMENTS: Tungsten is not subject to the reporting requirements of Sections 302, 304 and 313 of Title III of the Superfund Amendments and Reauthorization Act, as follows:

CHEMICAL NAME	SARA 302	SARA 304	SARA 313
	(40 CFR 355, Appendix A)	(40 CFR Table 302.4)	(40 CFR 372.65)
Thorium Oxide	No	No	Yes

U.S. SARA THRESHOLD PLANNING QUANTITY: There are no specific Threshold Planning Quantities for components of these products. The default Federal SDS submission and inventory requirement filing threshold of 10,000 lbs (4,540 kg) therefore applies, per 40 CFR 370.20.

U.S. TSCA INVENTORY STATUS: Components of these products are listed on the TSCA Inventory.

U.S. CERCLA REPORTABLE QUANTITY (RQ): Not applicable.

U.S. OTHER FEDERAL REGULATIONS: If these products are used during welding operations, follow the requirements of the Federal Occupational Safety and Health Welding and Cutting Standard (29 CFR 1910 Subpart Q). For those electrodes that contain thorium oxide, regulations of the Nuclear Regulatory Commission [Title 10, Parts 20 (Standards for Protection Against Radiation) and 40 (Domestic Licensing of Source Material)] should be consulted to determine if requirements of these regulations may apply to the use of these electrodes.

15. REGULATORY INFORMATION (Continued)

ADDITIONAL U.S. REGULATIONS (continued):

U.S. STATE REGULATORY INFORMATION: The components of these product are covered under specific State regulations, as denoted below:

- Alaska Designated Toxic and Hazardous Substances: Tungsten.
- California Permissible Exposure Limits for Chemical Contaminants: Tungsten.
- Florida Substance List: Thorium Dioxide, Tungsten.
- Illinois Toxic Substance List: Thorium Dioxide, Tungsten.
- Kansas Section 302/313 List: Thorium Dioxide.
- Massachusetts Substance List: Thorium Dioxide, Tungsten.
- Minnesota List of Hazardous Substances: Thorium Dioxide, Tungsten.
- Missouri Employer Information/Toxic Substance List: Tungsten.
- New Jersey Right to Know Hazardous Substance List: Thorium Dioxide, Tungsten.
- North Dakota List of Hazardous Chemicals, Reportable Quantities: No.
- Pennsylvania Hazardous Substance List: Thorium Dioxide, Tungsten.
- Rhode Island Hazardous Substance List: Tungsten.
- Texas Hazardous Substance List: No.
- West Virginia Hazardous Substance List: No.

Wisconsin - Toxic and Hazardous Substances: No.

CALIFORNIA PROPOSITION 65: Thorium Oxide is a component of some of these products. Thorium Oxide is on the California Proposition 65 lists. **WARNING: This product may contain chemicals, and when used for welding may produce fumes or gases containing chemicals, known to the State of California to cause cancer, and/or birth defects (or other reproductive harm.)**

ANSI LABELING (Z129.1) [Precautionary Statements]:

CAUTION! MAY CAUSE SKIN AND EYE IRRITATION. INHALATION OF FUMES OR DUSTS FROM PROUDCT MAY BE IRRITATING TO RESPIRATORY SYSTEM. Avoid inhalation of fumes or dusts from product during use. Avoid contact with skin and eyes. Wash thoroughly after handling. Wear gloves and goggles. FIRST-AID: In case of skin or eye contact, flush skin with water for 15 minutes. Seek medical attention if adverse reaction occurs. IN CASE OF FIRE: Use water fog, dry chemical, CO₂, or "alcohol" foam. IN CASE OF SPILL: Pick-up spilled material. Place in a suitable container. Consult Material Safety Data Sheet before use.

LABELING FOR WELDING PRODUCTS:

WARNING! PROTECT yourself and others. Read and understand this information.

FUMES and GASES can be hazardous to your health.

ARC RAYS can injure eyes and burn skin.

ELECTRIC SHOCK can KILL.

- Before use, read and understand the manufacturer's instructions, Safety Data Sheets (SDSs), and your employer's safety practices.
- Keep your head out of fumes.
- Use enough ventilation, exhaust at the arc, or both, to keep fumes and gases away from your breathing zone and the general area.
- Wear correct eye, ear, and body protection.
- Do not touch live electrical parts.

• See American National Standard ANSI/ASC Z49.1 "Safety in Welding, Cutting, and Allied Processes", published by the American Welding Society, 550 N.W., Lejeune Road, Miami, FL 33126; and OSHA Safety and Health Standards, 29 CFR 1910, available from the U.S. Government Printing Office, Washington, D.C.

DO NOT REMOVE THIS INFORMATION.

ADDITIONAL CANADIAN REGULATIONS:

CANADIAN DSL/NDSL INVENTORY STATUS: The components of these products are on the DSL Inventory.

OTHER CANADIAN REGULATIONS: Not applicable.

CANADIAN ENVIRONMENTAL PROTECTION ACT (CEPA) PRIORITIES SUBSTANCES LISTS: The components of these products are not on the CEPA Priorities Substances Lists.

CANADIAN WHMIS SYMBOLS: Not applicable.

16. OTHER INFORMATION

DATE OF PRINTING:

July 27th, 2015

This Material Safety Data Sheet is offered pursuant to OSHA's Hazard Communication Standard (29 CFR 1910.1200). Other government regulations must be reviewed for applicability to these products. The information contained herein relates only to the specific product. If the product is combined with other materials, all component properties must be considered. To the best of Midwest Tungsten Service's knowledge, the information and recommendations contained in this publication are reliable and accurate as the date of issue. However, accuracy, suitability, or completeness are not guaranteed, and no warranty, guarantee, or representation, expressed or implied, is made by Midwest Tungsten Service as to the absolute correctness or sufficiency of any representation contained in this and other publications Midwest Tungsten Service assumes no responsibility in connection therewith, nor can it be assumed that all acceptable safety measures may not be required under particular or exceptional conditions or circumstances. Data may be changed from time to time. Be sure to consult the latest edition.

DEFINITIONS OF TERMS

A large number of abbreviations and acronyms appear on a SDS. Some of these, which are commonly used, include the following:

CAS #: This is the Chemical Abstract Service Number, which uniquely identifies each constituent. **EXPOSURE LIMITS IN AIR:**

ACGIH - American Conference of Governmental Industrial Hygienists, a professional association which establishes exposure limits. TIV -Threshold Limit Value - an airborne concentration of a substance, which represents conditions under which it is generally believed that nearly all workers, may be repeatedly exposed without adverse effect. The duration must be considered, including the 8-hour Time Weighted Average (TWA), the 15-minute Short Term Exposure Limit, and the instantaneous Ceiling Level (C). Skin absorption effects must also be considered.

OSHA - U.S. Occupational Safety and Health Administration.

PEL - Permissible Exposure Limit - This exposure value means exactly the same as a TLV, except that it is enforceable by OSHA. The OSHA Permissible Exposure Limits are based in the 1989 PELs and the June, 1993 Air Contaminants Rule (Federal Register: 58: 35338-35351 and 58: 40191). Both the current PELs and the vacated PELs are indicated. The phrase, "Vacated 1989 PEL," is placed next to the PEL, which was vacated by Court Order. IDLH - Immediately Dangerous to Life and Health - This level represents a concentration from which one can escape within 30minutes without suffering escape-preventing or permanent injury. The DFG -MAK is the Republic of Germany's Maximum Exposure Level, similar to the U.S. PEL. NIOSH is the National Institute of Occupational Safety and Health, which is the research arm of the U.S. Occupational Safety and Health Administration (OSHA). NIOSH issues exposure guidelines called Recommended Exposure Levels (RELs). When no exposure guidelines are established, an entry of NE is made for reference.

HAZARD RATINGS:

HAZARDOUS MATERIALS IDENTIFICATION SYSTEM: Health Hazard: 0 (minimal acute or chronic exposure hazard); 1 (slight acute or chronic exposure hazard); 2 (moderate acute or significant chronic exposure hazard); 3 (severe acute exposure hazard; onetime overexposure can result in permanent injury and may be fatal); 4 (extreme acute exposure hazard; onetime overexposure can be fatal). Flammability Hazard: 0 (minimal hazard); 1 (materials that require substantial pre-heating before burning); 2 (combustible liquid or solids; liquids with a flash point of 38-93°C [100-200°F1): 3 (Class IB and IC flammable liquids with flash points below 38°C [100°F]); 4 (Class IA flammable liquids with flash points below 23°C [73°F] and boiling points below 38°C [100°F]. Reactivity Hazard: 0 (normally stable); 1 (material that can become unstable at elevated temperatures or which can react slightly with water); 2 (materials that are unstable but do not detonate or which can react violently with water); 3 (materials that can detonate when initiated or which can react explosively with water); 4 (materials that can detonate at normal temperatures or pressures).

NATIONAL FIRE PROTECTION ASSOCIATION: Health Hazard: 0 (material that on exposure under fire conditions would offer no hazard beyond that of ordinary combustible materials); 1 (materials that on exposure under fire conditions could cause irritation or minor residual injury); 2 (materials that on intense or continued exposure under fire conditions could cause temporary incapacitation or possible residual injury); 3 (materials that can on short exposure could cause serious temporary or residual injury); 4 (materials that under very short exposure causes death or major residual injury). Flammability Hazard and Reactivity Hazard: Refer to definitions for "Hazardous Materials Identification System".

FLAMMABILITY LIMITS IN AIR:

Much of the information related to fire and explosion is derived from the National Fire Protection Association (NFPA). Flash Point -Minimum temperature at which a liquid gives off sufficient vapors to form an ignitable mixture with air. Autoignition Temperature: The minimum temperature required to initiate combustion in air with no other source of ignition. LEL the lowest percent of vapor in air, by volume, that will explode or ignite in the presence of an ignition source. <u>UEL</u> - the highest percent of vapor in air, by volume, that will explode or ignite in the presence of an ignition source.

TOXICOLOGICAL INFORMATION:

Human and Animal Toxicology: Possible health hazards as derived from human data, animal studies, or from the results of studies with similar compounds are presented. Definitions of some terms used in this section are: LD₅₀ - Lethal Dose (solids & liquids) which kills 50% of the exposed animals; LC50 - Lethal Concentration (gases) which kills 50% of the exposed animals; ppm concentration expressed in parts of material per million parts of air or water; **mg/m³** concentration expressed in weight of substance per volume of air; mg/kg quantity of material, by weight, administered to a test subject, based on their body weight in kg. Other measures of toxicity include TDLo, the lowest dose to cause a symptom and TCLo the lowest concentration to cause a symptom; TDo, LDLo, and LDo, or TC, TCo, LCLo, and LCo, the lowest dose (or concentration) to cause lethal or toxic effects. Cancer Information: The sources are: IARC - the International Agency for Research on Cancer; NTP - the National Toxicology Program, RTECS - the Registry of Toxic Effects of Chemical Substances, OSHA and CAL/OSHA. IARC and NTP rate chemicals on a scale of decreasing potential to cause human cancer with rankings from 1 to 4. Subrankings (2A, 2B, etc.) are also used. Other Information: BEI - ACGIH Biological Exposure Indices, represent the levels of determinants which are most likely to be observed in specimens collected from a healthy worker who has been exposed to chemicals to the same extent as a worker with inhalation **Ecological Information:** exposure to the TLV. EC is the effect concentration in water. BCF = Bioconcentration Factor, which is used to determine if a substance will concentrate in lifeforms which consume contaminated plant or animal matter. Coefficient of Oil/Water Distribution is represented by $\log K_{ow}$ or $\log K_{oc}$ and is used to assess a substance's behavior in the environment.

REGULATORY INFORMATION:

This section explains the impact of various laws and regulations on the material. U.S.: EPA is the U.S. Environmental Protection Agency. DOT is the U.S. Department of Transportation. SARA is the Superfund Amendments and Reauthorization Act. TSCA is the U.S. Toxic Substance Control Act. CERCLA (or Superfund) refers to the Comprehensive Environmental Response, Compensation, and Liability Act. Labeling is per the American National Standards Institute (ANSI Z129.1). CANADA: WHMIS is the **CEPA** is the Canadian Environmental Protection Act. Canadian Workplace Hazardous Materials Information System. TC is Transport Canada. DSL/NDSL are the Canadian Domestic/Non-Domestic Substances Lists. The CPR is the Canadian Product Regulations. This section also includes information on the precautionary warnings, which appear, on the materials package label.


SAFETY DATA SHEET

Revision Date 24-Dec-2021

Revision Number 4

1. Identification

Product Name

Calcium fluoride

Cat No. :	C89-250; C89-500	
CAS No	7789-75-5	
Synonyms	Fluorspar; Fluorite; Calcium difluoride	
Recommended Use	Laboratory chemicals.	
Uses advised against	Food, drug, pesticide or biocidal product use.	

Details of the supplier of the safety data sheet

Company Fisher Scientific Company One Reagent Lane Fair Lawn, NJ 07410 Tel: (201) 796-7100

Emergency Telephone Number

CHEMTREC®, Inside the USA: 800-424-9300 CHEMTREC®, Outside the USA: 001-703-527-3887

2. Hazard(s) identification

Classification

Classification under 2012 OSHA Hazard Communication Standard (29 CFR 1910.1200)

This chemical is not considered hazardous by the 2012 OSHA Hazard Communication Standard (29 CFR 1910.1200)

Label Elements
None required

Hazards not otherwise classified (HNOC) None identified

3. Composition/Information on Ingredients

Component		CAS No	Weight %
Calcium fluoride (CaF2		7789-75-5	100
	4.	First-aid measures	
General Advice If symptoms p		persist, call a physician.	
Eye Contact	Rinse immediately with plenty of water, also under the eyelids, for at least 15 minutes. G medical attention.		ne eyelids, for at least 15 minutes. Get
Skin Contact	Wash off immediately with plenty of water for at least 15 minutes. Get medical attention immediately if symptoms occur.		
Inhalation	Remove to fresh air. Get medical attention immediately if symptoms occur.		
Ingestion	Clean mouth with water and drink afterwards plenty of water. Get medical attention if symptoms occur.		
Most important symptoms and effects	None reasonably foreseeable.		
Notes to Physician	Treat symptomatically		

5. Fire-fighting measures

Unsuitable Extinguishing Media	No information available
Flash Point Method -	Not applicable No information available
Autoignition Temperature Explosion Limits	No information available
Upper	No data available
Lower	No data available
Sensitivity to Mechanical Impact Sensitivity to Static Discharge	No information available No information available

Specific Hazards Arising from the Chemical

Keep product and empty container away from heat and sources of ignition.

Hazardous Combustion Products

None known.

Protective Equipment and Precautions for Firefighters

As in any fire, wear self-contained breathing apparatus pressure-demand, MSHA/NIOSH (approved or equivalent) and full protective gear.

NFPAHealth 2	Flammability 0	Instability 0	Physical hazards N/A
	6. Accidental re	lease measures	
Personal Precautions	Ensure adequate ventilation. Use personal protective equipment as required. Avoid dust formation.		
Environmental Precautions	Should not be released internation.	o the environment. See Section	n 12 for additional Ecological

Methods for Containment and Clean Sweep up and shovel into suitable containers for disposal. Avoid dust formation. Up

	7. Handling and storage
Handling	Wear personal protective equipment/face protection. Ensure adequate ventilation. Avoid ingestion and inhalation. Avoid contact with skin, eyes or clothing. Avoid dust formation.
-	

Storage.

Keep containers tightly closed in a dry, cool and well-ventilated place.

8. Exposure controls / personal protection

Exposure Guidelines

Component	ACGIH TLV	OSHA PEL	NIOSH IDLH	Mexico OEL (TWA)
Calcium fluoride (CaF2)	TWA: 2.5 mg/m ³	(Vacated) TWA: 2.5 mg/m ³	IDLH: 250 mg/m ³ TWA: 2.5 mg/m ³	TWA: 2.5 mg/m ³

<u>Legend</u>

ACGIH - American Conference of Governmental Industrial Hygienists OSHA - Occupational Safety and Health Administration NIOSH IDLH: NIOSH - National Institute for Occupational Safety and Health

Engineering Measures	Ensure that eyewash stations and safety showers are close to the workstation location.		
Personal Protective Equipment			
Eye/face Protection	Wear appropriate protective eyeglasses or chemical safety goggles as described by OSHA's eye and face protection regulations in 29 CFR 1910.133 or European Standard EN166.		
Skin and body protection	Wear appropriate protective gloves and clothing to prevent skin exposure.		
Respiratory Protection	Follow the OSHA respirator regulations found in 29 CFR 1910.134 or European Standard EN 149. Use a NIOSH/MSHA or European Standard EN 149 approved respirator if exposure limits are exceeded or if irritation or other symptoms are experienced.		
Hygiene Measures	Handle in accordance with good industrial hygiene and safety practice.		

9. Physical and chemical properties

y	· · ·
Physical State	Solid
Appearance	White
Odor	Odorless
Odor Threshold	No information available
pH	No information available
Melting Point/Range	1422.8 °C / 2593 °F
Boiling Point/Range	No information available
Flash Point	Not applicable
Evaporation Rate	Not applicable
Flammability (solid,gas)	No information available
Flammability or explosive limits	
Upper	No data available
Lower	No data available
Vapor Pressure	No information available
Vapor Density	Not applicable
Specific Gravity	3.180
Solubility	Insoluble in water
Partition coefficient; n-octanol/water	No data available
Autoignition Temperature	No information available
Decomposition Temperature	No information available
Viscosity	Not applicable
Molecular Formula	CaF2

Molecular Weight

78.08

10. Stability and reactivity

Reactive Hazard	None known, based on information available		
Stability	Stable under normal conditions.		
Conditions to Avoid	Incompatible products.		
Incompatible Materials	Strong oxidizing agents		
Hazardous Decomposition Products None under normal use conditions			
Hazardous Polymerization	Hazardous polymerization does not occur.		
Hazardous Reactions	None under normal processing.		

11. Toxicological information

Acute Toxicity

Product Information

Component information			
Component	LD50 Oral	LD50 Dermal	LC50 Inhalation
Calcium fluoride (CaF2)	LD50 = 4250 mg/kg (Rat)	LD50 = 4250 mg/kg (Rat) Not listed LC50 > 5070 mg/m ³	
Toxicologically Synergistic	No information available		
Products			
Delayed and immediate effects	as well as chronic effects fron	n short and long-term exposure	e_
Irritation	No information available		

No information available

Sensitization

Carcinogenicity

The table below indicates whether each agency has listed any ingredient as a carcinogen.

Component	CAS No	IARC	NTP	ACGIH	OSHA	Mexico
Calcium fluoride (CaF2)	7789-75-5	Not listed	Not listed	Not listed	Not listed	Not listed
Mutagenic Effects		No information ava	ailable			
Reproductive Effect	S	No information ava	ailable.			
Developmental Effect	cts	No information ava	ailable.			
Teratogenicity		No information available.				
STOT - single expos STOT - repeated exp	ure oosure	None known None known				
Aspiration hazard		No information ava	ailable			
Symptoms / effects delayed	both acute and	No information ava	ailable			
Endocrine Disruptor	Information	No information ava	ailable			
Other Adverse Effec	ts	The toxicological p	properties have not	been fully investig	ated.	

12. Ecological information

Ecotoxicity

Persistence and Degradability	No information available
oaccumulation/ Accumulation No information available.	
Mobility	No information available.
	13. Disposal considerations
Waste Disposal Methods	Chemical waste generators must determine whether a discarded chemical is classified as a hazardous waste. Chemical waste generators must also consult local, regional, and

national hazardous waste regulations to ensure complete and accurate classification.

	14. Transport information	
DOT	Not regulated	
TDG	Not regulated	
IATA	Not regulated	
IMDG/IMO	Not regulated	
	15. Regulatory information	

United States of America Inventory

Component	CAS No	TSCA	TSCA Inventory notification - Active-Inactive	TSCA - EPA Regulatory Flags
Calcium fluoride (CaF2)	7789-75-5	Х	ACTIVE	-

Legend:

TSCA US EPA (TSCA) - Toxic Substances Control Act, (40 CFR Part 710) X - Listed

'-' - Not Listed

TSCA 12(b) - Notices of Export Not applicable

International Inventories

Canada (DSL/NDSL), Europe (EINECS/ELINCS/NLP), Philippines (PICCS), Japan (ENCS), Japan (ISHL), Australia (AICS), China (IECSC), Korea (KECL).

Component	CAS No	DSL	NDSL	EINECS	PICCS	ENCS	ISHL	AICS	IECSC	KECL
Calcium fluoride (CaF2)	7789-75-5	Х	-	232-188-7	Х	Х	Х	Х	Х	KE-04538

KECL - NIER number or KE number (http://ncis.nier.go.kr/en/main.do)

U.S. Federal Regulations

SARA 313	Not applicable
SARA 311/312 Hazard Categories	See section 2 for more information
CWA (Clean Water Act)	Not applicable
Clean Air Act	Not applicable
OSHA - Occupational Safety and Health Administration	Not applicable

CERCLA

Not applicable

California Proposition 65

This product does not contain any Proposition 65 chemicals.

U.S. State Right-to-Know

Regulations

Component	Massachusetts	New Jersey	Pennsylvania	Illinois	Rhode Island
Calcium fluoride (CaF2)	-	Х	-	-	Х

U.S. Department of Transportation	
Reportable Quantity (RQ):	Ν
DOT Marine Pollutant	Ν
DOT Severe Marine Pollutant	Ν
U.S. Department of Homeland Security	This product does not contain any DHS chemicals.
Other International Regulations	

Mexico - Grade

No information available

Authorisation/Restrictions according to EU REACH

Safety, health and environmental regulations/legislation specific for the substance or mixture

Component	CAS No	OECD HPV	Persistent Organic Pollutant	Ozone Depletion Potential	Restriction of Hazardous Substances (RoHS)
Calcium fluoride (CaF2)	7789-75-5	Listed	Not applicable	Not applicable	Not applicable
Component	CAS No	Seveso III Directive (2012/18/EC) - Qualifying Quantities for Major Accident Notification	Seveso III Directive (2012/18/EC) - Qualifying Quantities for Safety Report Requirements	Rotterdam Convention (PIC)	Basel Convention (Hazardous Waste)
Calcium fluoride (CaF2)	7789-75-5	Not applicable	Not applicable	Not applicable	Not applicable

	16. Other information
Prepared By	Regulatory Affairs Thermo Fisher Scientific Email: EMSDS.RA@thermofisher.com
Revision Date Print Date Revision Summary	24-Dec-2021 24-Dec-2021 This document has been updated to comply with the US OSHA HazCom 2012 Standard replacing the current legislation under 29 CFR 1910.1200 to align with the Globally Harmonized System of Classification and Labeling of Chemicals (GHS).

Disclaimer

The information provided in this Safety Data Sheet is correct to the best of our knowledge, information and belief at the date of its publication. The information given is designed only as a guidance for safe handling, use, processing, storage, transportation, disposal and release and is not to be considered a warranty or quality specification. The information relates only to the specific material designated and may not be valid for such material used in combination with any other materials or in any process, unless specified in the text

End of SDS

Appendix D: Manufacturer Given Equipment Information

The following section includes the following manufacturer provided product information sheets,

in the order given:

- GAC Filtrasorb Product Manual
- GAC Vessel Manual
- P-200 Product Manual
- P-201 Product Manual
- P-202 Product Manual
- P-203 Product Manual
- P-204 Product Manual
- Sulzer Inline Mixer Product Brochure
- Pentair POINT FOURTM MICRO BUBBLE DIFFUSERS (MBD)
- Airgas Size 300 Argon Gas Cylinder
- NF 90 Membrane: 400 Manual
- NF 90 Membrane: 4040 Manual
- NF 90 Membrane: Cleaning Manual
- Rotary Drum Filter Product Manual



Basic Pedestal



Standard Centrifugal Pump

Model 6510A60-B

Size 12" x 10"

PUMP SPECIFICATIONS

Size: 12" x 10" 305 mm x 254 mm) Flanged. Casing: Ductile Iron 65-45-12. Maximum Casing Pressure 351 psi (2420 kPa).* Maximum Operating Pressure 250 psi (1723 kPa) at Temperatures up to 100° F (37° C) Based on System Component Limitations.* Enclosed Type, Four Vane Impeller: Ductile Iron 80-55-06. Handles 2" (50,8 mm) Diameter Spherical Solids. Suction Spool: Gray Iron 30. Impeller Shaft: Alloy Steel 4150. Replaceable Wear Rings: Ductile Iron 65-45-12. Pedestal: Gray Iron 30. Seal Plate: Ductile Iron 65-45-12. Shaft Sleeve: Stainless Steel 303/304. Radial Bearing: Open Single Row Ball. Thrust Bearing: Open Double Row Ball. Bearing and Seal Cavity Lubrication: SAE 30 Non-Detergent Oil. Gaskets: Vegetable Fiber, Red Rubber and Buna-N. O-Rings: Buna-N. Hardware: Standard Plated Steel. WARNING! Bearing and Seal Cavity Oil Level Sight Gauges. Do not use in explosive atmosphere or for pump-ing volatile flammable liquids. *Consult Factory for Applications Exceeding Maximum Pressure and/or Temperature Indicated. DISCHARGE SEAL PLATE BEARINGS WEAR RING SUCTION SPOOL IMPELLER **SEAL DETAIL** SHAFT PEDESTAL Mechanical. Oil-Lubricated. Silicon Carbide Rotating Face and Stationary Seat. Fluorocarbon Elastomers (DuPont SUPPORT Viton[®] or Equivalent). Stainless Steel 316 LIP SEALS Cage and Stainless Steel 18-8 Spring. WEAR RING IMPELLER SEAL ASSEMBLY Maximum Temperature of Liquid Pumped SUPPORT CASING 160°F (71°C).*



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Stand	dard C	onst	truc	tion							GHC, S	EC. 54 Ja	l0: PA anuar	\GE 11 y 2010			
EXTER-	ROTOR	HOUSI			IDLER		ПУЕТ	SHA	FT SE			ll RE	NTERN LIEF V	ALVE			
IOR	IDLER	PORT	S BUS	SUINCE	PIN	- Jor	пагі		JEAL			MATER		SETTING			
CAST IRON	HIGH STRENGTH IRON	180° TAPPE	D BF	ONZE	HARDEN STEEI	LED S	TEEL	VIT	ON	BUNA-I	N C.W.	DUCT IRO	TILE N	75 PSI [5 BAR]			
Stand	dard N	lode	ls		G F	I C	;	1	DC	3	– B						
					GEAR DU	JTY DES	IGN	PORT SIZE	HYDRA Size	IULIC SE	AL STYLE						
			NO	M. CAPA	CITY - S	PEED				MAX	MUM	•	SHIF	PING			
	MODEL		MAX	KIMUM	ALTE	RNATIV	E D	IFFERE	NTIAL	PRESSU	re-PSI [BAR]	TEMP.	D/	ATA I			
1	NUMBER		GPM	RPM	GPM		3 B	BELOW	38	TO SSU 4	100 TO	°F	Weight	t Volume			
			[LPM]	[50 HZ]	[LPM]	[50 Hz	[]	[4 cSt]	[21	cSt]	[55,000 cSt]	[°C]	LBS [KG]	FT.			
GHC 1DC GHC 1DC	C 3-B C 4-B	1	9 [28]		6 [19]								29 [13,2]	0.6			
GHC 1DE GHC 1DE	E 3–B E 4–B		11 [35]		7 [22]								30 [13,6]	0.6			
GHC 1-1/ GHC 1-1/	2 GC 3-B 2 GC 4-B		16		10								58 [26,4]	2.9			
GHC 2 G GHC 2 G	C 3-B C 4-B		[50]		[32]	[32]						300 [21]		58 [26,4]	2.9		
GHC 1-1/ GHC 1-1/	2 GF 3–B 2 GF 4–B		23 1750	15	1150	0					350 [177]	58 [26,4]	2.9				
GHC 2 G GHC 2 G	F 3-B F 4-B		[73]	[1460]] [47]	[960)]	100 150	0			58 [26,4]	2.9				
GHC 1-1 GHC 1-1	/2 GH 3-B /2 GH 4-B		31		20			[7]	[10)]			58 [26,4]	2.9			
GHC 2 G GHC 2 G	H 3-B H 4-B		[98]		[63]										225 [107]	58 [26,4]	2.9
GHC 1-1/ GHC 1-1/	2 GJ 3-B 2 GJ 4-B	2	38		25						200		58 [26,4]	2.9			
GHC 2 G GHC 2 G	J 3–B J 4–B	2	[120]		[79]						[14]		58 [26,4]	2.9			
GHC 2 JO GHC 2 JO	G 3-B G 4-B												128 [58,2]	5.3			
GHC 2-1/ GHC 2-1/	2 JG 3-B 2 JG 4-B		40 [126]	1150 [960]	30 [95]	870 [725) 5]				300 [21]		128 [58,2]	5.3			
GHC 3 JO GHC 3 JO	G 3-B G 4-B												128 [58,2]	5.3			
STAN	DARD MODE	LS		• MEC	CHANICA	L SEAL	L		LIPS	SEAL							

NOTE: RECOMMENDED PORT SIZES ARE SHOWN IN BOLDFACE. EXAMPLE: GHC 1 DC 3-B

- (1) 3450 [2875] RPM PERMISSIBLE TO 1,000 SSU [220 cSt] AND 100 PSI [7 BAR]
- (2) PUMP LIMITED TO 200 PSI MAXIMUM PRESSURE.
- (3) MAXIMUM SPEED FOR AMMONIA MODELS.

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GORMAN-RUPP OF CANADA LIMITED • ST. THOMAS, ONTARIO, CANADA

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Standard Models Cont'd

GHC, SEC. 540: PAGE 12 January 2010

		NOM. CAPACITY - SPEED				MAXIMUM					SHIPPING	
MODEL		MA	MAXIMUM ALTERNAT		RNATIVE	DIFFEREN	ITIAL PRESS	URE-PSI [BAR]	TEMP.	DATA		
NUMBER		GPM	RPM	GPM	RPM (2)	BELOW	38 TO	100 TO	°F	Weight	Volume	
Nombert		[LPM]	60 Hz [50 HZ]	[LPM]	60 Hz [50 Hz]	38 SSU [4 cST]	100 SSU [21 cST]	250,000 SSU [55,000 cSt]	[°C]	LBS [KG]	CU. FT.	
GHC 2 JJ 3-B GHC 2 JJ 4-B										132 [60]	5.3	
GHC 2-1/2 JJ 3-B GHC 2-1/2 JJ 4-B		56 [177]		42 [133]						132 [60]	5.3	
GHC 3 JJ 3-B GHC 3 JJ 4-B								300	● 350	132 [60]	5.3	
GHC 2 JL 3-B GHC 2 JL 4-B								[21]	[177]	132 [60]	5.3	
GHC 2-1/2 JL 3-B GHC 2-1/2 JL 4-B		77 [243]	1150 [960]	58 [183]	870 [725]	100 [7]	150 [10]			132 [60]	5.3	
GHC 3 JL 3-B GHC 3 JL 4-B									225	132 [60]	5.3	
GHC 2 JP 3-B GHC 2 JP 4-B	1								[107]	132 [60]	5.3	
GHC 2-1/2 JP 3-B GHC 2-1/2 JP 4-B	1	107 [338]		81 [256]				200 [14]		132 [60]	5.3	
GHC 3 JP 3-B GHC 3 JP 4-B	1									132 [60]	5.3	

NOTE: RECOMMENDED PORT SIZES ARE SHOWN IN BOLDFACE. EXAMPLE: GHC 1 DC 3-B

- (1) PUMP LIMITED TO 200 PSI MAXIMUM PRESSURE.
- (2) MAXIMUM SPEED FOR AMMONIA MODELS.

APPLICATION RECOMMENDATIONS:								
APPLICATION	OPTIONS REQUIRED (Select One from Each Row)	OPERATING LIMITATIONS						
AMMONIA	25G, 25H, 25R, 25S, 25T 40N 60K 70E 90A	PRESSURE: 200 PSI MAX. 2/3 RATED SPEED. 4 FEET NPSHr						
LP GAS	25G OR 25H 40F OR 40N 70D OR 70E	PRESSURE: 200 PSI MAX. 3 FEET NPSHr						

NOTE: PROPER PUMP APPLICATION REQUIRES CONSIDERATION OF ADDITIONAL FACTORS. PLEASE REVIEW APPLICATION GUIDE IN SECTION 500 OR CONSULT THE FACTORY.

Basic Pump Dimensions

GHC, SEC. 540: PAGE 14 January 2010



► PORTS ARE COMPATIBLE WITH 125# OR 250# ANSICAST IRON FLANGES. ALL OTHER PORTS ARE TAPPED NPT FOR ANSIPIPE. OPTIONAL (DIN) FLANGES OR TAPPED (BSP) PORTS AVAILABLE FOR EXPORT MARKET.

Continued -

Basic Pump Dimensions



† 90° HOUSING

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January 2010

(Drive Assembly Number Includes Base, Coupling & Guard, But NOT the Motor)





PUMP MODEL NUMBER	60 Hz RPM	50 Hz RPM	FRAME	MTG. FT. Option Req.	DRIVE ASSY NO.							
			56/56H	STD	90351-086							
	3450	2900	143T/145T	STD	90351-052							
GHC D	1/50	1450 950	184	80F	90351-089							
	850	700	182T/184T	80F	90351-090							
			213T/215T	80J	90351-094							
			56/56H	STD	90351-156							
		1450 950 700	1450 950 700	1450 950 700	143T/145T	STD	90351-162					
GHC G	1750				1450 950 700	1450 950 700	1450 950 700	1450 950 700	1450 950 700	182T/184T	80F	90351-168
	850									213T/215T	80J	90351-206
			213T/215T	80J	90351-172							
			254T	80P	90351-180							
			182T/184T	80F	90351-260							
GHC J	1150	950	213T/215T	STD	90351-268							
G00	850	700	254T/256T	80P	90351-276							
				284T/286T	80S	90351-280						

NOTE: CONSULT FACTORY FOR; HORSEPOWERS & FRAMES NOT SHOWN DRIP PAN BASES







SEC. 540

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January 2010

DIRECT FLEX C-FLANGE DRIVE OPTIONS

(Drive Assemby Number Includes Base & Coupling, But **NOT** the Motor)



PUMP MODEL NUMBER	60Hz RPM	FRAME	MTG. FT. Option Req.	DRIVE ASSY NO.
	3450	56C	80Y	90351-540
GHC D	1750	143TC	80Y	90351-541
	1150	145TC	80Y	90351-544
	850	184C	80Y	90351-590
		56C	80Y	90351-656
	1750	143TC	80Y	90351-659
снс с		145TC	80Y	90351-660
	850	184C	80Y	90351-668
		182TC	80X	90351-672
		184TC	80X	90351-674
		213TC	80X	90351-764
		215TC	80X	90351-768
GHC J	1150	254TC	80W	90351-772
	000	256TC	80W	90351-776
		184TC	80X	90351-814

NOTE: CONSULT FACTORY FOR; HORSEPOWERS & FRAMES NOT SHOWN DRIP PAN BASES



* STANDARD DIMENSION

PORTS ARE COMPATIBLE WITH 125# OR 250# ANSICAST IRON FLANGES. ALL OTHER PORTS ARE TAPPED NPT FOR ANSIPIPE. OPTIONAL (DIN) FLANGES OR TAPPED (BSP) PORTS AVAILABLE FOR EXPORT MARKET. † 90° HOUSING



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GRR REDUCER C-FLANGE FLEX DRIVE OPTIONS

(Drive Assy Number Includes Base, Coupling, Guard & Gear Reducer, But NOT the Motor)



	DDM	DDM		REDUCER	1							
MODEL	@ 1750	@ 1150	RATIO	MAX HP @ 1750	MAX HP @ 1150	FRAME	OPTION REQ.	ASSY NO.				
			2.00:1	6.00	3.96	56C	STD	90353-510				
	075			6.00	3.96	143TC/145TC	STD	90353-516				
	875	5/5		6.00	3.96	182C/184C	80F	90353-519				
GHC D				20.00	13.2	182TC/184TC	80F	90353-526				
	580	383	3.00:1	4.21	2.78	56C	STD	90353-530				
				8.10	5.35	143TC/145TC	STD	90353-536				
				8.10	5.35	182C/184C	80F	90353-539				
				12.98	8.57	182TC/184TC	80F	90353-546				
		288	4.00:1	3.63	2.39	56C	STD	90353-550				
	440			5.90	3.89	143TC/145TC	STD	90353-556				
	0			5.90	3.89	182C/184C	80F	90353-564				
				11.35	7.49	56C	STD	90353-568				
		230	5.00:1	3.00	1.98	143TC/145TC	STD	90353-570				
	350			3.00	1.98	182C/182C	80F	90353-573				
				5.90	3.89	182TC/184TC	80F	90353-579				
				10.07	6.65	182TC/184TC	80F	90353-586				

(CONT'D)

Listed reducer horsepower rated for Standard Service (8–10 hrs/day). For Light Service (3–5 hrs/day) multiply maximum rated horsepower by 1.1. For Heavy Service (16–24 hrs/day) multiply maximum rated horsepower by 0.9.

NOTE: CONSULT FACTORY FOR; HORSEPOWERS & FRAMES NOT SHOWN DRIP PAN BASES







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January 2010

GRR REDUCER C-FLANGE FLEX DRIVE OPTIONS

(Drive Assy Number Includes Base, Coupling, Guard & Gear Reducer, But NOT the Motor)

		REDUCER	$\overline{(1)}$							
PUMP		RPM		ΜΔΧΗΡ		FRAME	MTG.FT.	DRIVE		
MODEL	1750	1150	RATIO	@	@		OPTION	ASSY NO.		
				1750	1150					
				5.65	3.73	56C	STD	90353-610		
				11.70	7.72	143TC/145TC	STD	90353-619		
	875	575	2.00:1	11.70	7.72	182C/184C	80F	90353-622		
				13.01	8.59	182TC/184TC	80F	90353-625		
				13.01	8.59	213TC/215TC	80J	90353-627		
				3.76	2.48	56C	STD	90353-630		
				8.10	5.35	143TC/145TC	STD	90353-633		
GHC G	580	383	3.00:1	8.10	5.35	182C/184C	80F	90353-642	2	
				10.62	7.01	182TC/184TC	80F	90353-646		
				10.62	7.01	213TC/215TC	80J	90353-648		
		288	4.00:1	2.82	1.86	56C	STD	90353-660		
				5.90	3.89	143TC/145TC	STD	90353-663		
	440			5.90	3.89	182C/184C	80F	90353-672		
				7.24	4.78	182TC/184TC	80F	90353-675		
				7.24	4.78	213TC	80J	90353-677		
	350	230	5.00:1	2.26	1.49	56C	STD	90353-690		
				5.20	3.43	143TC/145TC	STD	90353-699		
				5.20	3.43	182C/184C	80F	90353-702		
				5.98	3.95	182TC/184TC	80F	90353-706	1	
				5.98	3.95	213TC	80J	90353-708		
	875	575	2.00:1	13.01	8.59	182TC/184TC	80F	90353-720		
				13.01	8.59	213TC/215TC	80J	90353-724		
				36.29	23.95	254TC/256TC	80P	90353-728		
				36.29	23.95	284TC/286TC	284TC/286TC 80P			
	580	383	3 00.1	10.62	7.01	182TC/184TC	80F	90353-735		
		505	5.00.1	10.62	7.01	213TC/215TC	80J	90353-739		
				25.76	17.00	254TC/256TC	80P	90353-743	-	
GHC J	555	365	3.15:1	25.76	17.00	284TC	80P	90353-746		
				42.96	28.35	286TC	80P	90353-747		
	440	000		7.24	4.78	182TC/184TC	80F	90353-750		
	440	288	4.00:1	7.24	4.78	213TC	80J	90353-754		
			5.00:1	5.98	3.95	182TC/184TC	80F	90353-765		
				5.98	3.95	213TC	80J	90353-769		
	350	230		16.01	10.57	215TC	80P	90353-774]	
				16.01	16.01 10.57 254T		80P	90353-778		
				30.49	20.12	356TC	80P	90353-780		

Listed reducer horsepower rated for Standard Service (8−10 hrs/day). For Light Service (3−5 hrs/day) multiply maximum rated horsepower by 1.1. For Heavy Service (16−24 hrs/day) multiply maximum rated horsepower by 0.9.

NOTE: CONSULT FACTORY FOR; HORSEPOWERS & FRAMES NOT SHOWN DRIP PAN BASES



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NOMINAL NOMINAL RPM VISCOSTY NUMP NLPR FRICTION PRIFICATION (SSU) FRICIDATION (SSU) FRICIN				8		7										S	SEC	. 50	0	P J	age anua	70 arv 2	2010
Nominal (AP) (AP) (AP) (AP) (AP) (AP) (AP) (AP)	G		N-RU					PU	IMP	HYE			SIZ	E CI	HAR	r				؛ 11؛	56 C 50 F	3PN RPN	1
Notice Notice<	NO	ΜΙΝΔΙ			FR	FRICTION PIPE LOSS FULL BYPASS RELIEF							CA	CAPACITY (GPM) / H.P. REQUIRED									
Net of the part of the pa				(Bas	(PSI/FT) (Based on Sch 40 Steel Pipe)				VALVE PRESSURE (PSI)				DIFFERENTIAL PR					RESSURE (PSI)					
	CAP. SPE GPM RF	00550	TRIM	(SSU)	(PSIA)	PIPE DIAMETER				CRACKING PRESS. (PSI)					25	50	75	100	150	200	300	400	
1150 1150 1150 1150 116<		RPM				1 ½"	/2" 2" 21/2" 3" 4" 50 75 100 150 200				HEAVY DUTY												
11:5010 </td <td></td> <td></td> <td>28</td> <td></td> <td>.01</td> <td>.01</td> <td>.01</td> <td>.01</td> <td>.01</td> <td></td> <td></td> <td></td> <td>100</td> <td>200</td> <td>54</td> <td>52</td> <td>52</td> <td>51</td> <td></td> <td></td> <td></td> <td></td>				28		.01	.01	.01	.01	.01				100	200	54	52	52	51				
11:0010000301 </td <td></td> <td></td> <td></td> <td>32</td> <td>4.0</td> <td>.07</td> <td>.02</td> <td>.01</td> <td>.01</td> <td>.01</td> <td>62</td> <td>87</td> <td>114</td> <td></td> <td></td> <td>1.0</td> <td>2.4</td> <td>3.3</td> <td>4.3</td> <td></td> <td></td> <td></td> <td></td>				32	4.0	.07	.02	.01	.01	.01	62	87	114			1.0	2.4	3.3	4.3				
$ 1150 \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \$				38	4.0	.09	.03	.01	.01	.01	62	89	116	166		55	54	53	53	51			
Note Note <th< td=""><td></td><td></td><td></td><td>50</td><td>4.0</td><td>.11</td><td>.03</td><td>.02</td><td>.01</td><td>.01</td><td></td><td>1.6</td><td>2.5</td><td>3.5</td><td>4.4</td><td>6.4</td><td></td><td></td><td></td></th<>				50	4.0	.11	.03	.02	.01	.01						1.6	2.5	3.5	4.4	6.4			
$ \ \ \ \ \ \ \ \ \ \ \ \ \ $			STD	70	4.0	.13	.04	.02	.01	.01	63 9	90	118	167	219	56	55	55	54	53	52		
$ \ \ \ \ \ \ \ \ \ \ \ \ \ $				100		.15	.05	.02	.01	.01						1.8	2.7	3.6	4.6	6.5	8.7		
1100110 </td <td></td> <td></td> <td>150</td> <td rowspan="2">4.0</td> <td>.16</td> <td>.05</td> <td>.02</td> <td>.01</td> <td>.01</td> <td rowspan="2">64</td> <td>91</td> <td>120</td> <td>167</td> <td>219</td> <td>57</td> <td>56</td> <td>56</td> <td>55</td> <td>54</td> <td>54</td> <td>53</td> <td>52</td>				150	4.0	.16	.05	.02	.01	.01	64	91	120	167	219	57	56	56	55	54	54	53	52
56 1150 4.0 4.0 20 0.6 0.3 0.1 0.1 0.6 0.2 0.1 0.6 0.2 0.1 0.6 0.2 0.1 0.6 0.2 0.1 0.6 0.2 0.1		1150		200		.18	.05	.02	.01	.01						2.1	3.0	3.9	4.8	6.6	8.7	12	16
$ 56 \ 11500 \ 11500 \ 11500 \ 11500 \ 1150 \ 1150 \ 1150 \ 1150$				300	4.0	.20	.06	.03	.01	.01	65	92 12	100	160	220	57	57	57	56	56	55	55	54
56 1150 1750 7750 1.0 .0	50			500	4.0	.25	.09	.05	.02	.01			122 10	100	220	2.8	3.6	4.6	5.4	7.1	9.0	13	16
$ \ \ \ \ \ \ \ \ \ \ \ \ \ $	50			750	4.0	.37	.14	.07	.03	.01	66	93	124	168	220	58	58	57	57	57	57	56	56
$ \left \left({ \ \ \ \ \ \ \ \ \ \ \ \ \$				1,000		.49	.18	.09	.04	.02						3.2	4.0	4.9	5.7	7.4	9.2	13	16
$ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \$				2,000	4.3	.98	.36	.18	.08	.03	70	95	124 16	168	222	58	58	58	58	58	57	57	56
````````````````````````````````````			"O"	3,500		1.72	.63	.31	.13	.05						4.6	5.7	6.6	7.4	9.2	11	14	18
$ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \$				5,000	4.5	2.45	.90	.44	.19	.06	72	97	126	170	224	59	58	58	58	58	58	57	57
$ \left( \begin{array}{cccccccccccccccccccccccccccccccccccc$				7,500		3.68	1.35	.67	.28	.10						6.6	7.3	8.0	8.8	11	13	16	20
$ \left( \begin{array}{cccccccccccccccccccccccccccccccccccc$			0	10,000	4.7	4.90	1.81	.89	.37	.13	74	99	128	172	226	59	58	58	58	58	58	57	57
$ \left( \begin{array}{cccccccccccccccccccccccccccccccccccc$				15,000		7.35	2.71	1.33	.56	.19						8.8	9.0	10	11	13	15	18	2.0
$ \begin{tabular}{ c c c c c c c c c c c c c c c c c c c$				20,000	4.9	9.80	3.61	1.77	.74	.25	78	103	128	174	226	58	58	58	58	58	58	57	57
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$				25,000		12.3	4.51	2.22	.93	.31						9.7	10	11	12	14	16	20	24
"D"       75,000       -       -       -       -       -       15       16       16       18       19       22       25       30         "D"       100,000       -       -       -       -       -       -       -       15       16       16       18       19       22       25       30         100,000       150,000       -       -       -       -       -       -       -       -       -       -       -       -       15       16       16       18       19       22       25       30         100,000       150,000       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -       -				50,000	6.9	24.5	9.02	4.43	1.86	.63	82	107	132	178	230	58	58	58	58	58	58	57	57
100,000     100,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000     150,000			"D"	75,000		-	-	-	-	-						15	16	16	18	19	22	25	30
150,000     150,000     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100     100 <t< td=""><td></td><td></td><td>"D"</td><td>100,000</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></t<>			"D"	100,000																			
				150,000																			
				200,000																			
				250,000																			
			B		_										8	SEC	. 50	0		age	71	04.0	
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		<b>N</b> P		V)															J	anua	iry 2	010	
G	ORMA									J									,	42 (	ЗРМ	1	
R	OTARY G	EAR PU	MPS		'		PU	MP	HYC	ORAL	JLIC	SIZ	E CI	HAR	Г				8	70 F	<b>≀</b> PM		
					ED				220						CA				7 ц				
NO	MINAL		VISCOSITY	N.I.P.R.	(Bas	ic nc (l	PSI/F Sch 40	TEL T) Steel	Pine)	VALV	L BY /E PF	RESS		(PSI)						SSUR			
		ROTOR TRIM			(Duo				<u>יייי</u>	CR/	ACKIN	IG PF	RESS.	(PSI)	25	50	75	100	150	200	300	400	
CAP. GPM	SPEED RPM		(SSU)	(PSIA)			DIAN		:K	LOW	PRES	R/V	hi pre	ES R/V		MED			<u>/  </u>	ŀ		Y /	
					<b>1</b> ½"	2"	<b>2</b> 1⁄2"	3"	4"	50	75	100	150	200		HEA	WY E	DUTY	 	Ļ	ONL	ſ	
			28	2.7	.01	.01	.01	.01	.01	60	85	117			40	39	39	38					
			32		.04	.01	.01	.01	.01						.98	1.7	2.5	3.2					
			38	2.7	.06	.02	.01	.01	.01	60	85	117	161		41	40	40	39	38	h			
			50		.07	.02	.01	.01	.01						1.1	1.8	2.5	3.3	4.8				
		отр	70	2.7	.08	.03	.01	.01	.01	60	85	117	161	213	42	42	41	40.8	40	39			
		510	100		.09	.03	.01	.01	.01						1.1	1.9	2.6	3.3	4.9	6.4			
			150	2.7	.10	.03	.01	.01	.01	61	86	119	161	213	43	42	42	42	41	41	40	39	
			200		.10	.03	.01	.01	.01						1.3	2.0	2.7	3.4	4.9	6.5	9.1	12	
		300	07	.11	.04	.02	.01	.01	61	00	110	161	010	43	43	43	42	42	42	41	41		
40	070		500	2.1	.19	.07	.03	.02	.01	01	00	119	101	213	1.8	2.4	3.0	3.7	5.0	6.6	9.2	12	
42	870		750	27	.28	.10	.05	.02	.01	61	88	110	161	213	43	43	43	43	43	42	42	42	
			1,000	2.1	.37	.14	.07	.03	.01	01	00	113	101	215	2.4	2.6	3.3	4.0	5.4	6.7	9.4	13	
			2,000	31	.74	.27	.13	.06	.02	63	90	121	163	215	44	44	43	43	43	43	42	42	
			3,500	0.1	1.29	.47	.23	.10	.03	00	00	121	100	210	3.0	3.7	4.5	5.2	6.5	7.8	11	13	
			5,000	3.4	1.84	.68	.33	.14	.05	65	92	123	163	215	44	44	44	43	43	43	43	42	
		"C"	7,500	0.11	2.76	1.02	.50	.21	.07		02			2.0	4.6	5.3	6.0	6.6	7.8	9.1	12	15	
		U	10,000	37	3.68	1.35	.67	.28	.10	67	94	126	163	217	44	44	44	44	43	43	43	42	
			15,000	0.7	5.51	2.03	1.00	.42	.14	07	5	120	100	217	5.5	6.3	7.0	7.7	9.0	10	13	16	
			20,000	3.9	7.35	2.71	1.33	.56	.19	69	96	129	163	217	44	44	44	44	43	43	43	42	
			25,000		9.19	3.38	1.66	.70	.24		•••				6.4	7.0	7.7	8.5	10	11	14	17	
			50,000	5.8	18.4	6.76	3.32	1.40	.47	73	100	133	167	221	44	44	44	44	43	43	43	42	
			75,000		27.6	10.2	4.99	2.09	.71						9.6	10	11	12	13	15	18	21	
		"D"	100,000	7.8	36.8	13.5	6.65	2.79	.94	77	104	137	171	225	44	44	44	44	43	43	43	42	
			150,000		-	-	-	-	-						12	13	14.	15	16	19	21	24	
			200,000																				
			250,000																				
NOTE	E) For sp	eeds no	ot shown o	n the pi	ump	hydra	aulic d	chart	s, co	nsult	facto	ry.											

															6		50		Р	age	72	
																	. 50		J	anua	ary 2	010
G	ORMA	N-RU								J		J							E	28 (	3PN	1
R	OTARY G	EAR PU	MPS				PU	MP	HYC	RAL	JLIC	SIZ	E CI	HAR	Г				5	ου Γ		I
NO	MINAL		VISCOSITY	N.LP.B.	FR	ICTIC	DN PI		OSS	FUL	L BY	'PAS	S REI	IEF	CA	PACI	TY (G	BPM)	/ н	.P. R	EQUI	RED
		DOTOD			(Bas	ed on	PSI/F Sch 40	I) Steel	Pipe)	VAL	/E PF	RESS	SURE	(PSI)	۵	IFFE	REN	TIAL	PRE	SSUR	E (P	SI)
CAP	SPEED	TRIM				PIPE	DIAN	NETE	R	CR			RESS.	(PSI)	25	50	75	100	150	200	300	400
GPM	RPM		(SSU)	(PSIA)	<b>1</b> 14"	<b>o</b> "	<b>0</b> 1/2"	<b>o</b> "	۸"	EOW	PRES	100		-5 R/V		WEL	ANE	) )	ľ		DUTY	1 /
					1 72	2	272	о 01	4	50	/5	100	150	200	00	HE	AVY I		, 		ONLY	/
			28	1.7	.01	.01	.01	.01	.01	54	80	111			26	25	25	24				
			32		.02	.01	.01	.01	.01						.61	1.2	1.7	2.2	•	ł		
			38	1.7	.03	.01	.01	.01	.01	54	80	111	157		26	26	26	25	24			
			50		.03	.01	.01	.01	.01						.64	1.2	1.7	2.2	3.4			
		STD	70	1.7	.04	.01	.01	.01	.01	54	81	111	157	209	27	27	26	26	25	24		
			100		.05	.02	.01	.01	.01						.69	1.2	1.8	2.2	3.4	4.2		
		150	1.7	.05	.02	.01	.01	.01	54	81	111	157	209	28	28	27	27	26	26	25	25	
			200		.05	.02	.01	.01	.01						.77	1.3	1.8	2.3	3.4	4.2	6.0	7.9
			300	1.7	.08	.03	.01	.01	.01	55	82	111	157	209	28	28	28	27	27	27	26	26
28	580		500		.12	.05	.02	.01	.01						.90	1.5	1.9	2.4	3.4	4.2	6.0	7.9
20			750	1.7	19	.07	.03	.02	.01	55	82	111	157	209	29	28	28	28	28	28	27	27
			1,000		.25	.09	.05	.02	.01						1.3	1.8	2.2	2.7	3.5	4.3	6.3	8.1
			2,000	2.1	.49	.18	.09	.04	.01	57	84	113	157	209	29	29	29	28	28	28	28	27
			3,500		.86	.32	.16	.07	.02						2.2	2.6	3.1	3.5	4.4	5.3	7.2	9.0
			5,000	2.4	1.23	.45	.22	.09	.03	59	86	115	158	210	29	29	29	29	28	28	28	28
		"C"	7,500		1.84	.68	.33	.14	.05						2.8	3.2	3.6	4.1	5.0	5.9	7.8	9.6
		U	10,000	07	2.45	.90	.44	.19	.06	61	88	11.0	150	211	29	29	29	29	29	29	28	28
			15,000	2.1	3.68	1.35	.67	.28	.10	01	00	110	133	211	3.3	3.7	4.2	4.7	5.6	6.6	8.5	10
			20,000	3.0	4.90	1.81	.89	.37	.13	64	Q1	121	159	211	30	29	29	29	29	29	29	28
			25,000	0.0	6.13	2.26	1.11	.47	.16	04	31	121	100	211	3.7	4.2	4.7	5.1	6.2	7.1	9.0	11
			50,000	46	12.3	4.51	2.22	.93	.31	67	QД	124	162	214	30	29	29	29	29	29	29	28
		75,000	ч. <b>0</b>	18.4	6.76	3.32	1.40	.47	07	7	124	102	214	5.6	6.2	6.7	7.4	8.0	9.6	11	14	
	"D"	100,000	6.6	24.5	9.02	4.43	1.86	.63	71	98	128	166	218	30	29	29	29	29	29	29	28	
		150,000		36.8	13.5	6.65	2.79	.94			120	100	210	7.0	7.8	8.4	9.3	9.6	12	13	16	
		200,000	10.0	49.0	18.0	8.86	3.72	1.25	74	101	131	169	221	30	29	29	29	29	29	29	28	
			250,000		-	-	-	-	-	. ,					8.4	9.4	9.9	11	11	13	15	17
	(NIOT)				مالد مر م				اء ما													

(NOTE) For speeds not shown on the pump hydraulic charts, consult factory.

			@		_										8	SEC	. 50	o  -	P	age	73	0.1.0
		<b>N</b> P		Y.														_	J	anua	ary 2	010
ſ	ORMA			*						J										17 (	ЗРN	1
R	OTARY G	EAR PU	MPS		'		PU	MP	HYC	RAL	JLIC	SIZ	E CI	HAR	Г				3	50 F	{PM	
					ED		ים וע		066	<b>_</b>			פ הרי		C 41	סאריי			/ 11	ים ם		
NO	MINAL		VISCOSITY	N.I.P.R.	(Bas	)  )  0 ho	PSI/F	TEL T)	DOO Pina)	VALV	LBY EPF	RESS	S REI	LIEF (PSI)				τιδι				
		ROTOR			(Das		<u> </u>		-	CR	ACKIN	IG PF	RESS.	(PSI)	25	50	75	100	150	200	300	400
CAP.	SPEED BPM		(SSU)	(PSIA)		PIPE	DIAN	/IETE	:R	LOW	PRES	R/V	hi pre	ES R/V		MED	NUM		Y	 	HEAV	γ v
					<b>1</b> ½"	2"	<b>2</b> ½"	3"	4"	50	75	100	150	200		HE/	AVY I	, DUTY	,		ONL	Y
			28	1.0	.01	.01	.01	.01	.01	50	70	100			15	15	15	14				
			32	1.2	.01	.01	.01	.01	.01	53	79	109			.33	.61	1.0	1.3				
			38	1.0	.01	.01	.01	.01	.01	E0	70	100	156		16	15	15	15	14			
			50	1.2	.02	.01	.01	.01	.01	53	79	109	100		.37	.64	1.0	1.4	2.1			
			70	10	.02	.01	.01	.01	.01	52	70	100	156	207	16	16	16	15	15	15		
		STD	100	1.2	.02	.01	.01	.01	.01	55	19	109	100	207	3.9	.69	1.1	1.4	2.1	2.8		
			150	10	.02	.01	.01	.01	.01	54	80	100	156	207	17	16	16	16	16	15	15	14
			200	1.2	.03	.01	.01	.01	.01	34	00	103	150	201	.48	.74	1.1	1.4	2.1	2.8	3.7	4.8
			300		.05	.02	.01	.01	.01						17	17	17	16	16	16	16	15
			500	1.2	.08	.03	.02	.01	.01	54	80	109	156	207	.63	.82	1.1	1.5	2.1	2.8	3.7	4.8
17	350		750		.11	.04	.02	.01	.01	- 4					17	17	17	17	17	16	16	16
			1,000	1.2	,15	.06	.03	.01	.01	54	80	109	156	207	.76	1.0	1.3	1.6	2.2	2.8	3.8	4.9
			2,000	47	.30	.11	.06	.02	.01		04	110	457	000	17	17	17	17	17	17	16	16
			3,500	1.7	.52	.19	.10	.04	.01	55	81	110	157	208	1.3	1.6	1.8	2.1	2.7	3.1	4.3	5.4
			5,000	2.0	.75	.28	.14	.06	.02	56	00	111	150	200	17	17	17	17	17	17	17	17
			7,500	2.0	1.12	.41	.20	.09	.03	50	02	111	150	209	1.6	1.9	2.2	2.4	3.0	3.5	4.6	5.7
		"C"	10,000		1.49	.55	.27	.11	.04						17	17	17	17	17	17	17	17
			15,000	2.3	2.23	.82	.40	.17	.06	57	84	112	159	210	1.8	2.2	2.5	2.8	3.4	3.9	5.0	6.2
			20,000		2.98	1.10	.54	.23	.08						18	17	17	17	17	17	17	17
			25,000	2.5	3.72	1.37	.67	.28	.10	59	86	113	159	210	2.0	2.5	2.8	3.0	3.7	4.3	5.4	6.5
			50,000		7.44	2.74	1.35	.57	.19						18	17	17	17	17	17	17	17
			75,000	3.9	11.2	4.11	2.02	.85	.29	61	88	115	161	212	3.0	3.7	4.0	4.4	4.6	5.9	6.7	8.1
		"D"	100,000		14.9	5.48	2.69	1.13	.38						18	17	17	17	17	17	17	17
			150,000	5.6	22.3	8.21	4.04	1.69	.57	64	91	118	164	215	3.7	4.7	5.0	5.4	5.7	7.0	7.8	9.3
			200,000		29.8	11.0	5.38	2.26	.76						18	17	17	17	17	17	17	17
			250,000	8.4	37.2	13.7	6.73	2.82	.95	67	94	121	167	218	4.5	5.6	5.9	6.4	6.5	8.1	8.7	10
	(NOTI	E) For s	peeds not :	shown	on th	e pui	mp hy	ydrau	ulic cl	narts,	cons	sult fa	actory	<i>.</i>								



SUPERSEDES ALL PREVIOUS ISSUES

Stand	Standard Construction GHC, SEC. 540: PART SEALING GHC, SEC. 540: PART SEALING INTER													
EXTER-	ROTOR	HOUSI			IDLER		ПУЕТ	SHA	FT SE			ll RE	NTERN LIEF V	ALVE
IOR	IDLER	PORT	S BUS	SUINCE	PIN	- Jor	пагі		JEAL			MATER		SETTING
CAST IRON	HIGH STRENGTH IRON	180° TAPPE	D BF	ONZE	HARDEN STEEI	LED S	TEEL	VIT	ON	BUNA-I	N C.W.	DUCT IRO	TILE N	75 PSI [5 BAR]
Stand	dard N	lode	ls		G F	I C	;	1	DC	3	– B			
					GEAR DU	JTY DES	IGN	PORT SIZE	HYDRA Size	IULIC SE	AL STYLE			
			NO	M. CAPA	CITY - S	PEED				MAX	MUM	•	SHIF	PING
	MODEL		MAX	KIMUM	ALTE	RNATIV	E D	IFFERE	NTIAL	PRESSU	re-PSI [BAR]	TEMP.	D/	ATA I
1	NUMBER		GPM	RPM	GPM		3 B	BELOW	38	TO SSU 4	100 TO	°F	Weight	t Volume
			[LPM]	[50 HZ]	[LPM]	[50 Hz	]	[4 cSt]	[21	cSt]	[55,000 cSt]	[°C]	LBS [KG]	FT.
GHC 1DC GHC 1DC	C 3-B C 4-B	1	9 [28]		6 [19]								29 [13,2]	0.6
GHC 1DE GHC 1DE	E 3–B E 4–B		11 [35]		7 [22]								30 [13,6]	0.6
GHC 1-1/2 GC 3-B GHC 1-1/2 GC 4-B GHC 2 GC 3-B GHC 2 GC 4-B		16		10								58 [26,4]	2.9	
		[50]		[32]						300 [21]		58 [26,4]	2.9	
GHC 1-1/ GHC 1-1/	2 GF 3–B 2 GF 4–B		23	1750	15	1150	0				[]	350	58 [26,4]	2.9
GHC 2 G GHC 2 G	F 3-B F 4-B		[73]	[1460]	[47]	[960	)]	100	15	0			58 [26,4]	2.9
GHC 1-1 GHC 1-1	/2 GH 3-B /2 GH 4-B		31		20			[7]	[10	)]			58 [26,4]	2.9
GHC 2 G GHC 2 G	H 3-B H 4-B		[98]		[63]							225 [107]	58 [26,4]	2.9
GHC 1-1/ GHC 1-1/	2 GJ 3-B 2 GJ 4-B	2	38		25						200		58 [26,4]	2.9
GHC 2 G GHC 2 G	J 3–B J 4–B	2	[120]		[79]						[14]		58 [26,4]	2.9
GHC 2 JO GHC 2 JO	G 3-B G 4-B												128 [58,2]	5.3
GHC 2-1/ GHC 2-1/	2 JG 3-B 2 JG 4-B		40 [126]	1150 [960]	30 [95]	870 [725	) 5]				300 [21]		128 [58,2]	5.3
GHC 3 JO GHC 3 JO	G 3-B G 4-B												128 [58,2]	5.3
STAN	DARD MODE	LS		• MEC	CHANICA	L SEAL	L		LIPS	SEAL				

NOTE: RECOMMENDED PORT SIZES ARE SHOWN IN BOLDFACE. EXAMPLE: GHC 1 DC 3-B

- (1) 3450 [2875] RPM PERMISSIBLE TO 1,000 SSU [220 cSt] AND 100 PSI [7 BAR]
- (2) PUMP LIMITED TO 200 PSI MAXIMUM PRESSURE.
- (3) MAXIMUM SPEED FOR AMMONIA MODELS.

### THE GORMAN-RUPP COMPANY • MANSFIELD, OHIO

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# GHC, SEC. 540: PAGE 11

### Standard Models Cont'd

### GHC, SEC. 540: PAGE 12 January 2010

		NO	M. CAPAC	XITY - S	PEED		MA	AXIMUM		SHIPI	PING
MODEL		MA	XIMUM	ALTEF	RNATIVE	DIFFEREN	ITIAL PRESS	URE-PSI [BAR]	TEMP.	DA	TA
NUMBER		GPM	RPM	GPM	RPM (2)	BELOW	38 TO	100 TO	°F	Weight	Volume
Nombert		[LPM]	60 Hz [50 HZ]	[LPM]	60 Hz [50 Hz]	38 SSU [4 cST]	100 SSU [21 cST]	250,000 SSU [55,000 cSt]	[°C]	LBS [KG]	CU. FT.
GHC 2 JJ 3-B GHC 2 JJ 4-B										132 [60]	5.3
GHC 2-1/2 JJ 3-B GHC 2-1/2 JJ 4-B		56 [177]		42 [133]						132 [60]	5.3
GHC 3 JJ 3-B GHC 3 JJ 4-B								300	● 350	132 [60]	5.3
GHC 2 JL 3-B GHC 2 JL 4-B								[21]	[177]	132 [60]	5.3
GHC 2-1/2 JL 3-B GHC 2-1/2 JL 4-B		77 [243]	1150 [960]	58 [183]	870 [725]	100 [7]	150 [10]			132 [60]	5.3
GHC 3 JL 3-B GHC 3 JL 4-B									225	132 [60]	5.3
GHC 2 JP 3-B GHC 2 JP 4-B	1								[107]	132 [60]	5.3
GHC 2-1/2 JP 3-B GHC 2-1/2 JP 4-B	1	107 [338]		81 [256]				200 [14]		132 [60]	5.3
GHC 3 JP 3-B GHC 3 JP 4-B	1									132 [60]	5.3

NOTE: RECOMMENDED PORT SIZES ARE SHOWN IN BOLDFACE. EXAMPLE: GHC 1 DC 3-B

- (1) PUMP LIMITED TO 200 PSI MAXIMUM PRESSURE.
- (2) MAXIMUM SPEED FOR AMMONIA MODELS.

APPLICATION RECOM	IMENDATIONS:	
APPLICATION	OPTIONS REQUIRED (Select One from Each Row)	OPERATING LIMITATIONS
AMMONIA	25G, 25H, 25R, 25S, 25T 40N 60K 70E 90A	PRESSURE: 200 PSI MAX. 2/3 RATED SPEED. 4 FEET NPSHr
LP GAS	25G OR 25H 40F OR 40N 70D OR 70E	PRESSURE: 200 PSI MAX. 3 FEET NPSHr

NOTE: PROPER PUMP APPLICATION REQUIRES CONSIDERATION OF ADDITIONAL FACTORS. PLEASE REVIEW APPLICATION GUIDE IN SECTION 500 OR CONSULT THE FACTORY.

## **Basic Pump Dimensions**

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► PORTS ARE COMPATIBLE WITH 125# OR 250# ANSICAST IRON FLANGES. ALL OTHER PORTS ARE TAPPED NPT FOR ANSIPIPE. OPTIONAL (DIN) FLANGES OR TAPPED (BSP) PORTS AVAILABLE FOR EXPORT MARKET.

Continued -

## **Basic Pump Dimensions**



† 90° HOUSING

**THE GORMAN-RUPP COMPANY • MANSFIELD, OHIO** GORMAN-RUPP OF CANADA LIMITED • ST. THOMAS, ONTARIO, CANADA







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(Drive Assembly Number Includes Base, Coupling & Guard, But NOT the Motor)





PUMP MODEL NUMBER	60 Hz RPM	50 Hz RPM	FRAME	MTG. FT. Option Req.	DRIVE ASSY NO.
			56/56H	STD	90351-086
	3450	2900	143T/145T	STD	90351-052
GHC D	1/50	1450 950	184	80F	90351-089
	850	700	182T/184T	80F	90351-090
			213T/215T	80J	90351-094
			56/56H	STD	90351-156
			143T/145T	STD	90351-162
GHC G	1750	1450	182T/184T	80F	90351-168
	850	700	213T/215T	80J	90351-206
			213T/215T	80J	90351-172
			254T	80P	90351-180
			182T/184T	80F	90351-260
GHC J	1150	950	213T/215T	STD	90351-268
G00	850	700	254T/256T	80P	90351-276
			284T/286T	80S	90351-280

#### NOTE: CONSULT FACTORY FOR; HORSEPOWERS & FRAMES NOT SHOWN DRIP PAN BASES







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### **DIRECT FLEX C-FLANGE DRIVE OPTIONS**

(Drive Assemby Number Includes Base & Coupling, But **NOT** the Motor)



PUMP MODEL NUMBER	60Hz RPM	FRAME	MTG. FT. Option Req.	DRIVE ASSY NO.
	3450	56C	80Y	90351-540
GHC D	1750	143TC	80Y	90351-541
	1150	145TC	80Y	90351-544
	850	184C	80Y	90351-590
		56C	80Y	90351-656
	1750	143TC	80Y	90351-659
снс с	1/50	145TC	80Y	90351-660
	850	184C	80Y	90351-668
		182TC	80X	90351-672
		184TC	80X	90351-674
		213TC	80X	90351-764
		215TC	80X	90351-768
GHC J	1150	254TC	80W	90351-772
	000	256TC	80W	90351-776
		184TC	80X	90351-814

#### NOTE: CONSULT FACTORY FOR; HORSEPOWERS & FRAMES NOT SHOWN DRIP PAN BASES



* STANDARD DIMENSION

PORTS ARE COMPATIBLE WITH 125# OR 250# ANSICAST IRON FLANGES. ALL OTHER PORTS ARE TAPPED NPT FOR ANSIPIPE. OPTIONAL (DIN) FLANGES OR TAPPED (BSP) PORTS AVAILABLE FOR EXPORT MARKET. † 90° HOUSING



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GRR REDUCER C-FLANGE FLEX DRIVE OPTIONS

(Drive Assy Number Includes Base, Coupling, Guard & Gear Reducer, But NOT the Motor)



	DDM	DDM		REDUCER	1				
MODEL	@ 1750	@ 1150	RATIO	MAX HP @ 1750	MAX HP @ 1150	FRAME	OPTION REQ.	ASSY NO.	
				6.00	3.96	56C	STD	90353-510	
	075		0.00.1	6.00	3.96	143TC/145TC	STD	90353-516	
	875	575	2.00:1	6.00	3.96	182C/184C	80F	90353-519	
				20.00	13.2	182TC/184TC	80F	90353-526	
				4.21	2.78	56C	STD	90353-530	
	580	383	3.00:1	8.10	5.35	143TC/145TC	STD	90353-536	
				8.10	5.35	182C/184C	80F	90353-539	
GHC D				12.98	8.57	182TC/184TC	80F	90353-546	
				3.63	2.39	56C	STD	90353-550	
	440	288	4 00.1	5.90	3.89	143TC/145TC	STD	90353-556	
	0	200	4.00.1	5.90	3.89	182C/184C	80F	90353-564	
				11.35	7.49	56C	STD	90353-568	
				3.00	1.98	143TC/145TC	STD	90353-570	
	350	230	5.00:1	3.00	1.98	182C/182C	80F	90353-573	
		200		5.90	3.89	182TC/184TC	80F	90353-579	
				10.07	6.65	182TC/184TC	80F	90353-586	

(CONT'D)

Listed reducer horsepower rated for Standard Service (8–10 hrs/day). For Light Service (3–5 hrs/day) multiply maximum rated horsepower by 1.1. For Heavy Service (16–24 hrs/day) multiply maximum rated horsepower by 0.9.

NOTE: CONSULT FACTORY FOR; HORSEPOWERS & FRAMES NOT SHOWN DRIP PAN BASES







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### **GRR REDUCER C-FLANGE FLEX DRIVE OPTIONS**

(Drive Assy Number Includes Base, Coupling, Guard & Gear Reducer, But NOT the Motor)

	1			REDUCER	$\overline{(1)}$				
PUMP		RPM		MAX HP		FRAME	MTG.FT.	DRIVE	
MODEL	1750	1150	RATIO	@	@		OPTION	ASSY NO.	
				1750	1150				
				5.65	3.73	56C	STD	90353-610	
				11.70	7.72	143TC/145TC	STD	90353-619	
	875	575	2.00:1	11.70	7.72	182C/184C	80F	90353-622	
				13.01	8.59	182TC/184TC	80F	90353-625	
				13.01	8.59	213TC/215TC	80J	90353-627	
				3.76	2.48	56C	STD	90353-630	
				8.10	5.35	143TC/145TC	STD	90353-633	
GHC G	580	383	3.00:1	8.10	5.35	182C/184C	80F	90353-642	
				10.62	7.01	182TC/184TC	80F	90353-646	
				10.62	7.01	213TC/215TC	80J	90353-648	
				2.82	1.86	56C	STD	90353-660	
				5.90	3.89	143TC/145TC	STD	90353-663	
	440	288	4.00:1	5.90	3.89	182C/184C	80F	90353-672	
				7.24	4.78	182TC/184TC	80F	90353-675	
				7.24	4.78	213TC	80J	90353-677	
				2.26	1.49	56C	STD	90353-690	
				5.20	3.43	143TC/145TC	STD	90353-699	
	350	230	5.00:1	5.20	3.43	182C/184C	80F	90353-702	
				5.98	3.95	182TC/184TC	80F	90353-706	
				5.98	3.95	213TC	80J	90353-708	
				13.01	8.59	182TC/184TC	80F	90353-720	
	075		0.00.1	13.01	8.59	213TC/215TC	80J	90353-724	
	875	5/5	2.00:1	36.29	23.95	254TC/256TC	80P	90353-728	
				36.29	23.95	284TC/286TC	80P	90353-732	
	580	383	3 00.1	10.62	7.01	182TC/184TC	80F	90353-735	
		505	5.00.1	10.62	7.01	213TC/215TC	80J	90353-739	
				25.76	17.00	254TC/256TC	80P	90353-743	-
GHC J	555	365	3.15:1	25.76	17.00	284TC	80P	90353-746	
				42.96	28.35	286TC	80P	90353-747	
	440	000	1.00.1	7.24	4.78	182TC/184TC	80F	90353-750	
	440	288	4.00:1	7.24	4.78	213TC	80J	90353-754	
				5.98	3.95	182TC/184TC	80F	90353-765	
				5.98	3.95	213TC	80J	90353-769	
	350	230	5.00:1	16.01	10.57	215TC	80P	90353-774	
				16.01	10.57	254TC	80P	90353-778	
				30.49	20.12	356TC	80P	90353-780	

Listed reducer horsepower rated for Standard Service (8−10 hrs/day). For Light Service (3−5 hrs/day) multiply maximum rated horsepower by 1.1. For Heavy Service (16−24 hrs/day) multiply maximum rated horsepower by 0.9.

NOTE: CONSULT FACTORY FOR; HORSEPOWERS & FRAMES NOT SHOWN DRIP PAN BASES





OEC.	
SEU.	200

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16 GPM 1750 RPM

GC

PUMP HYDRAULIC SIZE CHART



NO	MINAL		VISCOSITY	N.I.P.R.	FR		)n Pi Psi/F	PE LO	0SS	FUL	L BY	PAS	S REI		CA	PACI	TY (C	GPM)	/ н	.P. R	EQUI	RED
					(Bas	ed on	Sch 40	Steel	Pipe)	VAL		1ESS	ORE	(PSI)		DIFFE	REN	TIAL	PRE	SSUR	E (P	SI)
	000000	TRIM				PIPE	DIA	ИЕТЕ	R	CR	ACKIN	IG PF	RESS.	(PSI)	25	50	75	100	150	200	300	400
GPM	RPM		(SSU)	(PSIA)						LOW	PRES	R/V	HI PRI	ES R/V	-	MED	IUM AND	DUT' )	Y	 	HEAV	Y √
					3⁄4"	1"	11/4"	<b>1</b> ½"	2"	50	75	100	150	200		HE		OUTY	,		ONL	Y
			28	3.6	.01	.01	.01	.01	.01	60	87	112			14.0	13.0	13.0	12.0				
			32		.19	.06	.02	.01	.01						.58	.85	1.2	1.4		İ		
			38	3.6	.24	.08	.02	.01	.01	60	87	112	162		15.0	14.0	14.0	13.0	12.0	r   4		
			50		.30	.10	.03	.01	.01						.88	1.0	1.3	1.6	2.2			
			70	3.6	.35	.11	.03	.02	.01	61	88	114	164	216	16.0	15.0	15.0	14.0	14.0	13.0		
		STD	100		.40	.13	.03	.02	.01						1.1	1.2	1.5	1.8	2.3	2.8		
			150		.45	.16	.04	.02	.01						16.0	16.0	16.0	15.0	15.0	14.0	14.0	12.0
			200	3.6	.50	.19	.06	.04	.01	61	88	114	164	218	1.2	1.4	1.7	2.0	2.5	3.1	4.1	5.2
			300	0.0	.62	.24	.08	.04	.02		00	110	100	000	16.0	16.0	16.0	16.0	15.0	15.0	15.0	13.0
			500	3.0	1.02	.39	.13	.07	.03	01	88	110	100	220	1.4	1.6	2.0	2.2	2.8	3.3	4.2	5.4
16	16 1750		750	2.6	1.53	.59	.20	.11	.04	61	00	110	100	000	17.0	17.0	16.0	16.0	16.0	16.0	15.0	15.0
			1,000	3.0	2.04	.78	.26	.14	.05	01	00	110	100	223	1.5	1.8	2.0	2.3	2.8	3.3	4.3	5.5
		2,000	15	4.08	1.56	.52	.28	.11	63	01	116	166	223	17.0	16.0	16.0	16.0	16.0	16.0	16.0	15.0	
			3,500	ч. <b>у</b>	7.14	2.72	.91	.49	.18		31		100	220	1.8	2.1	2.4	2.7	3.1	3.6	4.7	5.7
		"C"	5,000	5.0	10.2	3.89	1.30	.70	.26	66	93	118	168	225	17.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0
			7,500		15.3	5.83	1.95	1.05	.39						2.2	2.6	3.0	3.2	3.7	4.1	5.2	6.2
			10,000	5.7	20.4	7.77	2.60	1.40	.52	69	95	120	170	225	17.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0
			15,000		30.6	11.7	3.89	2.10	.78						2.8	3.2	3.5	3.8	4.3	4.8	5.9	6.9
			20,000	6.1	40.8	15.6	5.19	2.80	1.03	70	00	100	170	0.05	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0
			25,000	0.1	51.0	19.4	6.49	3.50	1.29	13	90	123	173	225	3.4	3.9	4.2	4.6	5.0	5.6	6.6	7.7
			50,000																			
			75,000																			
		"D"	100,000																			
			150,000																			
		200,000																				
			250,000	-																		
	(NOT	E) For s	peeds not	shown	on th	e pur	np h	ydrau	ulic cl	harts,	cons	sult fa	actory	<i>I</i> .								

500
000

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10 GPM

1150 RPM

GC

PUMP HYDRAULIC SIZE CHART



NOMINAL			VISCOSITY	N.I.P.R.	FR		N PI	PE LO	OSS	FULL BYPASS RELIEF CAPACITY (GPM) / H.P. REQUIR										RED		
		BUTUB			(Bas	(Based on Sch 40 Steel			Pipe)	VALVE PRESSURE (P					DIFFERENTIAL PRESSURE					E (PS	SI)	
	ODEED	TRIM			PIPE DIAMETER					CRACKING PRESS. (PSI)					25	50	75	100	150	200	300	400
GPM	RPM		(SSU)	(PSIA)	³ / ₄ " 1" 1 ¹ / ₄ " 1 ¹ / ₂ " 2"		LOW 50	PRES	н/v 100	ні РКІ 150	200	MEDIUM DUTY AND				Υ ,	DUTY ONLY					
			28	0.0	.01	.01	.01	.01	.01		01	100			9.0	8.0	7.0	6.0				
			32	2.0	.08	.03	.01	.01	.01	90	01	100			.38	.56	.77	.94				
			38	20	.11	.04	.01	.01	.01	56	81	106	157		9.5	8.5	8.5	7.5	6.0	•		
			50	2.0	.13	.04	.01	.01	.01		01	100	157		.43	.62	.82	.99	1.6			
			70	2.0	.14	.05	.02	.01	.01	56	81	107	158	209	10.0	9.5	9.5	9.0	8.0	7.5		
		STD	100		.14	.05	.02	.01	.01						.54	.78	1.0	1.2	1.7	1.9		
			150		.17	.07	.03	.02	.01						10.0	10.0	10.0	10.0	9.5	8.5	7.5	6.0
			200	2.0	.30	.12	.04	.02	.01	57	82	108	158	211	.58	.82	1.0	1.2	1.7	2.0	2.7	3.4
			300		.39	.15	.05	.02	.01	57	82				11.0	10.0	10.0	10.0	10.0	10.0	9.0	7.5
			500	2.0	.64	.24	.08	.05	.02			109	159	212	.66	.95	1.2	1.4	1.8	2.0	2.8	3.5
10	1150		750	0.0	.96	.36	.12	.07	.03	67	00	111	161	014	11.0	11.0	11.0	11.0	10.0	10.0	9.5	9.0
			1,000	2.0	1.28	.49	.16	.09	.03	57	52	111	101	214	.73	1.0	1.2	1.4	1.8	2.1	2.9	3.5
			2,000	25	2.55	.97	.33	.18	.07	58	85	112	162	21/	11.0	11.0	11.0	11.0	10.0	10.0	10.0	10.0
		"C"	3,500	2.5	4.46	1.70	.57	.31	.12	50	00	112	102	214	.91	1.3	1.5	1.7	2.0	2.3	3.0	3.7
			5,000	2.9	6.38	2.43	.81	.44	.16	60	85 1 ⁻	112	162	214	11.0	11.0	11.0	11.0	11.0	10.0	10.0	10.0
			7,500		9.57	3.64	1.22	.66	.24						1.1	1.5	1.8	1.9	2.4	2.6	3.3	3.9
			10,000	3.2	12.8	4.86	1.62	.88	.32	63	88	114	166	216	11.0	11.0	11.0	11.0	11.0	11.0	10.0	10.0
			15,000		19.2	7.29	2.43	1.31	.49						1.3	1.9	2.1	2.2	2.7	2.9	3.6	4.3
			20,000	35	25.5	9.71	3.24	1.75	.65	66	91	116	168	218	11.0	11.0	11.0	11.0	11.0	11.0	10.0	10.0
			25,000	0.0	31.9	12.2	4.05	2.19	.81		0.			2.0	1.7	2.3	2.4	2.6	2.9	3.3	4.0	4.7
			50,000	5.4	63.8	24.3	8.11	4.38	1.61	69	94	122	172	224	11.0	11.0	11.0	11.0	11.0	11.0	10.0	10.0
		"D"	75,000		95.7	36.4	12.2	6.56	2.42						2.6	3.6	3.8	4.0	4.5	5.2	6.0	6.8
		"D"	100,000																			
			150,000																			
			200,000																			
			250,000																			
			aaada nati	-	on th		nn hi	dra	ام مال	o rto	~~~~~	ult fo	oton	,								

(NOTE) For speeds not shown on the pump hydraulic charts, consult factory.

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PUMP HYDRAULIC SIZE CHART

8 GPM 870 RPM

NO	NOMINAL VISCOSITY N.I.P.R. FRICTION PIPE LOSS (PSI/FT)				FULL BYPASS RELIEF CAPACITY (GPM) / H.P. REQUIRE										RED							
		ROTOR			(Bas	(Based on Sch 40 Steel Pipe)																SI)
CAP.	SPEED	TRIM	(0011)		R	UKACKING PRESS. (PSI)											1 200 300 400 HEAVY					
GPM	RPM		(550)	(PSIA)	3/4" <b>1</b> " <b>1</b> 1/4" <b>1</b> 1/2" <b>2</b> "			50 75 100 f		150 200							DUTY					
					01	01	01	01	01	50	15	100	100	200	65	HEA 5.5	4VY L					/ 
			28	1.4	.01	.01	.01	.01	.01	56	81	106			0.0	5.5	4.0	4.0				
			32		.06	.02	.01	.01	.01						.28	.45	.61	.//		ļ		
			38	1.4	.07	.03	.01	.01	.01	56	81	106	157		7.0	6.5	6.0	5.5	4.5			
			50		.09	.03	.01	.01	.01						.39	.49	.65	.79	1.2			
			70	1.4	.10	.04	.01	.01	.01	56	81	107	158	209	7.5	7.5	7.0	6.5	6.0	5.5		
		STD	100		.10	.04	.01	.01	.01						.42	.53	.71	.83	1.2	1.4		
			150	1.4	.15	.05	.02	.01	.01	57	82	108	158	211	8.0	8.0	7.5	7.5	7.5	7.0	6.0	4.5
			200		.24	.08	.03	.02	.01						.44	.55	.74	.90	1.2	1.5	2.0	2.6
	870		300	0 1.4	.31	.12	.04	.02	.01	57	82	109	159	212	8.5	8.0	8.0	8.0	7.5	7.0	6.5	5.5
0			500		.51	.19	.07	.04	.01						.52	.64	.80	.97	1.3	1.5	2.1	2.6
0	070		750	14	.77	.29	.10	.05	.02	57	82	111	161	214	8.5	8.5	8.0	8.0	8.0	8.0	7.0	6.5
			1,000		1.02	.39	.14	.07	.03	0.	01		101	2	.62	.71	.86	1.0	1.3	1.5	2.1	2.6
			2,000	18	2.04	.78	.26	.14	.05	58	85	112	162	214	8.5	8.0	8.0	8.0	8.0	8.0	7.5	7.5
			3,500		3.57	1.36	.46	.25	.09						.76	.90	1.0	1.4	1.5	1.6	2.2	2.7
		"C"	5,000	2.1	5.01	1.94	.65	.35	.13	60	85	112	162	214	8.5	8.0	8.0	8.0	8.0	8.0	8.0	7.5
		Ū	7,500		7.65	2.91	.97	.53	.19		00		102		.92	1.2	1.3	1.4	1.6	1.9	2.3	2.9
			10,000	24	10.2	3.88	1.30	.70	.26	63	88	114	166	216	8.5	8.0	8.0	8.0	8.0	8.0	8.0	7.5
			15,000		15.3	5.83	1.95	1.05	.39		00		100	210	1.1	1.4	1.5	1.6	1.8	2.1	2.6	3.2
			20,000	0.7	20.4	7.77	2.59	1.40	.52	00	01	110	100	010	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
			25,000	2.1	25.5	9.71	3.24	1.75	.65	00	91	110	100	210	1.2	1.6	1.7	1.8	2.1	2.3	2.9	3.4
			50,000	4.2	51.1	19.4	6.50	3.50	1.29	60	02	100	170	222	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
			75,000	4.3	76.5	29.1	9.73	5.25	1.93	00	90	120	170	222	1.8	2.5	2.6	2.7	3.0	3.3	3.8	4.3
		"D"	100,000	62	102	38.9	13.0	7.00	2.58	70	05	100	170	224	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
			150,000	0.2	153	58.0	19.5	10.5	3.87	10	95	122	172	224	2.3	3.1	3.3	3.4	3.6	3.9	4.4	5.0
			200,000							<u> </u>												
			250,000																			
	(NOTE) For speeds not shown on the pump hydraulic charts, consult factory.																					

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GC



5 GPM 580 RPM

NOMINAL			VISCOSITY	N.I.P.R	FR		)n pi Psi/f	PE L( T)	OSS	FULL BYPASS RELIEF					CAPACITY (GPM) / H.P. REQUIRED								
					(Based on Sch 40 Steel Pipe)						E PF	RESS	URE	(PSI)	DIFFERENTIAL PRESSURE (PSI)								
	00550	TRIM				PIPE	DIAN	ИЕТЕ	R	CR/	ACKIN	IG PF	RESS.	(PSI)	25	25 50 75 100 150					300	400	
GPM	SPEED RPM		(SSU)	(PSIA)		· ·· -			LOW PRES R/V HI PRES R/V														
-					3⁄4"	1"	<b>1</b> ¼"	<b>1</b> ½"	2"	50	75	100	150	200	HEAVY DUTY					(	ONLY		
			28	1.0	.01	.01	.01	.01	.01	55	80	105			4.0	3.5	3.0	2.5					
			32		.03	.01	.01	.01	.01						.19	.29	.40	.50					
			38	1.0	.04	.01	.01	.01	.01	55	80	105	156		4.5	4.0	3.5	3.0	2.5				
			50		.05	.02	.01	.01	.01						.21	.32	.45	.52	.76				
			70	1.0	.06	.02	.01	.01	.01	55	80	106	157	208	5.0	4.5	4.0	4.0	3.5	3.5			
		STD	100		.07	.03	.01	.01	.01						.25	.34	.46	.54	.78	.93			
			150		.09	.04	.01	.01	.01	56		107			5.0	5.0	4.5	4.5	4.5	4.0	3.5	3.0	
			200	1.0	.17	.06	.02	.01	.01		81	107	157	210	.28	.36	.48	.59	.78	.95	1.3	1.3	
			300	1.0	.22	.08	.03	.02	.01	56	01	100	158	011	5.5	5.0	5.0	5.0	4.5	4.5	4.0	3.5	
_	500		500	1.0	.35	.14	.05	.03	.01		01	100	100	211	.34	.42	.52	.63	.80	.97	1.3	1.6	
5	580		750	1.0	.53	.20	.07	.04	.02	56	81	110	160	010	5.5	5.5	5.5	5.5	5.0	5.0	4.5	4.0	
			1,000	1.0	.70	.27	.09	.05	.02	50			100	215	.41	.46	.56	.65	.82	.99	1.4	1.7	
		"C"	2,000	13	1.40	.54	.18	.10	.04	57	84	111	161	213	5.5	5.5	5.5	5.5	5.0	5.0	5.0	4.5	
			3,500		2.46	.94	.31	.17	.06		0.			2.0	.49	.59	.67	.77	.92	1.1	1.4	1.7	
			5,000	1.6	3.51	1.34	.45	.24	.09	59	84	111	161	213	5.5	5.5	5.5	5.5	5.5	5.5	5.0	5.0	
		-	7,500		5.26	2.00	.67	.36	.13	•••	•				.61	.75	.84	.93	1.1	1.2	1.5	1.9	
			10,000	1.9	7.01	2.67	.89	.48	.18	62	87	113	165	215	5.5	5.5	5.5	5.5	5.5	5.5	5.0	5.0	
			15,000		10.5	4.00	1.34	.72	.27						.70	.89	.96	1.1	1.2	1.4	1.7	2.1	
			20,000	21	14.1	5.34	1.78	.96	.36	65	90	115	167	217	5.5	5.5	5.5	5.5	5.5	5.5	5.0	5.0	
			25,000	2.1	17.6	6.68	2.23	1.20	.44	00	00	110	107	217	.75	.94	1.0	1.1	1.3	1.5	1.9	2.2	
			50,000	3.6	35.0	13.4	4.46	2.41	.89	67	92	119	169	221	5.5	5.5	5.5	5.5	5.5	5.5	5.0	5.0	
			75,000		52.6	20.0	6.69	3.61	1.33	0.	02		100		1.3	1.6	1.7	1.7	1.9	2.1	2.4	2.8	
		"D"	100,000	5.4	70.2	26.7	8.92	4.81	1.77	69	94	121	171	223	5.5	5.5	5.5	5.5	5.5	5.5	5.0	5.0	
			150,000		105	40.1	13.4	7.22	2.66					223	1.6	2.1	2.1	2.2	2.4	2.5	2.8	3.2	
			200,000	8.6	140	53.4	17.8	9.63	3.54	75	100	129	179	235	5.5	5.5	5.5	5.5	5.5	5.5	5.0	5.0	
			250,000		175	66.8	22.3	12.1	4.43						1.9	2.5	2.5	2.6	2.8	2.9	3.2	3.6	
	(NOTI	E) For s	peeds not :	shown o	on th	e pur	np h	ydrau	ulic cł	narts,	cons	sult fa	actory	<i>.</i>									



# Mixing and Reaction Technology Pace Setting Technology



## Sulzer Chemtech – Mass Transfer Technology

Your Partner in Separation and Mixing Technology

# The Highest Level of Application Know-how

Our team provides state-of-the art expert know-how for more than 500 applications in 100 processes, this enables us to optimize the performance and your installation.

### Fast and Reliable Turnaround Services

We don't shut-down, when you shut-down. You can rely on Sulzer professionals, expertise and procedures to get you back and running in the shortest possible time.

# Comprehensive Engineering and Technology Services

We provide a full scope of associated engineering and technology services to optimize or trouble-shoot your installation.





### A Broad Range of Innovative and High-performing Products

Our more than 200 products cover a wide range of needs in the field of separation and mixing technology.

They have proven their performance in more than 100,000 columns, 40,000 gas/liquid separators and 100,000 mixers in operation worldwide.



0602 2510

MellapakPlus™ Packing Often copied, never equaled



0605 2504

VGPlus™ Trays One of the best high performance trays ever tested at FRI



0603 2535-3

NeXRing™ The next big thing in random packing



0694 2720

SMV™ static mixer High mixing efficiency combined with large turn-down processing capabilities



Dusec Plus™ Coalescer High performance with minimum pressure drop Sulzer Mixing and Reaction Technology Pacesetting Technology for Mixers 3

- Selection of Mixers for Your Application 4
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  - Comprehensive Engineering Services 23

## Sulzer Mixing and Reaction Technology Pacesetting Technology for Mixer

Since early 1970s Sulzer Chemtech has pioneered static mixing to enable homogenization and dispersion of liquids and gases without resorting to moving parts.

The ongoing development and innovation brought diversification in the area of heat- and mass transfer and reaction technology over a wide range of fluid properties and process conditions.

Today, we are the undisputed market and technology leader, serving the global needs of our customers with the widest range of products and applications. Our solutions are backed by the experience of more than 100'000 references and the latest methods in development, client testing, engineering and fabrication to meet the processing challenges of our customers and create long term benefits. With technical sales offices all over the world and four regional centres supporting them, Sulzer is able to provide you with the same excellent service around the globe.

With manufacturing capabilities around the regions, distances to your factories are kept short which supports a quick delivery.

### **Decades of Experience!**

- · Well established methodology for scale ups
- · R&D facilities existing and testing equipment available
- Improvement of your process reliability, energy consumption and product quality









### **Selection of Static Mixers**

Static mixers are an arrangement of mixing elements installed in a pipe or duct. They function without moving parts and are used to achieve specific mixing and dispersion in continuous processes.

The mixing process is not random. Rather, it follows precise patterns. The performance is therefore predictable. Scale-up methodology is well defined depending on the process objective.

Static mixers are compact, robust, and essentially maintenance free. They perform over a broad range of conditions. Operating and investment costs are low compared with those of dynamic mixers.



Picture 1: Static mixers are applied in continuous processes.



Turbulent mixing in an SMV mixer with 3 mixing elements.

Mixing is one of the most important unit operations. The quality of mixing and dispersion and the rate it is achieved often have a major impact on the product quality, production yield and overall process economics.

The correct selection and design of the applied static mixer is therefore of high importance. Take advantage of 40 years of experience of Sulzer in thousands of applications!

#### Mixers tailored for specific applications

Sulzer offers various types of static mixers optimized for specific applications:

- Blending of miscible liquids or gases is achieved by both the continuous splitting and radial transposition of the flow. Depending on the physical properties of the fluids, the flow may be laminar, transitional or turbulent. In the presence of turbulence, mixing is enhanced by the generation and control of large scale turbulent eddies.
- Dispersions are created when the involved components are immiscible and a liquid component forms the continuous phase. The desired mean drop size and a narrow drop size distribution are achieved through uniform energy dissipation in the total mixer volume and the simultaneous distribution of the components over the entire pipe cross-section.
- A combination of mist and film flow is created when a gas forms the continuous phase of a multi-phase flow. The mixing elements can be configured to achieve a large mass transfer area and a high turbulence, resulting in intensive contact between the gas and the liquid, which is essential for gas scrubbing applications.
- In plug flow and loop reactors equipped with static mixing elements, chemical reactions can be performed under precisely controlled conditions, which is in particular relevant for highly exothermic and endothermic reactions. In addition to rapidly mixing and/or dispersing feed components, the Sulzer mixers create plug flow and greatly enhance heat transfer both within the fluid, and with contacting surfaces for temperature control.

### Compact dimensions, low pressure drop

The energy needed for the mixing process in a static mixer is that required to overcome the pressure drop associated with the flow through the device. This energy is typically supplied by a pump or a blower installed in-line with the mixer. Excessive pressure drop and resulting energy cost is undesirable. Sulzer mixers are optimized for low pressure drop and compact dimensions. Their demand for energy and space is therefore small, thus having a positive impact on both operating and investment costs.

The pressure drop  $\Delta p$  in [Pa] of single-phase flows in different Sulzer mixer types can be roughly estimated as follows:

Laminar flow	
• SMX:	$\Delta p = 1150 \ \eta \ v \ L \ / \ D2$
SMX plus:	Δp = 570 η v L / D2
• SMXL:	$\Delta p = 250 \ \eta \ v \ L \ / \ D2$
<b>Turbulent flow</b>	
• SMV:	$\Delta p = 2.0 \rho v^2 L/D$
• SMV-X:	$\Delta p = 1.0 \rho v^2 L/D$

•	SMX plus:	$\Delta p = 1.7 \rho v^2 L/D$
•	SMI:	$\Delta p = 2.2 \rho v^2$
•	CompaX, KVM:	$\Delta p = 1.4 \rho v^2$
•	Contour:	$\Delta p = 0.5 \rho v^2$

where v = superficial velocity in [m/s], L = mixer length in [m] without empty spaces required by the selected mixer type to achieve a specific mixing task, D = inner pipe diameter in [m],  $\eta$  = dynamic viscosity in [Pa s] and  $\rho$  = density in [kg/m3].

### Examples of typical pressure drops:

<ul> <li>Flue gas (Contour):</li> </ul>	Δp = 1 mbar
• Water (CompaX):	$\Delta p = 20 \text{ mbar}$
Polymer melt (SMX plus):	Δp = 10 bar

This summary is intended to be a guideline only. Please contact one of our sales engineers for exact calculations, special designs and complex mixing tasks.

# High degree of homogeneity with miscible fluids

Sulzer static mixers are designed to generate a homogeneous mixture in a short pipe section at low pressure drop. They have been investigated and optimized using the most advanced experimental and numerical methods to maximize performance and to make sure that the best design can be selected for the mixing task. The achieved degree of homogeneity depends on the type and number of mixing elements, the available mixing length and the product properties.

It is quantified by the coefficient of variation (CoV), which describes the averaged local deviations of a property (such as the concentration) from the mean value in a given cross-section downstream the mixer.

$$\textbf{CoV} = \frac{1}{\bar{x}} \sqrt{\frac{1}{n-1} \quad (x_i - \bar{x})^2}$$

Where  $x_i$  = measured concentration,  $\overline{x}$  = mean concentration and

n = number of samples.

The goal for many industrial processes is to achieve a CoV of 0.05 (5%), which guarantees a high product quality. If a sufficient number of samples are taken from such a mixture, then 95% of the samples will have a concentration which deviates less than 10% from the mean value. A higher or lesser degree of homogeneity can be achieved if required by adjusting the mixer design.



Experimental investigation of homogeneity using LIF (Laser induced fluorescence).

### **Properties of Sulzer Mixers**

### Uniform drop size

Sulzer mixers are capable of generating a dispersion with a specified mean drop or bubble size and a narrow size distribution if immiscible liquids or gases and liquids are involved (the gas has to be the dispersed phase in this case). Sulzer developed a correlation that allows the prediction of the drop or bubble size based on the specific process conditions and fluid properties. The correlation has been verified for various mixer types and a wide range of process conditions. From the calculated specific surface area of the dispersed phase, the mass transfer achieved can be estimated.



Gas-liquid dispersion generated by an SMV mixer.

### Intensive heat transfer

Intensive radial mixing in static mixers evens out deviations in concentration as well as in temperature. Fluid at the core of the pipe is continuously exchanged with that at the wall. The thermal boundary layers at the wall are renewed, and this results in higher heat transfer coefficients than would be possible in a bare pipe or tube. The outcome is particularly valuable when processing high-viscosity fluids in laminar flow. The required heat transfer is achieved with small temperature differences, short residence time, and uniform shear stress—all characteristics favorable for the processing of sensitive products.

Sulzer mixing elements are applied in monotube and multitube heat exchangers. They can also be installed in loop reactors to ensure safety in even very highly exothermic chemical reactions.

### Narrow residence time distribution

Radial mixing in static mixers equalizes not only concentrations and temperatures, but also velocity distribution. Equal velocity means uniform residence time and little axial backmixing. Neither breakthroughs nor stagnant zones are observed. Static mixers are therefore employed as plug flow reactors. The flow regime in the reactor may be laminar or turbulent.

Example: The residence time distribution of an SMXL mixer DN 32 with a length of 1 m corresponds to a cascade of approximately 30 Ideally Stirred-Tank Reactors.







Comparison of residence time distribution of SMX mixer and empty pipe.

## **Product Portfolio**

### SMV

The SMV mixer is made of corrugated plates that form open, intersecting channels in which the flow is divided into many substreams. The SMV mixer is used in the turbulent and transitional flow regime, in particular, to intensify mass transfer between immiscible fluids. The SMV structure is extremely adaptable. The energy input and internal surface area can be optimized to meet the specific requirements of the application. Mixing elements can be built for round, square, rectangular, and even conical and ring-shaped pipes and ducts. They are available in various materials, including plastics such as PP, PVDF, and PTFE.



SMV mixer applied for mixing of ethyl benzene and steam in a styrene production plant

### SMI™/KVM™

The Sulzer mixer types SMI and KVM are vortex mixers, which are designed for fully turbulent flow. Typically, these are made up of two mixing elements configured with an empty pipe section between them. Each mixing element is designed to create two large counter-rotating eddies, which provide intensive mixing with very low pressure drop.

The SMI mixer has a pair of inclined winglets attached to the pipe wall. The KVM mixer has blades in the center of the pipe. Both structures are extremely open, which eliminates any risk of clogging. SMI and KVM mixers are available in a broad selection of metals; stainless and carbon steels are commonly used.

### CompaX™

The Sulzer CompaX mixer, like the SMI and KVM, is designed for fully turbulent flow. It is especially suitable to mixing small amounts of additive into a bulk flow within a very short mixing length. The CompaX mixer has a single mixing element integrated into a short ring or flanged housing, which is installed between two flanges of a pipeline. The additive is injected through the integrated feeding device into a highly turbulent zone behind the central blade of the mixer, where it is immediately diluted. Further downstream, it is distributed over the entire cross-section by the two large counter-rotating eddies that are produced by the mixing element. Good mixing quality is achieved only three pipe diameters downstream. CompaX mixers are available in stainless steel and various plastic materials, such as PP and FRP. PTFE coated stainless steel is also available.



SMI and KVM mixer





CFD simulation showing the mixing mechanism of the CompaX mixer

### **Product Portfolio**

### Contour™

The Sulzer Contour mixer is designed for the installation in large rectangular flue gas ducts. The mixer consists of a set of pairs of short wings. Each pair of wings generates a large-scale vortex downstream without any flow detachment. This equalizes concentration deviations in the duct very quickly at extremely low pressure drop. Co-rotating or counter-rotating vortices can be generated depending on the mixing task. The wings of the Contour mixer are very lightweight. They can be easily installed using simple wall adapters in new or existing ducts of any shape.

### SMX[™]/SMX plus[™]

The Sulzer SMX mixer has been the industry standard for demanding mixing applications – especially in the laminar flow regime – for more than 30 years. The SMX mixer has a grid of inclined bars, which repeatedly divide the components into layers and spread them over the entire cross-section of the pipe. Very large flow ratios, extremely large viscosity ratios, and complex rheological product behaviors can be handled effectively within short mixing lengths.

The new SMX plus mixer applies the same effective mixing principle, but it is significantly more energyefficient. Compared with an SMX mixer of equal size, it reduces the pressure drop by 50% while achieving the same mixing result. Alternatively, the mixer diameter can be reduced for a given allowed pressure drop. The SMX plus mixer is also an attractive option for turbulent flow, especially when there are differences in component viscosity.

### **SMXL™**

Sulzer SMXL mixer is a low intensity design applied whenever a continuous mixing action over a relatively long pipe section is required with low pressure drop. Typical application is heat transfer enhancement when installed as internals in mono-tube and multi-tube heat exchangers and plug flow reactors. Proprietary manufacturing methods enable production of long lengths at low cost relative to other designs.



SMV mixer applied for mixing of ethyl benzene and steam in a styrene production plant



SMX plus mixing elements installed in a flanged housing



Multi-tube heat exchanger equipped with SMXL mixing elements.

### SMR

Sulzer SMR mixer reactor is built with mixing elements made from bent tubes. These allow heat transfer fluids to flow through the structure, thus creating a mixing element with temperature-controlled surfaces. The mixing elements provide a very high specific heat transfer area, intensive radial mixing, and a narrow residence time distribution. The SMR mixer reactor is the ideal equipment for the execution of even very highly exothermic reactions, such as polymerizations. As a heat exchanger, it is applied mostly in cooling where fluid viscosity is increasing as temperature is reduced.



### Selection of Static Mixers



## **Solid Application Expertise**

Sulzer mixers have been performing successfully in the petroleum industry for many years. They are employed where different liquid or gaseous media have to be thoroughly mixed or intensively contacted.

Many years of experience and continuous development in static mixing technology have enabled Sulzer to offer economic, practical solutions to a wide range of mixing problems. When using Sulzer mixers, oil refineries and gas plants can avoid or reduce some widely recognized corrosion problems.

#### Some examples of applications are:

- Crude oil sampling for representative determination of the water content according to the ISO 3171 code
- Overhead desalting after the atmospheric distillation column for dissolving salts into injected wash water
- Blending natural gas streams with steam, propane, or other gases
- · Adjusting the viscosity of heavy oil with gas oil
- · Adjusting the calorific value of natural gases
- Adjusting the sulfur content of heavy oil by mixing fractions that have different sulfur contents
- Mixing of air and process gas in SUPERCLAUS[®] units
- · Contacting multiphase mixtures
- · Saturating hydrocarbons with hydrogen before they enter the catalytic reactor bed in hydroprocessing units
- · Desulfurizing distillates in Merox process units
- · Treatment of service and wastewater
- · Admixing of aids into water during tertiary crude oil extraction
- Seawater deoxingenation
- · Mixing of bitumen or heavy crude oils
- · Homogenizing solvent and feedstock in deasphalting units
- · Producing bioethanol and biodiesel, which requires static in-line mixing for many process steps



## **Oil and Gas**

### Gas Dehydration with TEG

Sulzer co-current MIXDRY static mixers offer an attractive alternative to typical counter-current contactors where natural gas has to be dehydrated. Dehydration is performed by intensively contacting the wet gas with lean glycol (mainly TEG) within the compact MIXDRY system. There, high interfacial surface area is provided, which promotes the desired mass transfer. One single stage of removal can be achieved in a single mixer. Multiple stages of removal are available using multiple mixers with separators between the mixers

### **Customer Benefits**

- Dew point reductions up to 40°C possible
- Simple installation
- · Low weight and small footprint
- Low investment costs

### LNG Desuperheating

Sulzer Chemtech has developed a new injection-mixing device for LNG desuperheating. With this device, LNG is injected, atomized, and intensively contacted with the gas phase (NG or BOG). This novel mixing system enhances and speeds up the evaporation through greater turbulence, higher residence time of the liquid, and a large exchange surface area. It is a directcontact, high-efficiency evaporator as opposed to an in-line spray system, for example.

- · Typically complete evaporation of the liquid LNG
- Cold spots are avoided enhancing overall evaporation efficiency
- More representative temperature measurement for liquid load control
- Reduction of liquid consumption resulting in savings on liquid pumping energy
- Proven technology



### **Oil and Gas**

### **BOG Recondensing**

Recondensers are used in LNG receiving terminals to recondense LNG boil-off gas (BOG) using subcooled LNG. This technique reduces the operating cost associated with the pressurization of the BOG to pipeline pressure level. With Sulzer's mixing and contacting technology, the BOG enters the mixing section in the tube with high speed, and an intense mixing process occurs. The process is reinforced by the installed mixing elements and results in more-efficient condensation than in the conventional packed bed columns design.

#### **Customer Benefits**

- Efficient condensation at pressure drops in the range of 0.3-0.5 bar
- Compact design, i.e. small volume compared to conventional packed-column type of recondensers – typically 5 times smaller in size
- Smooth operating conditions and self-regulating behaviour



### **Crude Oil Desalting**

Effective crude desalting is reached by first optimizing the crude/wash water contacting for the dissolution of the salt, followed by an effective separation of the two phases to avoid water carry-over in the crude.

Sulzer Chemtech is a supplier of specially configured SMV-type crude/wash water dispersers to enable intensive contacting of the two immiscible liquids so that a swarm of water droplets is formed. A homogenous distribution of these droplets is created in the crude oil, as is a large, continuously renewed interfacial area. These accelerate mass transfer.

- Predictable drop size and narrow drop size distribution preventing undesirable emulsification and allowing safe dimensioning of the settler
- Reduction of carry-over and under-carry phenomena resulting in lower reprocessing costs of about 2000 EUR per day
- Maximized interfacial surface area for optimal mass transfer
- High turn-down capacity
- At least 0.5 bar less pressure drop than mixing valve resulting in significant cost savings

### **CCR Reformer**

During the regeneration of catalyst reactors, the regeneration gas has to be intensively contacted with a caustic water stream before entering the loop trim cooler.

A gas-liquid contacting system consisting of a Sulzer mixer installed after a liquid distribution nozzle generates a flow of fine droplets. The flow provides a large interfacial surface area for most-intensive contacting.

### **Customer Benefits**

- Flexible wash efficiency through liquid load changes
- Pressure drop smaller than 0.1 bar giving low energy requirement
- Experience in providing special arrangement designs made of high alloy steels

### **Gas Treating**

The Sulzer SMV co-current gas scrubber is often installed for process gas treatment in refineries to remove impurities from a gas. During the process, the gas is contacted with a scrubbing liquid to promote the desired mass transfer from the gas to the liquid phase. Typical refinery gas washing removes sulphur compounds like H2S, COS, and SO2, acids like HCI and HF, and many salts. Gas washing systems with Sulzer SMV mixers give highest removal rates.

- Small equipment volume resulting from high permissible gas velocities
- Optimum results using chemical absorption
   process
- Pressure drop usually between 0.1 and 0.5 bar giving low energy requirement



### **Oil and Gas**

### **Sulphuric Acid Alkylation Unit**

The sulphuric acid alkylation process from DuPont Stratco calls for specially configured Sulzer SMV[™] mixers and dispersers. The caustic wash mixers are designed to comply with the requirements of the downstream settler, and to fully neutralize acid components. The neutralization is of great importance for the downstream process. The separation columns located after the separators are corrosion protected by the static mixer efficiency. Bad designed mixers result in great corrosion problems in the columns.

#### **Customer Benefits**

- The SMV configuration can be attuned to the pressure drop and drop size as well as drop distribution expectations
- Low acid and caustic carry over protect downstream columns
- Acid wash and product-neutralizing SMV Static Mixers improve plant overall efficiency

### Hydrocracking Unit

Vapor effluent flashed off from the high-pressure (HP) hydrocracker reactor is mixed with wash water to dissolve ammonium bisulfides (NH4HS) upstream of the HHP off-gas cooler.

The water wash prevents salt deposit buildup on the cooler tubes and the associated increased corrosion rates. Using a specially configured SMV mixer installed after the spraying nozzles gives the best washing efficiencies in the process stream (HHPS vapor).

- · Higher run length of the unit
- · Less salt deposits (HN4HS) in the cooler
- Reduced maintenance work allowing operational reliability
- Pressure drop usually between 0.3 and 0.5 bar giving low energy requirement
- Proven technology specified by process licensor with more than 100 references




# **Chemical/Petrochemical Industry**

Thousands of references document the versatility of Sulzer mixers in the chemical process industry. The applications include: mixing liquids at various viscosities, mixing including reactions, gas-liquid contacting, mass transfer and absorption, gas mixing, and liquid evaporation as well as heat removal in exothermal reactions.

The mixers are available in a wide range of materials, which allows users to handle even corrosive chemicals effectively.

#### **Applications**

- Diluting of strong acids and bases
- Adding additives, catalysts and inhibitors to process streams
- Mixing of different liquid streams to attain uniformity of concentration and temperature
- · Dispersing of alkali in hydrocarbons

#### **Gas Phase Reactions**

To attain high selectivity and a high yield in catalytic gas phase reactions, uniform concentration and temperature distributions plus a flat velocity profile at the reactor inlet are essential. Sulzer mixers are used upstream of reactors to attain continuous mixing of additives and conditioning of the inlet gases. As a result, catalyst life is extended considerably in plants.

#### **Applications**

- Production of monomers, as Styrene Monomer
- · Production of organic acids
- · Production of anhydrides

- · Uniform concentration and temperature distribution
- · Low pressure drop
- Longer catalyst lifetime







# **Chemical/Petrochemical Industry**

## Gas liquid contacting and absorption

Sulzer dispersers are used for considerably different operations as physical or chemical absorption of gases into liquids, mass transfer for homogeneous or heterogeneous chemical or biochemical reactions, stripping gases from liquids with a stripping agent.

#### **Applications**

- Production of Ethylbenzene
- Production Dichlorethylene
- Hydrogenation of aromatics

#### **Customer Benefits**

- Uniform droplets range
- High mass transfer area



## Heat exchange in exothermic reactions

The Sulzer SMR mixer-reactor is well suited for the performance of continuous temperature-controlled chemical reactions since mixing and heat transfer occur simultaneously. There are different modes of operation:

- with once-through product flow (plug-flow system)
- with recycled product flow (loop system)
- · combination of loop and plug-flow system

#### **Applications**

- Alkylation reactions
- Sulphonation reactions
- Switching batch to continuous process for constant product quality and smaller reactor volumes

- · High heat transfer capacities
- Uniform temperature profile
- Low pressure drop



# **Chemicals**

# Homogeneous and disperse plug flow reactors reactions

With the various Sulzer mixing elements, it is possible to have reactions within a narrow residence time distribution and with a maximum possible driving force.

The plug flow behavior can be achieved in a laminar flow regime as well as in a homogeneous and dispersed phase.



#### Further examples of applications

- · Optimized gas/liquid distribution at the inlet of two-phase reactors to improve the efficiency of the reactor
- · Liquid/liquid dispersion for extraction reactions
- · Plug flow reactor for homogenous or dispersed-liquids systems

- · Excellent mixing and flow characteristics (plug flow) with low shear
- Narrow residence time distribution
- · Excellent in-line cleaning and sterilization ability
- · Fewer wall effects prevent overheating
- · High selectivity for desired product
- Modular design for flexible operation
- · Scale-up correlations well established

# **Solid Application Expertise**

## Mixing in large gas ducts

Static mixers are often used in the flue gas treatment systems of thermal power stations, cement works, refineries, steam reformers, steelworks and so on. They are used to homogenize the gas temperature or the concentrations of components of the gas stream, to admix small amounts of additives for chemical processes such as the reactions taking place in the selective catalytic reduction (SCR) process, or to homogenize or distribute the dust or ash in the flue gas. These mixing tasks are often crucial for the effectiveness of the whole flue gas treatment process.

The static mixers from Sulzer Chemtech are high-fidelity solutions that have been optimized for extremely low pressure drops and very efficient mixing over short mixing lengths. Our offering for such applications, the Sulzer Contour Mixer, leads the industry in terms of its excellent mixing performance at an unrivalled pressure drop. In addition, the classical Sulzer SMV mixer offers outstanding performance and is still regarded as the standard solution for such applications by many of our customers.

For DeNOx applications with SCR reactors, our solution for admixing the NH3 to the flue gas for a NOx conversion of >90% and < 2ppm NH3 slip typically generates less than a 1 mbar pressure drop. If even higher conversion rates are required, our bespoke mixer solutions can help achieve outstanding performance.

The static mixers from Sulzer Chemtech work equally well at a wide range of loads. This is very important for units that experience frequent changes in load. Typically, the incoming profiles of temperature, NOx, and dust can vary significantly, depending on the load case and the fuel used in the boiler. With a Sulzer static mixer solution, such changes in the operational conditions will not cause significant changes in the overall performance of the flue gas treatment system.

Optionally, the equipment can be thermally coated with an extra hard skin. This coating increases the equipment's resistance in situations with flue gas that contains highly erosive dust, and it significantly reduces damage to the equipment.



Installation of Sulzer Contour™ mixers in a large gas duct



Installation of a Sulzer SMV™ mixer with Ammonia Injection Grid



Sulzer Contour™ mixer wing pair for static mixing tasks in flue gas applications

# Energy

In order that the mixer can work properly and the pressure loss remains low, the flow in the whole flue gas duct needs to be analyzed and optimized. This is why Sulzer Chemtech always makes use of CFD during the design of mixing systems for large scale flue gas ducts. The whole package of duct, guide vanes, turning vanes, dampers, dosing grids, static mixers and rectifiers need to work together in an optimal way to achieve the desired system performance. Therefore all these components are included in the CFD analysis.

Many customers require an additional experimental verification of the whole solution in scaled down cold flow experiments. Sulzer Chemtech is both ready to take responsibility for such physical model tests or to cooperate with its customer to perform these tests elsewhere.

Sulzer Chemtech not only manufactures the dosing grids and static mixers, it is also a valuable partner for the design of the whole set of duct internals and it is ready to take guarantees for the performance of the solutions developed.

Depending on the quality of the coal fired in the boiler, the dust contained in the flue gas can have highly erosive properties, which can lead to quick degradation of the SCR catalyst. This is particularly true for lignite or brown coal. Sulzer static mixers can be designed to distribute the dust in the flue gas uniformly in order to avoid localized peaks in erosion of the catalyst.



Streamlines through gas duct with AIG, Sulzer Contour mixers and SCR catalyst, colored by local NH3 concentration

- · Well proven, highly efficient dosing and static mixing equipment
- · Solution with lowest pressure drop on the market
- Customer support through extensive CFD analysis during design phase
- · Optional erosion protection coating
- Static mixers for catalyst erosion protection

# Water



## **Function**

A static mixer consists of a sequence of stationary guide plates. When media is pumped through the mixer, the plates achieve the systematic, radial mixing of media flowing through the pipe. The flow path follows a geometrical pattern, precluding any random mixing. The mixing operation is therefore completed within a very short flow distance.

In gas/liquid contacting, e.g., in ozonation, the formation of fine gas bubbles in a water/gas mixture promotes intensive contact between the two phases. The result is high mass transfer—for instance, a high oxygen transfer rate or an excellent ozone utilization factor.

In contrast to stirred tanks or empty pipe systems, static mixers ensure that the complete fluid stream is subjected to compulsory or enforced mixing or contacting. The energy required for mixing or for mass transfer is taken from the main stream itself, which is manifested by an insignificant pressure drop than in an empty pipe system. This value depends on the design of the mixer and on the relative operating conditions. It is generally in the range of 5-300mbar.

The energy requirements of static mixers is at least an order of magnitude smaller than that of dynamic agitator systems. In addition, the energy is evenly dissipated throughout the entire mixer volume.

- Continuous process
- Short installation length
- Low pressure drop
- High mixing efficiency = less chemical used
- Clogging free
- · Independent of mixing ratio
- Wide size range from as small as DN15 to DN2200
- Multiple dosing possible
- Wide range of material available, See Figure 3 and 4
- · Installations in rectangular ducts possible

# **Wider Application Fields – Other Markets**

While static mixing was initially an alternative to batch processing with agitators in tanks, the role of the technology in the continuous production of all types of fluids in many industries has increased in importance. The main business drivers are:

- high-quality products
- cost-effectiveness
- high production yield
- reproducible product quality
- a solution with minimum space requirements
- energy efficiency
- rapid line transition capability with minimum waste

High efficiency static mixer designs from Sulzer have enabled industry to meet these goals. Mixing and Dispersion to meet specific process/product requirements are routine with application across the full range of flow conditions in the laminar, transition and turbulent flow regimes. Additionally, Sulzer designs are applied to enhance heat transfer and establish plug flow in single pass and loop reactors.

The technology is available in a broad selection of materials of construction. Equipment is designed to meet industrial requirements for chemical, sanitary and hygienic service.

#### Food and Beverage Industry

- Blending flavor, color, nutritional supplements and other ingredients with base products in the production of soups, cereal, yogurt, chocolate and concentrates
- · Bulk product dilution Sugars, syrups and juice
- Heat Exchange
  - Heating and Cooling chocolate for tempering
  - Cooling after grinding
  - Devolatilization of syrups for coating
- Dispersion of Gases into liquids
  - Carbonization of beer
  - Aeration to lower bulk density
- · Dissolving solids after induction into a bulk stream



#### **Customer Benefits**

- Clean, in-place design features
- · Cost effective, compact and energy efficient

#### **Personal Care Products**

- Mixing and dispersion in high volume continuous production processes
  - Feed stocks, emulsifiers, surfactants with water and oils
- Admixing proprietary ingredients to achieve product identity qualities, e.g., color, texture, and scent, etc.
  - In the production of detergents, fabric softeners and household cleaners
  - In the production of tooth paste, deodorant, shampoo and body lotions
- · Composition and temperature homogenization
  - Filling speed and uniformity in high speed packaging
- Heat Exchange
  - Cooling in processing loops and prior to packaging
  - Heating viscous feed stocks between storage and processing
- Maintaining temperature to control viscosity

- Predictable performance, constant over time
- Reliable scale-up
- Turndown capability

# **Wider Application Fields – Other Markets**

# Reactive Resins, Adhesives, Sealants, Paint and Coatings

- · Mixing and dissolution of blowing agents
  - Foamed insulation, sheet and shapes
- · Mixing fillers and additives with base product
  - Mixing and distribution of cross linking agents in base fluid addition of color, UV stabilizer and fire retardant
- Two part component mixing
  - Equal parts and viscosity (disposable mixer market)
  - With high flow and viscosity ratios
- Heat Exchange
  - Cooling in high energy dissipation process loops
  - Post reactor cooling prior to packaging
  - Heating and cooling on roll coating lines
  - Devolatilization to remove solvents and excess monomers

## **Pharmaceutical and Biotech**

- Rapid Mixing
  - For fast reations high selectivity with parallel and sequential reactions
  - To initiate precipitation continuous crystallization processes
  - Salt base dilution
- Plug flow reactors meeting uniform residence time requirements
  - Hydrolysis
  - Dissolving crystals
  - Expanded fluidized bed processes
- High intensity dispersion
  - Oil-water dispersions to create microspheres of controlled diameter
  - Purification of products, extraction of contaminates
- · Heat exchange with plug flow
  - Temperature control heating and cooling with single and multiphase fluids
  - Control of exotherms
- · High surface mixer substrates for cell growth

#### **Customer Benefits**

- · Mixing intensity to meet process requirements
- · High degree of color or additive uniformity
- · Temperature control for process and packaging

- · Sanitary design, kilolab to commercial scale
- Precise temperature control
- Plug flow characteristics
- Mixing and dispersion to meet specific process requirements





# **Comprehensive Engineering Services Markets**

## **Development and Technology**

Sulzer makes every effort to support our customers and continuously improve our design tools. Engineers in the R&D lab develop new and improved products, analyze and optimize processes.

We maintain close relationships to universities and independent research organizations to support these efforts.

## **Engineering and Manufacturing**

Sulzer has a long-standing manufacturing tradition. Sulzer owns dedicated factories in every region to produce mixers, columns, reactors, and heat exchangers.

For certain sizes and certain countries, we work with well-known and proven subcontractors who are bound by Sulzer manufacturing policies and quality standards.

## Capabilities

Manufacturing according to PED 97/23/EC, ASME VIII Div.1, and ASME B31.3/U-Stamp, Gost (TR), China Stamp, Norsok, or NACE

Design codes acc. to AD2000, EN 13445, ASME Broad selection of material for construction available

Non-destructive testing (LPT, X-ray, pressure testing up to 500 bar, PMI, MT, UT etc. acc. EN and ASME)

Designing with SolidWorks

Strength calculations, FEM analysis, nozzle loads etc.

Certification for ISO 9001, ISO 14001 and ISO 18001

Experienced project management team

## **CFD** Analysis

CFD calculations done in advance of fabrication can support the decision to go for a particular technology, and can save on the time required for commissioning and testing later. Sulzer uses CFD technology both for the modeling of existing and the development of new products.







#### www.sulzer.com

Please check for your local contact

Sulzer Chemtech Ltd, a member of the Sulzer Corporation, with headquarters in Winterthur, Switzerland, is active in the field of process engineering and employs some 4000 persons worldwide.

Sulzer Chemtech is represented in all important industrial countries and sets standards in the field of mass transfer and static mixing with its advanced and economical solutions. The activity program comprises:

- Process components such as fractionation trays, structured and random packings, liquid and gas distributors, gas-liquid separators, and internals for separation columns
- Engineering services for separation and reaction technology such as conceptual process design, feasibilities studies, plant optimizations including process validation in the test center
- Recovery of virtually any solvents used by the pharmaceutical and chemical industry, or difficult separations requiring the combination of special technologies, such as thin film/short-path evaporation, distillation under high vacuum, liquid-liquid extraction, membrane technology or crystallization.
- Complete separation process plants, in particular modular plants (skids)
- Advanced polymerization technology for the production of PLA and EPS
- Tower field services performing tray and packing installation, tower maintenance, welding, and plant turnaround projects
- · Mixing and reaction technology with static mixers
- Cartridge-based metering, mixing and dispensing systems, and disposable mixers for reactive multi-component material

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# AQUATIC ECO-SYSTEMS™

# COMMERCIAL AQUACULTURE

# PENTAIR AQUATIC ECO-SYSTEMS POINT FOUR™ MICRO BUBBLE DIFFUSERS (MBD)

#### The original ... since 1988

These aquaculture-duty diffusers are among the most efficient diffusers available, allowing you to increase yield while controlling the cost of expensive gases. Made from premium materials and subject to rigorous testing, MBD diffusers provide the kind of performance and reliability our reputation is built on.

Point Four diffusers use a specially developed, ultra fine pore ceramic plate that produces a cloud of extremely fine bubbles of approximately 100–500 microns; far superior to airstones, porous hose or membrane type designs. The flat plate design ensures uniform bubbles across the entire surface and minimizes bubble coalescence to achieve an absorption rate in excess of 80%, depending on depth and flowrate. Bubbling Pressure is 25 to 35 psi. (1.7 to 2.4 bar).

- One of the most efficient diffusers available.
- Easy to install and use-trouble-free operation.
- Robust construction—ceramic plates set in a rigid aluminum base with solid brass connection fittings (MBD Series).
- Also available with a weighted plastic base (1PMBD075).
- Flexible, modular design lets you easily add or subtract diffusers as your needs change (1PMBD075).



PentairAES.com

1PMBD075



# PENTAIR AQUATIC ECO-SYSTEMS POINT FOUR™ MICRO BUBBLE DIFFUSERS (MBD)

	Overall Size (in/cm)	Weight (lbs/kg)	Rec. Operating Range (Lpm/scfh)	Max Flowrate @ 50 psi (3.5 bar) (Lpm/scfh)	Gas Inlet Connection
1PMBD075	85⁄8" x 23⁄4" / 22 x 7	1/0.45	0.75 / 1.6	2.2 / 9.5	1¼" Hose Barb
1DMBDC100	14½" x 1¾" / 37 x 4.5	1.2 / 0.535	up to 1.5 / 3.2	4.5 / 9.5	1⁄4" Hose Barb
1DMBDC300	15¼" x 3¼" / 39 x 8.3	2.8 / 1.3	up to 3 / 6.5	9/19	1⁄4" Female
1DMBDC600	271⁄2" x 31⁄4" / 70 x 8.3	5/2.3	up to 6 / 12.7	18 / 38	1⁄4" Female
1DMBDC900	39¾" x 3¼" / 102 x 8.3	7.3 / 3.3	up to 9 / 19.5	27 / 58	1⁄4" Female
1DMBDC120	52" x 3 ¼" / 132 x 8.3	9.5/4.3	up to 12 / 26	36 / 78	1⁄4" Female



#### 2395 APOPKA BLVD., APOPKA, FL 32703 407.886.3939 PentairAES.com

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#### Home / AR 300



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# Industrial Grade Argon, Size 300 High Pressure Steel Cylinder, CGA-580

Airgas Part #: AR 300		
Manufacturer #: 300		
Log in to get your price		
Enter Zip Code		
CHECK PRICE		
Qty 1		
Package Size: 1		
Cylinder		
Typically in Stock		

ADD TO CART

#### Item Details

Argon (Ar) - an inert colorless, odorless, tasteless, noncorrosive, nonflammable and nontoxic gas. Argon is used primarily for applications such as arc welding, steel making, heat-treating and electronics manufacturing. Available in high-pressure and liquid

cylinders, as well as MicroBulk and bulk deliveries.

Specifications

- > Size 300 High Pressure Industrial Cylinder
- > DOT Specification: 3AA-2400 Canada 3AA-M183
- > 0.D.: 9.25" 235 mm
- > Length: 55" 1397 mm
- > Weight: 132 lbs 60 kg
- > Water Volume: 2990 Cubic Inches 49 Itrs
- > Airco/BOC = T
- > Praxair = T
- > Air Products = A
- > Sizes may vary by location. Contact your Airgas representative or local branch location for availability in your area.

#### **Product Attributes**

## CGA Connection

» CGA 580

Cylinder Size » 300 Steel HP

#### Gas Grade

» Industrial

» Show less



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**Product Data Sheet** 

# DOW FILMTEC[™] NF90-400/34i Element

Description	Ideal for: utility managers and operators looking for a technology that delivers high quality permeate water while removing specific contaminants such as salts, nitrates, iron, and organic compounds.					
	<ul> <li>The DOW FILMTEC[™] NF90-400/34i Element:</li> <li>Delivers high productivity and cleanability due to its high active area and widest cleaning pH range (1-13) tolerance</li> <li>Offers a nanofiltration technology that selectively removes these components, color and operates at low operating pressures</li> <li>Including iLEC[™] interlocking end caps, reducing system operating costs and the risk of o-ring leaks that can cause poor water quality</li> </ul>					
Product Type	Spiral-wound element with polyamide thin-film composite membrane					

## **Product Specifications**

		Activ	e Area	Feed Spacer	Permeate	Flow Rate	Typical Stabilized Salt	Minimum Salt
DOW FILMTEC™ Element		(ft²)	(m²)	Thickness (mil)	(GPD)	(m³/d)	Rejection (%)	Rejection (%)
NF90-400/34i		400	37	34-LDP	10,000	38	>97%	98.7%
	1. 2. 3. 4. 5.	Permea 2,000 r Flow ra Stabiliz charact Sales s Active a membr	ate flow an ng/l MgSO tes for indi ed salt reje eristics an pecificatio area guara ane area c	d salt passage based on f 4, 70 psi (4.8 bar), 77°F (2 vidual elements may vary cction is generally achieve d operating conditions. ns may vary as design rei nteed ± 3%. Active area fiten stated by some manu	the following tes 25°C) and 15% / but will be no r ad within 24-48 visions take plac as stated by Do ufacturers. Mea	st conditions: recovery. nore than <u>+</u> 15% hours of continu ce. ww Water & Proc asurement meth	). Ious use; depending upo cess Solutions is not cor od described in Form No	on feedwater nparable to nominal o. 609-00434.
Element Dimensions		D	dia <u> </u>		BA		→ →	<b>c</b> DIA

	I	Feed'   U-C	up Brine Seal	Fiberglass C	)uter Wrap	End Cap	Brine IF	Permeate	
		Α		В		С		0	)
DOW FILMTEC [™] Element	(in.)	(mm)	(in.)	(mm)	(in.)	(mm)		(in.)	(mm)
NF90-400/34i	40.0	1,016	40.5	1,029	7.9	201	1	.125 ID	29 ID

1. Refer to Dow Water & Process Solutions Design Guidelines for multiple-element applications. 1 inch = 25.4 mm

2. Element to fit nominal 8-inch (203-mm) I.D. pressure vessel.

3. Individual elements with *iLEC* endcaps measure 40.5 inches (1,029 mm) in length (B). The net length (A) of the elements when connected is 40.0 inches (1,016 mm).

Operating and	Maximum Operating Temperature ^a	113°F (45°C)			
Cleaning Limits	Maximum Operating Pressure	600 psig (41 bar)			
	Maximum Element Pressure Drop	15 psig (1.0 bar)			
	pH Range, Continuous Operation ^a	2 – 11			
	pH Range, Short-Term Cleaning (30 min.) ^b	1 – 13			
	Maximum Feed Silt Density Index (SDI)	SDI 5			
	Free Chlorine Tolerance °	< 0.1 ppm			
	<ul> <li>^a Maximum temperature for continuous operation above pH 10 is 95°F (35°C).</li> <li>^b Refer to Cleaning Guidelines in specification sheet 609-23010.</li> <li>^c Under certain conditions, the presence of free chlorine and other oxidizing agents will cause premature membrane failure. Since oxidation damage is not covered under warranty, Dow Water &amp; Process Solutions recommends removing residual free chlorine by pretreatment prior to membrane exposure. Please refer to technical bulletin <u>"Dechlorinating Feedwater"</u> for more information.</li> </ul>				
Additional	Before use or storage, review these additional r	resources for important information:			
Important					
Information	<ul> <li>Usage Guidelines for DOW FILMTEC™ 8" Elements</li> </ul>				
	System Operation: Initial Start-Up				
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Product Data Sheet



## FilmTec[™] Membranes

FilmTec[™] NF90 Nanofiltration Elements for Commercial Systems

**Description** The FilmTec[™] NF90 Membrane Elements provide high productivity performance while removing a high percentage of salts, nitrate, iron and organic compounds such as pesticides, herbicides and THM precursors. The low net driving pressure of the NF90 membrane allows the removal of these compounds at low operating pressures.

## **Typical Properties**

		Applied Pressure	Permeate Flow Rate	Minimum Salt
Product	Part Number	psig (bar)	gpd (m³/d)	Rejection (%)
NF90-2540	149982	70 (4.8)	680 (2.6)	97.0
NF90-4040	149983	70 (4.8)	2,000 (7.6)	98.7

1. Permeate flow and salt rejection based on the following test conditions: 2,000 ppm MgSO₄, 77°F (25°C) and 15% recovery at the pressure specified above.

2. Permeate flows for individual NF90-2540 Elements may vary by -20% / +30%. NF90-4040 individual elements may vary -15% / +50%.

3. Developmental products available for sale.

## Element Dimensions





FilmTec sells coupler part number 89055 for use in multiple element housings. Each coupler includes two 2-210 EPR o-rings, FilmTec part number 89255.

	Dime	nsions – Inches (mm)		1 inch = 25.4 mm
Product	Α	В	C	D
NF90-2540	40.0 (1,016)	1.19 (30)	0.75 (19)	2.4 (61)
NF90-4040	40.0 (1,016)	1.05 (27)	0.75 (19)	3.9 (99)

1. Refer to FilmTec[™] Design Guidelines for multiple-element systems of midsize elements

(Form No. 45-D01588-en).

2. NF90-2540 has a tape outer wrap. NF90-4040 has a fiberglass outer wrap.

Operating and	Membrane Type	Polyamide Thin-Film Composite			
Cleaning Limits	Maximum Operating Temperature	113°F (45°C)			
	Maximum Operating Pressure	600 psi (41 bar)			
	Maximum Feed Flow Rate	1			
	4040 elements	16 gpm (3.6 m°/hr)			
	2540 elements	6 gpm (1.4 m°/hr)			
	Maximum Pressure Drop				
	tape wrapped	13 psig (0.9 bar)			
		15 psig (1.0 bar)			
		0.44			
	Short Torm Clooping (30 min ) ^b	2 - 11			
	Maximum Food Silt Density Index				
	Free Chlorine Tolerance ^c	<0.1 0 mag 10.1 0 mag			
		··· FF			
	<ul> <li>a. Maximum temperature for continuous op</li> <li>b. Refer to <u>Cleaning Guidelines</u> (Form No. 4</li> <li>c. Under certain conditions, the presence of membrane failure. Since oxidation dama recommends removing residual free chlosen <u>FilmTec™ Design Guidelines for multiple</u> for more information.</li> </ul>	eration above pH 10 is 95°F (35°C). 45-D01696-en) for NF90. of free chlorine and other oxidizing agents will cause premature age is not covered under warranty, DuPont Water Solutions orine by pretreatment prior to membrane exposure. Please refer to le-element systems of 8-inch elements (Form No. 45-D01695-en)			
Important Information	Proper start-up of reverse osmosis w membranes for operating service and or hydraulic shock. Following the pro system operating parameters conforr quality and productivity goals can be	ater treatment systems is essential to prepare the I to prevent membrane damage due to overfeeding oper start-up sequence also helps ensure that m to design specifications so that system water achieved.			
	Before initiating system start-up procedures, membrane pretreatment, loading of the membrane elements, instrument calibration and other system checks should be completed.				
	Please refer to the application informa (Form No. 45-D01609-en) for more in	ation literature entitled <u>Start-Up Sequence</u> formation.			
Operation Guidelines	<ul> <li>Avoid any abrupt pressure or cross-flashutdown, cleaning or other sequence start-up, a gradual change from a start follows: <ul> <li>Feed pressure should be increasing of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the construction of the co</li></ul></li></ul>	ow variations on the spiral elements during start-up, es to prevent possible membrane damage. During ndstill to operating state is recommended as eased gradually over a 30-60 second time frame. erating point should be achieved gradually over 15-			
General Information	<ul> <li>Keep elements moist at all times a</li> <li>If operating limits and guidelines g limited warranty will be null and vo</li> <li>To prevent biological growth during that membrane elements be imme The customer is fully responsible lubricants on elements.</li> <li>Maximum pressure drop across an Avoid static permeate-side backp</li> </ul>	after initial wetting. given in this bulletin are not strictly followed, the bid. g prolonged system shutdowns, it is recommended ersed in a preservative solution. for the effects of incompatible chemicals and n entire pressure vessel (housing) is 30 psi (2.1 bar). pressure at all times.			

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	<ul> <li>Please be aware of the following:</li> <li>The use of this product in and of itself does not necessarily guarantee the removal of cysts and pathogens from water. Effective cyst and pathogen reduction is</li> </ul>

- dependent on the complete system design and on the operation and maintenance of the system.
- Permeate obtained from the first hour of operation should be discarded.



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# LENNTECH

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# **DOW FILMTEC™ Membranes**

Cleaning Procedures for DOW FILMTEC FT30 Elements

The following are general recommendations for cleaning DOW FILMTEC[™] FT30 elements. More detailed procedures for cleaning a reverse osmosis (RO) system are typically included in the operating manual provided by the system supplier. It should be emphasized that frequent cleaning is not required for a properly designed and properly operated RO system however, because of the FT30 membrane's distinct combination of pH range and temperature resistance, cleaning may be accomplished very effectively.

## Cleaning Requirements

In normal operation, the membrane in reverse osmosis elements can become fouled by mineral scale, biological matter, colloidal particles and insoluble organic constituents. Deposits build up on the membrane surfaces during operation until they cause loss in normalized permeate flow, loss of normalized salt rejection, or both.

Elements should be cleaned when one or more of the below mentioned parameters are applicable:

- The normalized permeate flow drops 10%
- The normalized salt passage increases 5 10%
- The normalized pressure drop (feed pressure minus concentrate pressure) increases 10 15%

If you wait too long, cleaning may not restore the membrane element performance successfully. In addition, the time between cleanings becomes shorter as the membrane elements will foul or scale more rapidly.

Differential Pressure ( $\Delta P$ ) should be measured and recorded across each stage of the array of pressure vessels. If the feed channels within the element become plugged, the  $\Delta P$  will increase. It should be noted that the permeate flux will drop if feedwater temperature decreases. This is normal and does not indicate membrane fouling.

A malfunction in the pretreatment, pressure control, or increase in recovery can result in reduced product water output or an increase in salt passage. If a problem is observed, these causes should be considered first. The element(s) may not require cleaning. A computer program called FTNORM is available from DW&PS for normalizing performance data of DOW FILMTEC[™] RO membranes.

#### **Safety Precautions**

**Flow Diagram** 

- 1. When using any chemical indicated here in subsequent sections, follow accepted safety practices. Consult the chemical manufacturer for detailed information about safety. handling and disposal.
- 2. When preparing cleaning solutions, ensure that all chemicals are dissolved and well mixed before circulating the solutions through the elements.
- 3. It is recommended the elements be flushed with good-quality chlorine-free water (20°C minimum temperature) after cleaning. Permeate water or deionized water are recommended. Care should be taken to operate initially at reduced flow and pressure to flush the bulk of the cleaning solution from the elements before resuming normal operating pressures and flows. Despite this precaution, cleaning chemicals will be present on the permeate side following cleaning. Therefore, the permeate must be diverted to drain for at least 30 minutes or until the water is clear when starting up after cleaning.
- 4. During recirculation of cleaning solutions, the maximum temperature must not be exceeded. The maximum allowed temperature is dependent on pH and membrane type. Table 1 contains information on the maximum allowed temperatures.
- For elements greater than six inches in diameter, the flow direction during cleaning 5. must be the same as during normal operation to prevent element telescoping, because the vessel thrust ring is installed only on the reject end of the vessel. This is also recommended for smaller elements. Equipment for cleaning is illustrated below.



## Suggested Equipment

The equipment for cleaning is shown in the Cleaning System Flow Diagram. The pH of cleaning solutions used with FILMTEC[™] elements can be in the range of 1 to 13 (see Table 1), and therefore non-corroding materials should be used in the cleaning system.

- 1. The mixing tank should be constructed of polypropylene or fiberglass-reinforced plastic (FRP). The tank should be provided with a removable cover and a temperature gauge. The cleaning procedure is more effective when performed at a warm temperature, and it is recommended that the solution be maintained according to the pH and temperature guidelines listed in Table 1. It is not recommended to use a cleaning temperature below 20°C because of the very slow chemical kinetics at low temperatures. In addition, chemicals such as sodium lauryl sulfate might precipitate at low temperatures. Cooling may also be required in certain geographic regions, so both heating/cooling requirements must be considered during the design. A rough rule of thumb in sizing a cleaning tank is to use approximately the empty pressure vessels volume and then add the volume of the feed and return hoses or pipes. For example, to clean ten 8-inch diameter pressure vessels with six elements per vessel, the following calculations would apply:
  - A. Volume in Vessels V1 =  $\pi r^2 L$ = 3.14 (4 in)² (20 ft) (7.48 gal/ft³) / (144 in²/ft²) V1 = 52 gal/vessel (0.2 m³) V10 = 52 x 10 = 520 gal (1.97 m³) B. Volume in Pipes, assume 50 ft. length total 4" Sch 80 pipe Vp =  $\pi r^2 L$ = 3.14 (1.91 in)² (50 ft) (7.48 gal/ft³) / (144 in²/ft²) = 30 gals (0.11 m³)

Vct =  $V_{10}$  + Vp = 520 + 30 = 550 gal.

Therefore, the cleaning tank should be about 550 gals (2.1 m³).

- 2. The cleaning pump should be sized for the flows and pressures given in Table 2, making allowances for pressure loss in the piping and across the cartridge filter. The pump should be constructed of 316 SS or nonmetallic composite polyesters.
- 3. Appropriate valves, flow meters, and pressure gauges should be installed to adequately control the flow. Service lines may be either hard piped or hoses. In either case, the flow rate should be a moderate 10 ft/sec (3 m/sec) or less.

#### Cleaning Elements In Situ

1. Make up cleaning solution.

There are six steps in the cleaning of elements:

- 2. Low-flow pumping. Pump mixed, preheated cleaning solution to the vessel at conditions of low flow rate (about half of that shown in Table 2) and low pressure to displace the process water. Use only enough pressure to compensate for the pressure drop from feed to concentrate. The pressure should be low enough that essentially no or little permeate is produced. A low pressure minimizes redeposition of dirt on the membrane. Dump the concentrate, as necessary, to prevent dilution of the cleaning solution.
- 3. Recycle. After the process water is displaced, cleaning solution will be present in the concentrate stream. Then recycle the concentrate and permeate to the cleaning solution tank and allow the temperature to stabilize. Measure the pH of the solution and adjust the pH if needed.

# Table 1. pH range andtemperature limitsduring cleaning

Element type	Max Temp 50°C (122°F) pH range	Max Temp 45°C (113°F) pH range	Max Temp 35°C( 95 °F) pH range	Max Temp 25°C (77°F) pH range
BW30, BW30LE, LE, XLE,	Please contact Dow for	1 - 10.5	1 - 12	1 - 13
TW30, TW30HP, NF90, LC	assistance			
SW30HR, SW30HR LE,	Please contact Dow for	1 - 10.5	1 - 12	1 - 13
SW30XLE, SW30	assistance			
NF200, NF270	Not allowed	3 - 10	1 - 11	1 - 12
SR90	Not allowed	3 - 10	1 - 11	1 - 12

# Table 2. Recommendedfeed flow rate per pressurevessel during high flowrate recirculation

Feed Pressure ¹		Element Diameter	Feed Flow Rate	per Pressure Vessel
(psig)	(bar)	(inches)	(gpm)	(m³/hr)
20-60	1.5-4.0	2.5	3-5	0.7-1.2
20-60	1.5-4.0	4 ²	8-10	1.8-2.3
20-60	1.5-4.0	6	16-20	3.6-4.5
20-60	1.5-4.0	8	30-40	69.1
20-60	1.5-4.0	8 ³	35-45	8.0-10.2

1. Dependent on number of elements in pressure vessel.

2. 4-inch full-fit elements should be cleaned at 12-14 gpm (2.7-3.2 m³/hr).

3. For full-fit and 440 sq. ft. area elements.

- 4. Soak. Turn the pump off and allow the elements to soak. Sometimes a soak period of about 1 hour is sufficient. For difficult fouling an extended soak period is beneficial; soak the elements overnight for 10-15 hours. To maintain a high temperature during an extended soak period, use a slow recirculation rate (about 10 percent of that shown in Table 2).
- 5. High-flow pumping. Feed the cleaning solution at the rates shown in Table 2 for 30-60 minutes. The high flow rate flushes out the foulants removed from the membrane surface by the cleaning. If the elements are heavily fouled, a flow rate which is 50 percent higher than shown in Table 2 may aid cleaning. At higher flow rates, excessive pressure drop may be a problem. The maximum recommended pressure drops are 15 psi per element or 50 psi per multi-element vessel, whichever value is more limiting. Please note that the 15 psi per element or the 50 psi per multi-element vessel should NOT be used as a cleaning criteria. Cleaning is recommended when the pressure drop increases 15%. Pressure drop above 50 psi in a single stage may cause significant membrane damage.
- Flush out. RO permeate or deionized water is recommended for flushing out the cleaning solution. Prefiltered raw water or feed water should be avoided as its components may react with the cleaning solution: precipitation of foulants may occur in the membrane elements. The minimum flush out temperature is 20°C.

## Cleaning Tips

 It is strongly recommended to clean the stages of the RO or NF system separately. This is to avoid having the removed foulant from stage 1 pushed into stage 2 resulting in minimal performance improvement from the cleaning. If the system consists of 3 stages, stage 2 and stage 3 should also be cleaned separately. For multi-stage systems, while each stage should be cleaned separately, the flushing and soaking operations may be done simultaneously in all stages. Fresh cleaning solution needs to be prepared when the cleaning solution becomes turbid and/or discolored. High-flow recirculation, however, should be carried out separately for each stage, so the flow rate is not too low in the first stage or too high in the last. This can be accomplished either by using one cleaning pump and operating one stage at a time, or by using a separate cleaning pump for each stage.

2. The fouling or scaling of elements typically consists of a combination of foulants and scalants, for instance a mixture of organic fouling, colloidal fouling and biofouling. Therefore, it is very critical that the first cleaning step is wisely chosen. FilmTec strongly recommends alkaline cleaning as the first cleaning step. Acid cleaning should only be applied as the first cleaning step if it is known that only calcium carbonate or iron oxide/hydroxide is present on the membrane elements.

Acid cleaners typically react with silica, organics (for instance humic acids) and biofilm present on the membrane surface which may cause a further decline of the membrane performance. Sometimes, an alkaline cleaning may restore this decline that was caused by the acid cleaner, but often an extreme cleaning will be necessary. An extreme cleaning is carried out at pH and temperature conditions that are outside the membrane manufacturer's guidelines or by using cleaning chemicals that are not compatible with the membrane elements. An extreme cleaning should only be carried out as a last resort as it can result in membrane damage.

If the RO system suffers from colloidal, organic fouling or biofouling in combination with calcium carbonate, then a two- step cleaning program will be needed: alkaline cleaning followed by an acid cleaning. The acid cleaning may be performed when the alkaline cleaning has effectively removed the organic fouling, colloidal fouling and biofouling.

- 3. Always measure the pH during cleaning. If the pH increases more than 0.5 pH units during acid cleaning, more acid needs to be added. If the pH decreases more than 0.5 pH units during alkaline cleaning, more caustic needs to be added.
- 4. Long soak times. It is possible for the solution to be fully saturated and the foulants can precipitate back onto the membrane surface. In addition, the temperature will drop during this period, therefore the soaking becomes less effective. It is recommended to circulate the solution regularly in order to maintain the temperature (temperature should not drop more than 5°C) and add chemicals if the pH needs to be adjusted.
- 5. Turbid or strong colored cleaning solutions should be replaced. The cleaning is repeated with a fresh cleaning solution.
- 6. If the system has to be shutdown for more than 24 hours, the elements should be stored in 1% w/w sodium metabisulfite solution.

## Effect of pH on foulant removal

In addition to applying the correct cleaning sequence (alkaline cleaning step first), selecting the correct pH is very critical for optimum foulant removal. If foulant is not successfully removed, the membrane system performance will decline faster as it is easier for the foulant to deposit on the membrane surface area. The time between cleanings will become shorter, resulting in shorter membrane element life and higher operating and maintenance costs.

Most effective cleaning allows longer system operating time between cleanings and results in the lowest operating costs.

Figure 1 and 2 below show the importance of the selecting the right pH for successful cleaning.

2.5 Relative change permeate flow 2 1.5 1 0.5 0 2% citric HCI@pH HCI@pH 2, HCI@pH 1, HCI@pH1, acid@pH 4, 2.5,35C 35 C 25C 35C 40 C **Recommended Cleaning Conditions** Less Effective More Effective

Figure 1. Effect of pH on the removal of calcium carbonate

Calcium carbonate is best removed by cleaning with hydrochloric acid at pH 1-2.

Figure 2. Effect of pH on the removal of biofouling



Biofouling is best removed by cleaning at pH 12.

Cleaning Chemicals Table 3 lists suitable cleaning chemicals. Acid cleaners and alkaline cleaners are the standard cleaning chemicals. The acid cleaners are used to remove inorganic precipitates including iron, while the alkaline cleaners are used to remove organic fouling including biological matter. Sulfuric acid should never used for cleaning because of the risk of calcium sulfate precipitation. Reverse osmosis permeate or deionized water should be used for the preparation of cleaning solutions.

# Table 3. Simplecleaning solutionsfor FT30 membrane

Cleaner						
	0.1% (W) NaOH and 1.0% (W) Na₄EDTA, pH 12, 35°C max.	0.1% (W) NaOH and 0.025% (W) Na-DSS, pH 12, 35°C max.	0.2% (W) HCI, 25°C and pH 1 - 2	1.0% (W) Na₂S₂O₄, 25°C and pH 5	0.5% (W) H₃PO₄ , 25 °C and pH 1 - 2	1.0% (W) NH2SO3H , 25°C and pH 3 - 4
Foulant						
Inorganic Salts (for example, CaCO ₃ )			Preferred	Alternative	Alternative	
Sulfate Scales (CaSO ₄ , BaSO ₄ )	OK					
Metal Oxides (for example, iron)				Preferred	Alternative	Alternative
Inorganic Colloids (silt)		Preferred				
Silica	Alternative	Preferred				
Biofilms	Alternative	Preferred				
Organic	Alternative	Preferred				

The temperatures and pH listed in table 3 are applicable for BW30, BW30LE, LE, XLE, TW30, TW30HP, SW30HR, SW30HR LE , SW30XLE, SW30 and NF90 membrane elements. For more information regarding the allowed temperatures and pH for cleaning, please refer to table 1.

Notes:

- 1. (W) denotes weight percent of active ingredient.
- 2. Foulant chemical symbols in order used: CaCO₃ is calcium carbonate; CaSO₄ is calcium sulfate; BaSO₄ is barium sulfate.
- Cleaning chemical symbols in order used: NaOH is sodium hydroxide; Na₄EDTA is the tetra-sodium salt of ethylene diamine tetraacetic acid and is available from Dow under the trademark VERSENE™ 100 and VERSENE 220 crystals; Na-DSS is sodium salt of dodecylsulfate; Sodium Laurel Sulfate; HCI is hydrochloric acid (Muratic Acid); H₃PO4 is phosphoric acid; NH₂SO₃H is sulfamic acid; Na₂S₂O4 is sodium hydrosulfite.
- For effective sulfate scale cleaning, the condition must be caught and treated early. Adding NaCl to the cleaning solution
  of NaOH and Na4EDTA may help as sulfate solubility increases with increasing salinity. Successful cleaning of sulfate
  scales older than 1 week is doubtful.
- Citric Acid is another cleaning alternative for metal oxides and calcium carbonate scale. It is less effective (see also figure 1 of this document). It may contribute to biofouling especially when it is not properly rinsed out.

**NOTICE:** The use of this product does not necessarily guarantee the removal of cysts and pathogens from water. Effective cyst and pathogen reduction is dependent on the complete system design and on the operation and maintenance of the system.

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v1.0

# **DRUMFILTER PP35**







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	<ul><li>3.1 Placing filter system</li><li>3.2 Set level control:</li></ul>	9 10



Basic requirements every filter system must meet:

- The filter system should be placed on a ground surface with sufficient carrying capacity, for instance:
  - a well-vibrated sand bed of 10 cm, possibly with concrete tiles
  - a concrete floor

In the event of subsidence, the filter may not function properly!

- The filter system should be placed fully level.
- Leave sufficient space around the filter, to perform cleaning and maintenance work.
- The filter control should be in a dry area, preferably indoors.
- The drive motor must be protected against weather influences.

The filter system can be used as gravity-system or pump fed system.



# IMPORTANT!

The correct placement and constant water level in the pond are important conditions for optimal and problem-free operation of the filter system.



# IMPORTANT!

The use of salt in the pond can cause stainless steel components of the filter to oxidize.





## 1.1 Control unit









5

# GRAVITY

# QUICKGUIDE

# 2 A. Gravity-system

# 2.1 Placing the filter system

- Determine the maximum water level of the pond.
- Align the base plate horizontally (the filter should be placed fully level).
- The filter should be placed the height of the installation height (fig. 2.1) above water level. (installation height is the distance from maximum water level to top of filter).

Type filter	Installation height
	[cm]
PP35	17





- 1. Water level with running pump after rinse (short pen 8 cm in water)

- Start rinsing
   Pond pump switches off
   Installation height PP is 17 cm

# GRAVITY



# 2.2 Set level control:

- For the operation of the gravity system a constant water level in the pond is necessary. A tolerance of up to 20 mm below maximum water level is allowed.
- Should the maximum water level in the pond exceed this, the water excess water will be disposed of via the waste water drain, until the maximum water level has been reached



Pic. 2.2 Sensor

- 1. Water level with running pump after rinse (short pen 8 cm in water)
- 2. Start rinsing
- 3. Pondpump switches off



Pic. 3.1

2.

# PUMP FED



#### B. Pump fed system 3

#### Placing filter system 3.1

- Determine the maximum water level of the pond ٠
- Align the base plate horizontally (the filter should be completely level). •
- The installation height is 30 cm ٠ (installation height is the distance from maximum water level to the top of the filter)





Ρ

## PUMP FED



## 3.2 Set level control:



# Pic. 3.2 Sensor

- 1. Water level with running pump after rinse
- 2. Start rinsing
- 3. Pond pump switches off

