

PFAS Effects

**Worldwide update and recommendations
for its successful destruction
A White Paper**

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Introduction

This white paper has been written to convey today's challenge in accurately quantifying PFAS's threats, in its many derivations, to our environment and to human health. The paper then attempts to detail a solution to minimize or ideally eliminate its pernicious effects through thermal destruction in a permanent and safe way. This paper is intended to be far-reaching and considers available data collected from scientists, processes, and resources from around the world. It is the intention of the author to communicate this significant quantity of information in a simple straightforward manner.

In an effort to thoroughly examine the problem a variety of complicated studies, including long-term toxicology studies, were utilized and then synthesized. Thousands of pages of the latest technical papers were identified and studied. Additionally, information and data which has been gained as a result of over ten years of research, development, and testing of Plasma Power's ultra-high temperature destruction technology, has been integrated into the contents of this paper. As indicated, integral in this effort is to communicate the results in a simplified manner for purposes of bringing clear understanding of key concepts.

As is customary, references to other content sources in the form of parenthetical citations, footnotes, and endnotes are included for the technical purists who wish to do further investigations.

Resulting technical information, specifications, and recommendations for the ultra-high temperature thermal destruction of PFAS were generated at Plasma Power's test and short run production facility located in Fort Lauderdale, Florida.

This paper is a short and concise summary, with the hope that the reader will be inspired to further investigate the plethora of PFAS source information available.

Sincerely,



Jim Juranitch

Note: In this white paper, "I", "me", and "my" all refer to the author, James C. Juranitch. Additionally, since this paper was first published, the company Plasma Power, LLC has participated in a merger and is now a part of Helios Environmental Advanced Technologies, LLC.

What is PFAS?

PFAS or per and polyfluoroalkyl substances are synthetic organofluorine chemical compounds also known as perfluorinated chemicals (PFCs). They are also referred to as “Forever Chemicals” which is a play on their physical characteristics and inverting the F and C. They are basically in their original form all manmade chemicals. According to the world Organization for Economic Cooperation and Development there are over 4,730 forms of PFAS. PFAS chemicals are some of the strongest chemicals known to man due to their carbon fluorine bonds (C-F) which is one of the strongest molecular bonds in nature. PFAS chemicals by design have different amounts of the C-F molecules chained together. Early PFAS products developed by 3M and Dupont from the 1940’s and up to 2014 typically utilized a quantity of eight C-F chains. Hence, they are commonly referred to as C8. Other C-F chain lengths have also existed for some time. Recently an acceleration in shorter chain development and commercial production has occurred. PFAS chemicals typically range in C-F chain lengths of 4 to 14. “Short Chain” PFAS chemicals typically refer to PFAS chemicals where the C-F chain length is less than 8. The majority of modern development and production of PFAS outside of China is in short chain PFAS. China still produces and uses C8 in products it sells to the rest of the world.

PFAS describes the broad form of a family of robust chemical substances. Since much of the discussion of PFAS will revolve around toxicology it may be useful to compare PFAS to another toxic group of chemicals we are typically more familiar with. In this recurring example we will use alcohol that is consumed by humans. Both PFAS and human consumed alcohol are families of chemical substances found in many forms.

Whereas alcohol can take many forms such as vodka, gin, bourbon, whiskey, tequila, etc. this is also the case with PFAS. Two of the best-known major forms or subgroups of PFAS are perfluoro-alkyls (the most common being PFOS and PFOA) and polyfluoro-alkyls. For this example, perfluoro-alkyls could be thought of as any of the common brown liquors and thus PFOA could be brandy and PFOS could be whiskey. Polyfluoro-alkyls could be white liquors like vodka or tequila. Short chain PFAS, another major subgroup, could be thought of as wine, an appropriate comparison as both families of chemicals have many subtypes. In each of these cases the many forms of alcohol and forms of PFAS compounds have different characteristics and typically different effects as a result of their exposure to humans.

A good depiction of the structure of PFAS chemicals illustrating the above example, is shown below in Figure 1.

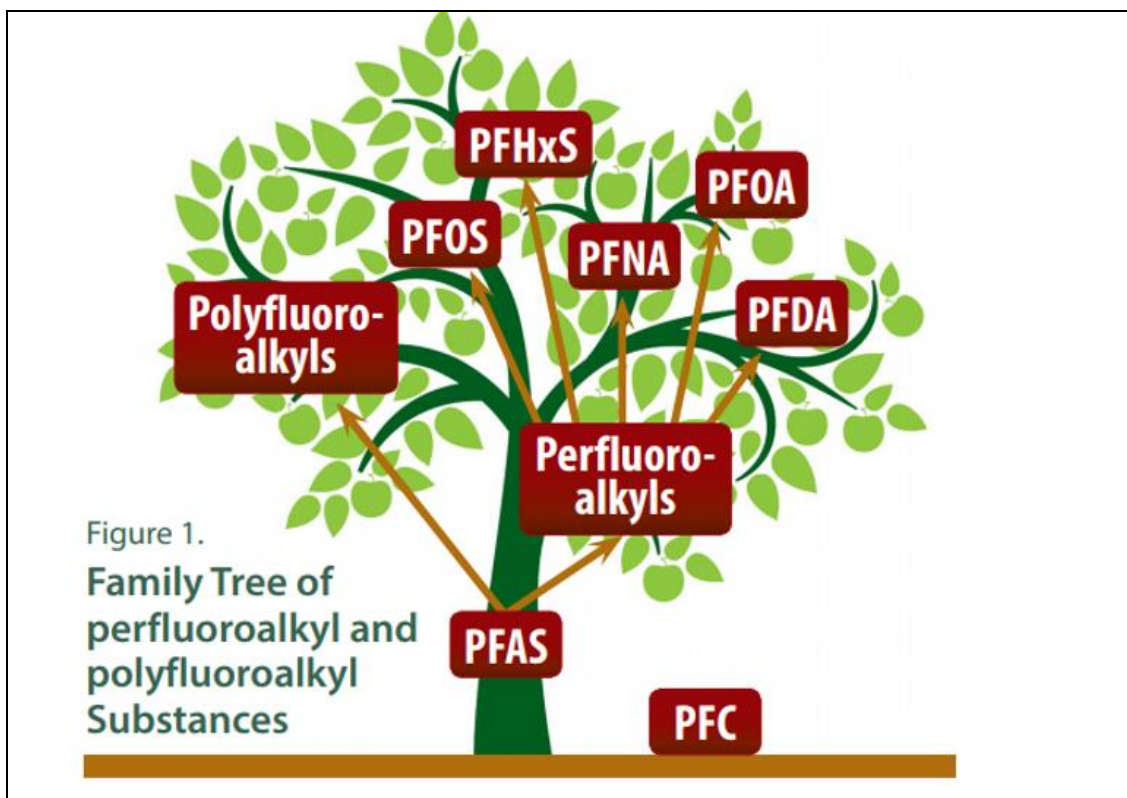


Figure 1. "Family Tree of Perfluoroalkyl and Polyfluoroalkyl Substances". Agency for Toxic Substances and Disease Registry, 9 June 2017, https://www.atsdr.cdc.gov/pfas/docs/PFAS_FamilyTree_EnvHealthPro-508.pdf

How and why PFAS is prevalent in the world?

Almost all living things on earth are contaminated with PFAS. In fact, nearly 97% of all humans are contaminated with PFAS^{1,2}. Much of this is due to a period of more than 3 decades, from 1970–2002, where approximately 96,000 tons of perfluorooctane sulfonyl fluoride (PFOSF, a precursor of PFOS) and 26,500 tons of related by-products and wastes were produced worldwide. Subsequently approximately 6800–45,250 tons were eventually released directly or indirectly into the environment³.

However, the contamination issue is not limited to just the large quantity of PFAS in the environment. It is also due to the fact that a very small amount of the substance has a huge impact. Both independent and government sponsored organizations, such as the Wisconsin Department of Health Services, have determined that PFAS in a media such as drinking water is dangerous to humans at levels above 20 parts per trillion (ppt) for any significant amount of time⁴. To put this in perspective, one part per trillion is equal to one drop of fluid being added to 20 Olympic size swimming pools. It may seem incomprehensible that such a minute amount of PFAS can cause such significant problems in all living things, but it is the incredibly strong C-F bond which provides useful characteristics for manmade products, that conversely wreaks havoc in our environment by preventing its natural breakdown.

Another characteristic of PFAS is its ability to attach to proteins within the human body. The body does not readily rid itself of these chemicals and instead it remains in the body for a significant period of time.

PFAS also is multigenerational. It is transferred through the placenta and breast milk from a mother to its offspring. This can accelerate the bioaccumulation in future generations. More about this will be covered in later sections of this paper.

PFAS is also a very mobile substance. It travels through the environment using a variety of mechanisms.

It has been observed that PFAS when airborne settles in the predominant downwind direction. This is depicted in data reflecting PFAS manufacturing facility sites as shown below in Figures 2 and 3.

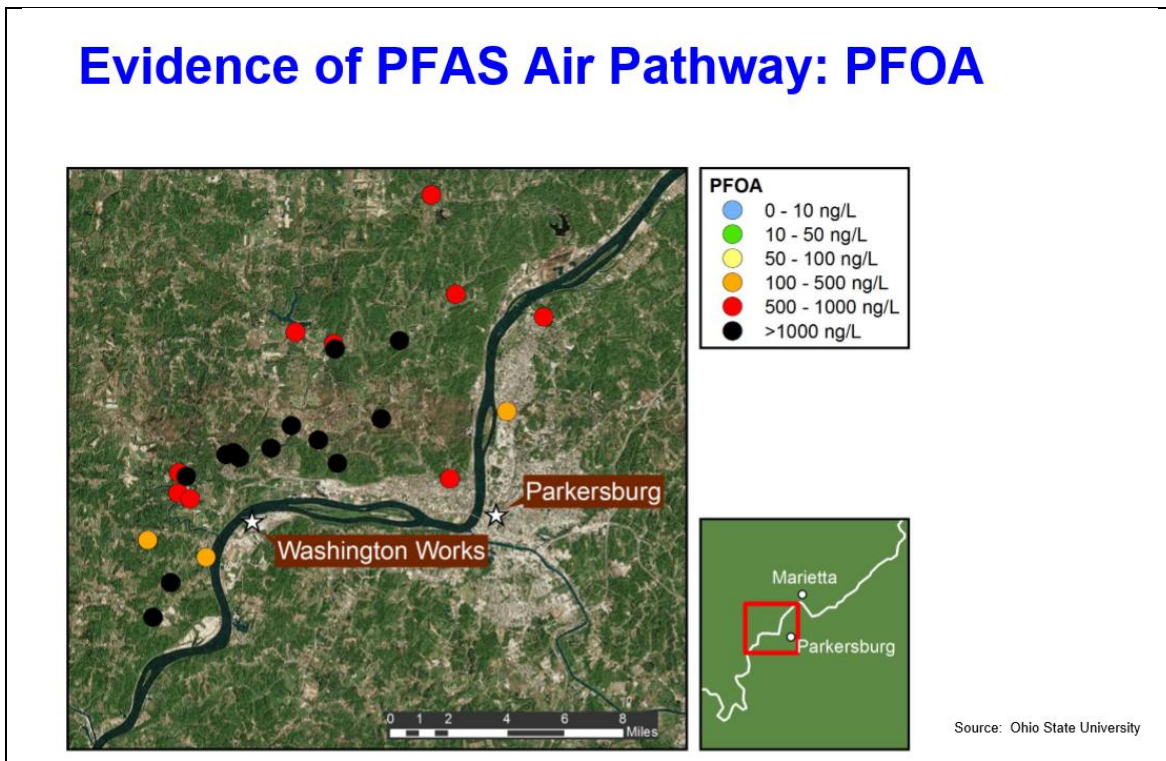


Figure 2. Ryan, Jeff. "EPA PFAS Air Emission Measurements: Activities and Research". US EPA – Office of Research and Development National Risk Management Research Laboratory, EPA Region 4 Spring Grants/Planning Meeting Atlanta, GA, Slide 8, 23 May 23, 2019 Atlanta, https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NRML&dirEntryId=345766

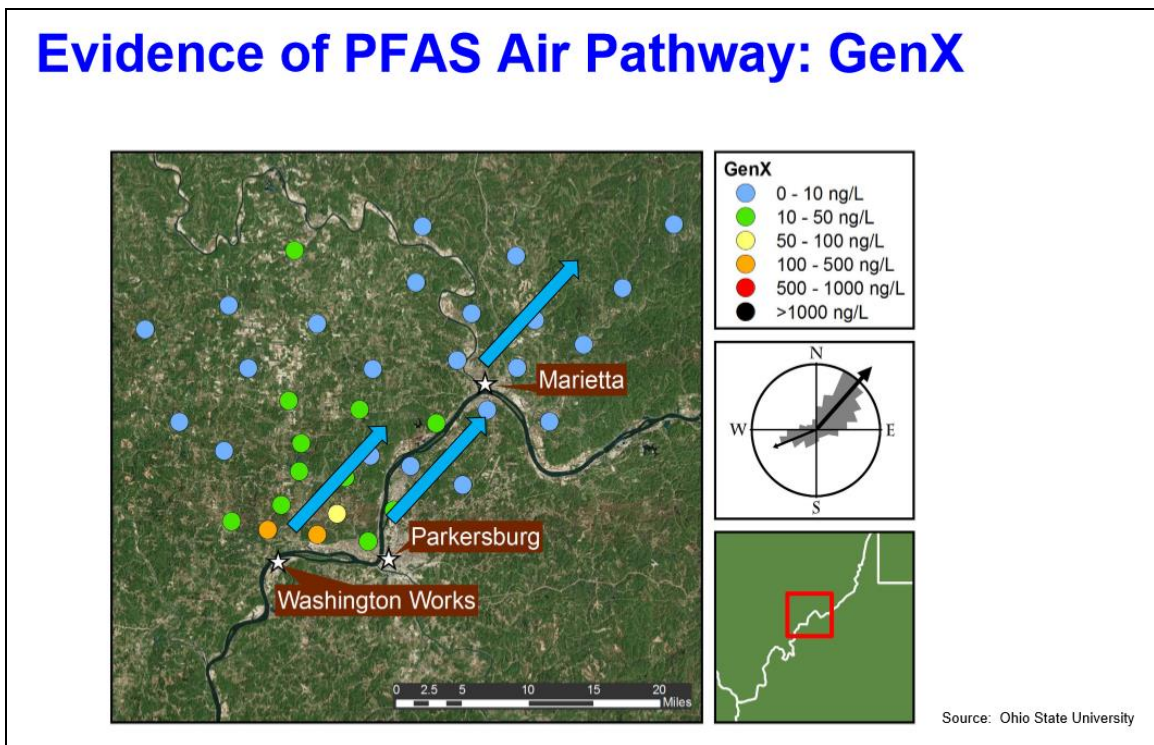


Figure 3. Ryan, Jeff. "EPA PFAS Air Emission Measurements: Activities and Research". US EPA – Office of Research and Development National Risk Management Research Laboratory, EPA Region 4 Spring Grants/Planning Meeting Atlanta, GA, Slide 8, 23 May 23, 2019 Atlanta, https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NRMRL&dirEntryId=345766

The above images demonstrate PFAS, as expected, precipitates from the air downstream of the predominate wind direction.

A more encompassing example of the mobility of PFAS is shown in Figure 4.

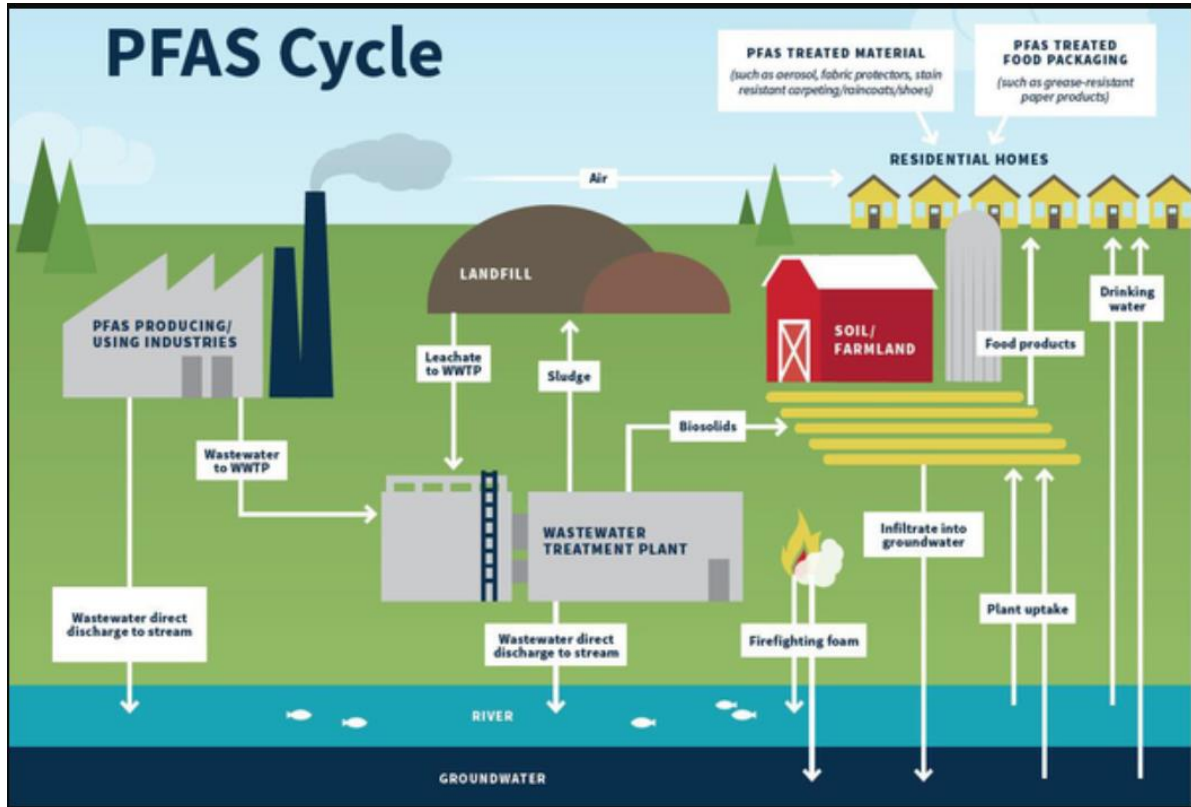


Figure 4. "Is Your State or System Being Affected by PFAS?". Natural Rural Water Association, Retrieved 5 May, 2020, <https://nrwa.org/initiatives/pfas/>

Another more human centric example of contamination paths for PFAS is shown below in Figure 5 graphic and its contextual note.

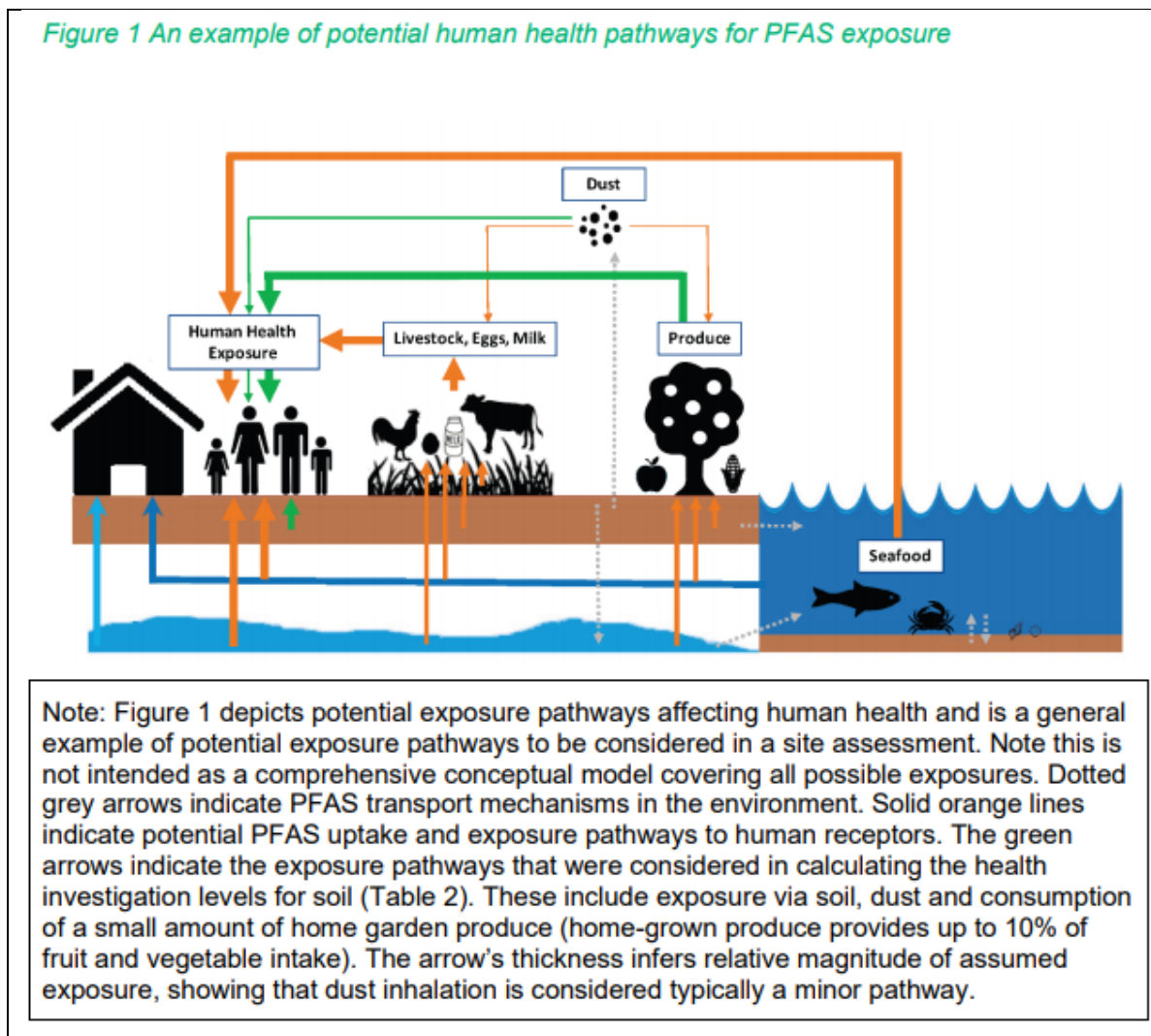


Figure 5. "PFAS National Environmental Management Plan Version 2.0". National Chemicals Working Group of the Heads of EPAs Australia and New Zealand, January 2020, <https://www.environment.gov.au/system/files/resources/2fadf1bc-b0b6-44cb-a192-78c522d5ec3f/files/pfas-nemp-2.pdf>

A desirable trait of PFAS is it adds characteristics to products that cause them to feel slippery, or repel water or other staining fluids and oils. Many surfactants use a PFAS additive which reduces the surface tension of whatever it is mixed with. Aqueous Film Forming Foams (AFFF) were used heavily for the last 40 years in fighting fires. AFFF has high concentrations of PFAS and has worldwide presence. These foams have been deployed and are present at airports and military bases where AFFF was used to train fire fighters. Examples of PFAS products and uses are depicted in the graphic shown below in Figure 6.



Figure 6. "Is Your State or System Being Affected by PFAS?". Natural Rural Water Association, Retrieved 5 May, 2020, <https://nrwa.org/initiatives/pfas/>

US prevalence and government actions

As a result of the widespread use of products containing PFAS, at this time there are an estimated 26,000 PFAS contaminated sites in the United States alone⁵. Soil contamination from AFFF has occurred at over 600 sites on military bases. Airport and firefighting training locations combined with product production sites that were associated with PFAS, make up the remainder of the estimated 26,000 contaminated areas in the US.

Whether it is as a result of firefighting foam or the plethora of products containing PFAS used throughout the world, PFAS has a significant presence in the world's drinking water sources. As of the date of this white paper, the US EPA has established a health advisory regarding long-term exposure of PFAS to 70 ppt in drinking water⁶. On February 6, 2020 the California State Water

Resource Control Board lowered its response level guidelines for PFAS in drinking water to 10 ppt for PFOA and 40 ppt for PFOS⁷. California's previous standards were based on the US EPA's recommendation of 70 ppt. It is thought that over 6 million people in the US are drinking unacceptable levels of contaminated PFAS water at the higher 70 ppt limit. Examples demonstrating this are many. The following are recent examples found in the southeastern United States.

On March 2, 2020 the Miami New Times reported that some ground water wells around the Miami Dade North Campus that were tested, have shown levels of up to 26,100 ppt of PFAS⁸. This water is used in the campus area drinking water. No effective system for removing the PFAS is being utilized before students and others consume the water. I am of the opinion that with the multigenerational bioaccumulation of this toxin and the exposure to the young women present on campus and the surrounding areas this condition is unconscionable. The conditions in the regulating environment that allow this to continue will be covered in later parts of this paper.

On February 3, 2020 an article appearing in North Carolina Health News reported the North Carolina department of Environmental Quality has found high levels of PFAS being discharged by state sewage treatment plants into local rivers which in turn, in some cases due to intakes downstream of discharge points, get processed into drinking water⁹. I am of the opinion that this recycling of PFAS into the environment, along with the food and drinking water supply chains, is a common problem that needs to be ended.

A summary of the PFAS effluent testing levels in North Carolina included in the article is shown in the chart below in Figure 7.

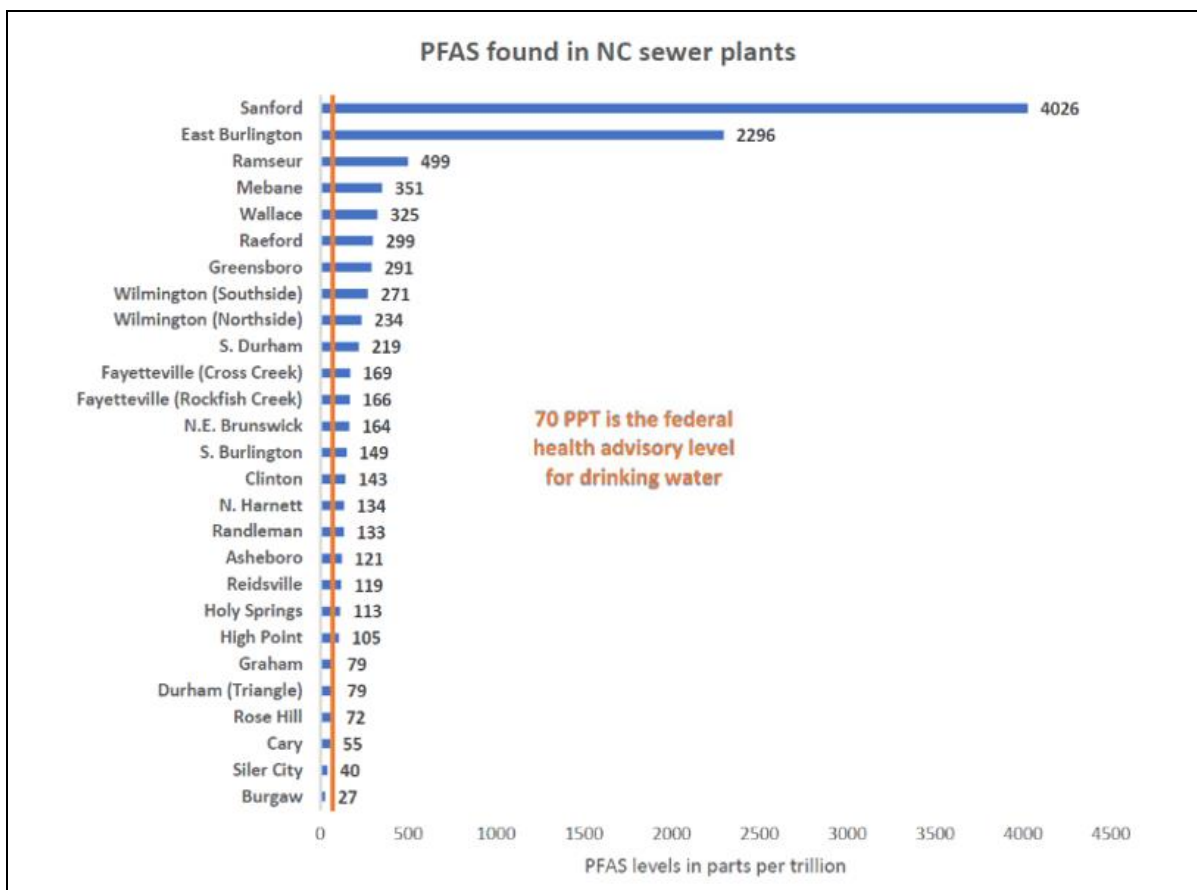


Figure 7. Barnes, Greg. “New DEQ data show ‘staggering’ levels of PFAS in Cape Fear River basin”, North Carolina Health News, 3 February, 2020, <https://www.northcarolinahealthnews.org/2020/02/03/new-deq-data-show-high-levels-of-pfas-in-cape-fear-river-basin/>

On January 22, 2020 Environmental Working Group researchers reported that the highest level of PFAS found in drinking water in an extremely small testing program in North Carolina was at an elementary school in Brunswick County, NC where the levels were at 186 ppt¹⁰. The drinking water source was the Cape Fear River. Again, young unsuspecting school children are drinking this water.

Drinking water is also contaminated by PFAS through airborne sources. Airborne PFAS can distribute the toxin into the human food supply in many ways besides drinking water as shown in Figure 5 previously. Further details on this subject is covered in the section “A better path using Ultra-high Temperature Thermal Destruction”.

To date there are no US EPA standards for the control of PFAS in the air, water, soil, food or in consumer products. There is only a recommendation of the allowable long-term levels of PFAS in drinking water. There is no clear reasoning to date, as to what could be perceived to be a weak response by the US EPA, to the health hazards known to exist from PFAS.

Typically, scientific bodies including the US EPA have used toxicology studies to guide them in the preparations of standards. The science and study of toxicology is a difficult pursuit. It is a technically

difficult subject and requires large sample sizes of data to draw scientifically valid toxicology conclusions due to the principles of statistics. In short, it is difficult to do a toxicology study well or to reach complete and scientifically valid conclusions. I am of the opinion that the practice of the US EPA using toxicology testing to drive its promulgation of laws may no longer be a valid process to keep up with the preponderance of new toxic substances that industry has become so efficient at producing on a worldwide basis. It is believed that this is one of the reasons that the US EPA is so far behind in protecting the US public from PFAS substances. The problem with PFAS is it comes in thousands of forms much like alcohol as mentioned previously. To be scientifically valid, each form would need its own toxicology study. Therefore, it is believed that industry has used this situation and the difficulty in completing toxicology studies to their advantage. Conversely there is little doubt that many C8 compounds have been proven to be extremely toxic to humans, but still no US EPA standards exist even for C8 compounds.

Health Hazards Associated with Long and Short Chain PFAS

The health hazards of PFAS have been known since at least the 1970's. In July of 2018 it was reported that a document was on file with the US EPA, indicating that Minnesota Mining and Manufacturing Company (3M) "knew as early as the 1970s that PFAS was accumulating in human blood"¹¹ and that 3M's own experiments on rats and monkeys concluded that PFAS compounds "should be regarded as toxic."

Figure 8 below provides a clear illustration of what health hazards have been identified through PFAS toxicology studies.

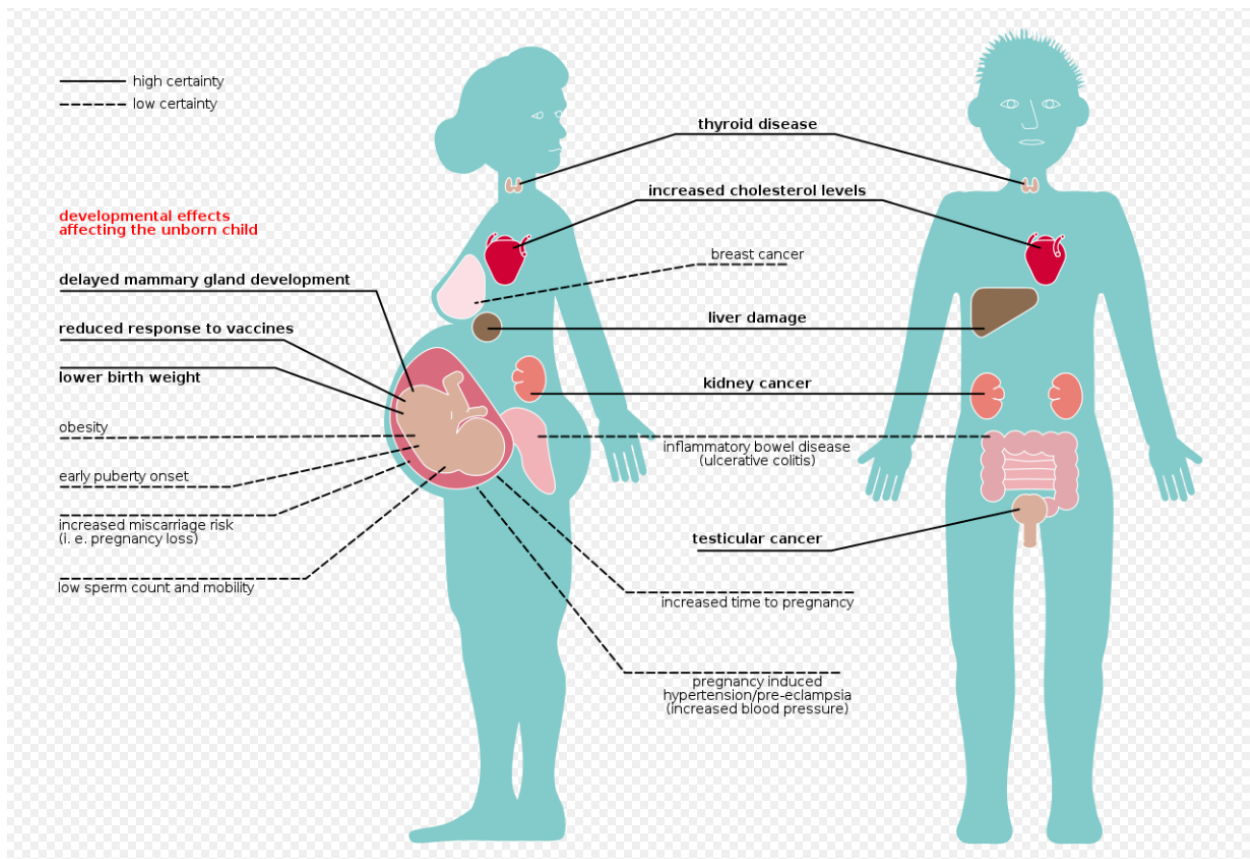


Figure 8. “Effects of PFAS on human health, Emerging chemical risks in Europe — ‘PFAS’”. European Environmental Health Agency, 12 Dec 2019, <https://www.eea.europa.eu/themes/human/chemicals/emerging-chemical-risks-in-europe>

Industry has further complicated the issue of PFAS toxicity by producing many derivative short chain PFAS substances and then proclaiming that short chains are “safe”. World toxicity studies from areas such as Denmark are showing that short chain PFAS are not safe¹².

In general, there appears to be significant PFAS testing being performed in the Scandinavian region of the world. The Danish Environmental Protection Agency provides a summary of many of the region’s papers in the publication “Short-chain Polyfluoroalkyl Substances (PFAS)”¹². Included in this paper is the following quote, “The blood elimination half-lives of PFAAs decrease generally with shorter chain length. An exemption is PFHxS (C6), which has a longer half-life in humans than PFOA and PFOS (C8).” This statement is particularly disturbing because industry is heavily invested in replacing C8 with C6 compounds and labeling them as “safe”.

The Danish publication further reveals other significant issues, “The high presence of short-chain PFAS in human tissue, including brain from deceased people, especially PFBA, is worrying and it shows that the short-chain PFAS and a fluorotelomer metabolite may be much more bioaccumulative in humans, than the studies with experimental animals conclude. That may compromise the safety of the alternatives.”

“Alternatives” in the above quote refers to the theoretically safe short chain PFAS alternatives to C8. Other toxicology reports have indicated similar results for short chain PFAS, pointing out the ubiquitous presence of these alternatives in our daily lives, “6:2 Fluorotelomer alcohol (6:2 FTOH) is an impurity in polymeric PFAS used in fast food packaging”¹³, further noting that “Use of studies conducted with PFHxA to assess 6:2 FTOH may significantly underestimate human health risk”.

As indicated previously, on a global basis the chemical industry is currently heavily invested in producing tons of short chain PFAS daily, while convincing the world that short chain PFAS is not a problem. An additional concern is that the destruction of long chain and C8 PFAS can also inadvertently produce short chain PFAS which will add to this problem. The reformation or lack of short chain PFAS destruction will be covered in later sections of this paper.

The following quote and data in Figure 9 are taken from the Danish EPA summary¹²:

“Although PFAS accumulation followed particular trends depending on the specific tissue, some similarities were found. In kidney and lung, perfluorobutanoic acid (PFBA) was the most frequent compound, and found at the highest concentrations (median values: 263 and 807 ng/g in kidney and lung, respectively). In liver and brain, perfluorohexanoic acid (PFHxA) showed the maximum levels (median: 68.3 and 141 ng/g, respectively), while perfluorooctanoic acid (PFOA) was dominating in bone (median: 20.9 ng/g). Lung tissues accumulated the highest concentration of PFAS. However, perfluorooctane sulfonic acid (PFOS) and perfluorooctanoic acid (PFOA) were more prevalent in liver and bone, respectively. The high levels of perfluorohexyl ethanoic acid (FHEA), a metabolite of 6:2 FTOH, in some organs of some individuals were surprising and show that the metabolism of PFAS in humans must be different from metabolism in rodents. This needs to be taken into consideration in relation to risk assessment based on studies in rat where other metabolites dominate (discussed later). The high levels of the short chain PFAS are worrying and in contradiction to the claims from industry that there is no significant bioaccumulation by these PFAS. Some data for the content of short chain PFAS in five organs and PFOA/PFOS as references are shown in Table 3.1.”

TABLE 3-1
DISTRIBUTION OF SHORT CHAIN PFAS IN 5 AUTOPSY TISSUES FROM 20 HUMAN INDIVIDUALS OF TARRAGONA, SPAIN (PEREZ ET AL. 2013).

PFAS substance	Mean concentrations ng/g w. w.				
	Liver	Bone	Brain	Lung	Kidney
PFBA	12.9	<LOD	13.5	304	464
PFBS	0.9	3.2	<LOD	17.8	8
PFPeA	1.4	0.8	<LOD	44.5	<LOD
PFHxA	11.5	35.6	18.0	50.1	5.6
PFHxS	4.6	1.8	3.2	8.1	20.8
Perfluorohexyl ethanoic acid (FHEA); metabolite of 6:2 FTOH	92.6	42.5	18.6	2.4	23.7
PFOA	13.6	60.2	<LOD	29.2	2.0
PFOS	102	<LOD	4.9	29.1	75.6

LOD = Limit of detection

Figure 9. “Short-chain Polyfluoroalkyl Substances (PFAS)”. The Danish Environmental Protection Agency, Environmental project No. 1707, 2015, <https://www2.mst.dk/Udgiv/publications/2015/05/978-87-93352-15-5.pdf>

I am of the opinion that the above information makes it clear that the production of short chain PFAS needs to be questioned and the destruction of all PFAS needs to be controlled to make certain short chain PFAS is not created and redistributed into the human population, food supply chain and surrounding environment. It is alarming to consider the data found in human autopsies and indicated above is a condition that now exists, to some degree, in essentially all living humans on the planet. In other words, it is not a question if the reader is contaminated with PFAS, but instead to what degree the contamination has occurred.

The fact that short and long chain PFAS can transfer to the brain in humans should be considered especially troubling. Direct linkage from PFAS contamination to childhood attention deficit-hyperactivity disorder (ADHD) has been found.

To further quote the Danish EPA summary¹² relating to shorter chain C6:

“Children behavior Data from the NHANES 1999-2004 and the C8-Health Project in the USA surveys showed positive association between some serum PFAA levels and attention deficit-hyperactivity disorder (ADHD) in children (Hoffman et al. 2010; Stein and Savitz 2011). The later study found a specific association with ADHD and PFHxS blood levels. The prevalence of ADHD plus medication increased with perfluorohexane sulfonate (PFHxS) levels, with an adjusted odds ratio of 1.59 (95% confidence interval, 1.21–2.08) comparing the highest quartile of exposure to the lowest. Higher blood levels of PFOS, PFNA, PFDA, PFHxS and PFOSA (but not PFOA) were associated with significantly shorter “Impaired Response Inhibition” (IRT) during the “differential reinforcement of low rates of responding (DRL) tasks measuring children’s impulsivity (Gump et al. 2011). PFHxS was the second

most abundant in the blood with a mean blood concentration of about 6 ng/mL. The mean concentration of PFOS was higher and about 10 ng/mL, and the mean concentration of PFOA was about 3 ng/mL.”

It has also been found that the ability of the human body to fight off viruses is inhibited due to PFAS contamination. This becomes more concerning as more viruses such as the recent Covid strain tax the populations of the world.

In a recent March 2020 paper¹⁴ it has been found and reported that PFAS can be readily absorbed by humans through the skin. Previously this was not thought to be the case. This makes showering or swimming in PFAS contaminated water a more critical issue and of course the use of PFAS laden skin products a significant problem.

Since the production of C8 in the world is declining (excluding China) the previous C8 PFAS production is being shifted to short chain PFAS substances like C6 (PFHxS). The following quote from a Danish study¹² is significant:

“In most studies the levels of PFOS and PFOA in human blood are declining, and levels of the shorter and longer chain congeners are increasing. In Sweden, levels of PFBS and PFHxS in blood serum from pregnant women have increased 11% and 8.3% per year respectively from 1996-2010 (Glynn et al. 2012) while during the same period the concentrations of PFOS and PFOA decreased 8.4% and 3.1% per year, respectively.”

The Swedish study also showed short chain PFAS transfer to newborns more readily than long chains which may make them more toxic in this instance:

“3.1.6 Fetal and lactational transfer

In Norway the human maternal and fetal levels of up to seven PFAS were significantly correlated. The relative proportion of PFHxS was higher than that of PFOS in cord blood compared to maternal blood. This indicated that the chain length of the fluorinated compound was an important determinant for placental passage, and that shorter chain PFASs were transferred relatively more (Thomsen et al. 2010). That was confirmed in a later study 19 PFAS were analyzed in maternal and cord plasma (Gützkow et al. 2012). The median PFAS concentrations (ng/mL) in cord blood were between 30% and 79% of the maternal concentrations. In maternal samples, the median of PFNA was slightly higher than for PFHxS, while the opposite was seen in cord plasma, with a two-fold higher PFHxS concentration compared to PFNA. The ratio between cord concentration (0.23 ng/mL) and maternal concentrations (0.34 ng/mL) of PFHxS was about 0.67.”

Elsie Sunderland, Professor of Environmental Science and Engineering in the Department of Environmental Health at Harvard T.H. Chan School of Public Health, told ProPublica that scientists are just beginning to understand the effects of the more than 4,000 different types of PFASs. She also noted that the chemical industry routinely uses new compounds to replace old ones, further indicating in her words “People call it chemical whack-a-mole”.

I am of the opinion that the chemical industry is doing the equivalent of the following:

An example is presented where, tequila is produced and sold to college students on spring break. It is then discovered that the tequila is harmful to the students, so the tequila is switched out for vodka. The producers of the alcohol now state to the public, “don’t worry we’re not selling tequila to the

students anymore...we're all good." As with PFAS, one type of the compound is switched out for another on a continual basis.

The Scandinavian studies also found that most humans are exposed to a mix of PFAS which is many times more toxic than what the current toxicology studies have revealed, which typically involve studying the effects of only one form of PFAS at a time. Those of us who have drunk different mixtures of alcohol verses just consuming one type at a time can identify with this conclusion. This situation again becomes important in making sure the destruction of PFAS is handled in a way that does not produce and release short chain PFAS derivatives.

I am of the opinion that the US EPA cannot continue to rely on specific toxicology testing to promulgate specific PFAS limits. It will be a never-ending game of "Chemical Whack a Mole" as the US EPA will continually be too late to have any impact. With its extensive resources like SERDP and ESTCP, the US EPA can accomplish most anything it desires. Therefore, it is believed that as a first step a class ruling on PFAS in general relating to acceptable content or PFAS levels in consumer products, air, water and soil in the US needs to be rapidly issued and as important, it should be independent of the type of PFAS in consideration.

Where to go from here

I am of the opinion that if the US EPA makes headway based on the suggested actions above; 1) they would limit the public's exposure to newly produced PFAS in the consumer's environment and products, 2) they could impose limits on the existing PFAS contamination in legacy issues such as AFFF contaminated soil or contaminated water, 3) they can then focus on the remaining challenge, the need for complete destruction of the legacy PFAS without endangering the public any further. As for the final challenge, current attempts of destroying PFAS have resulted in inadvertently producing and redistributing the chemicals in an incompletely destroyed or altered short chain form. In other words, captured and concentrated PFAS is simply re-distributed back in the air or other medias to continue to harm the public on a potentially broader scale and thus resulting in a step backwards.

A very effective process in cleaning up PFAS contaminated water is filtering it through granulated charcoal filters or resins to remove and concentrate the PFAS. However, the end result of the process includes a PFAS contaminated solid that needs to be dealt with. So, in reality the water filtering process is only one step of the process which must additionally include the destruction of the PFAS contaminated solids.

Although it is believed that high temperature thermal destruction holds the most promise for the large-scale destruction of PFAS compounds and PFAS contaminated soils, the most common current choice for PFAS destruction is incineration which is a continuing practice in many locations throughout the US and the world. Figures 2 and 3 appearing in section "How and why PFAS is prevalent in the world?" demonstrates how airborne PFAS is distributed downwind as a part of the manufacturing process. It is critical that these same effects need to be examined when evaluating the incineration process as well as other challenges present in the process.

Does PFAS incineration work and is it safe?

The data available from around the world appears to show incineration of PFAS even in the state-of-the-art incinerators is not effective. Even when using very simplistic ways of analyzing the results of PFAS destruction, which are most likely too liberal, the incineration process' still fails at its intended goals. Here are examples.

In Alaska, Moose Creek Facility is an incineration facility used to remediate PFAS contaminated soil much of which originated at Edwards Airforce Base. The facility is a modern Rotary Kiln incinerator with a scrubber and packed column emissions control system integrated into the process. The facility design is intended to expose PFAS contaminated soils to temperatures up to 850 degrees C and the exhaust gasses in a separate afterburner are to be processed at temperatures of 1200 degrees C.

Two series of air emissions tests were conducted and reported¹⁵. In both tests the facility was found to be emitting PFAS compounds in its exhaust. Of the 21 PFAS compounds that were being tested for, 10 were found to be present in the exhaust of the facility. If it were assumed that the levels of PFAS emissions measured in the exhaust fell out over an acre they would re-contaminate the potentially existing clean soil to the state limits for PFAS contamination in 4.2 months of operation.

In Harlingen, Netherlands a state-of-the-art refractory lined moving grate PFAS incinerator was tested for its air emissions. A summary of the facility and the conditions that initiated air emissions testing is quoted below:

Long-term sampling emission of PFOS and PFOA of a Waste-to-Energy incinerator

Arkenbout, Abel

NGO ToxicoWatch, Harlingen, 8862 VS, arkenbout@toxicowatch.org

Introduction

In 2011 a 'state of the art' incinerator was established in Harlingen, The Netherlands, with a stringent permit for dioxin emissions of 0,01 ng TEQ/Nm³. In 2013 NGO ToxicoWatch found high concentration PCDD/Fs/dl-PCBs in eggs of backyard chicken in the surroundings of the incinerator [1]. To determine or to exclude the source in August 2015 a long-term sampling program of flue gases was started on halogenated UPOPs. In this report we present the results of perfluorooctanesulfonic acid, PFOS and perfluorooctanoic acid (PFOA) in flue gas and discussed these results in relation with other UPOPs, heterogeneous temperatures in the post combustion zone and interruptions in long-term sampling.

Figure 10. Arkenbout, Abel. "Long-term sampling emission of PFOS and PFOA of a Waste-to-Energy incinerator". 10.13140/RG.2.2.14281.19046., 17 September, 2018, https://www.researchgate.net/publication/327701467_Long-term_sampling_emission_of_PFOS_and_PFOA_of_a_Waste-to-Energy_incinerator

The facility is pictured below:



Figure 11. Reststoffen Energie Centrale, Harlingen, The Netherlands



Figure 12. Reststoffen Energie Centrale, Harlingen, The Netherlands

The data from the report¹⁶ filed on the facility showed it emitted PFAS above permitted limits. The violations were not during upset conditions. Upset conditions could have emitted higher levels. Somehow during upset conditions, the continuous data system did not record results. It is also regrettable that only PFOS and PFOA were monitored. This is only 2 PFAS compounds out of over 4,000 that could be present. The reformation of short chain PFAS or the multitude of other PFAS chemicals were not considered. If a broader emissions test were undertaken the results would most likely be worse. A summary plot of the data is shown below in Figures 13 and 14:

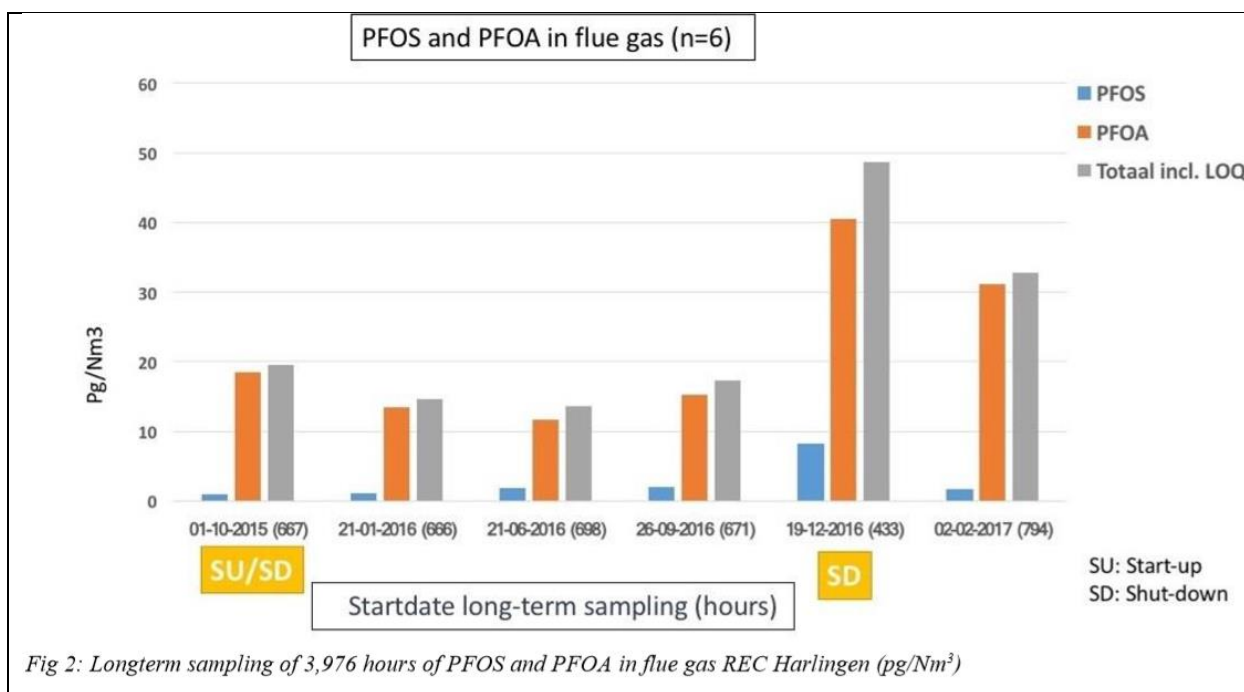


Figure 13. Arkenbout, Abel. "Long-term sampling emission of PFOS and PFOA of a Waste-to-Energy incinerator". 10.13140/RG.2.2.14281.19046., 17 September, 2018, https://www.researchgate.net/publication/327701467_Long-term_sampling_emission_of_PFOS_and_PFOA_of_a_Waste-to-Energy_incinerator

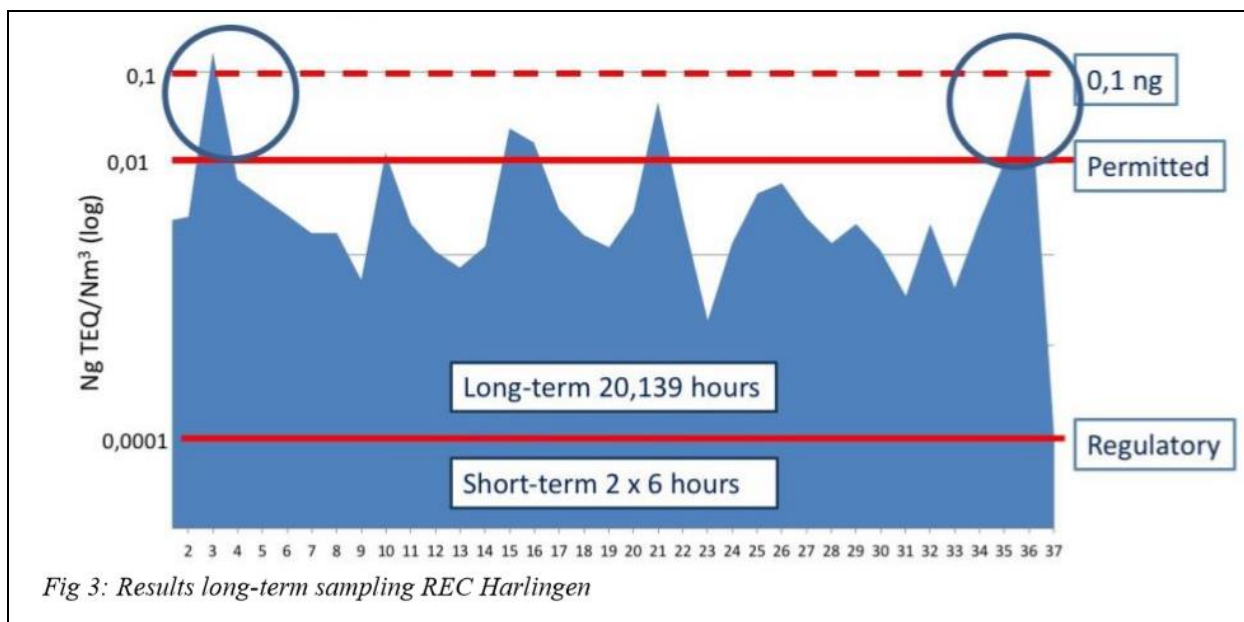


Fig 3: Results long-term sampling REC Harlingen

Figure 14. Arkenbout, Abel. "Long-term sampling emission of PFOS and PFOA of a Waste-to-Energy incinerator". 10.13140/RG.2.2.14281.19046., 17 September, 2018, https://www.researchgate.net/publication/327701467_Long-term_sampling_emission_of_PFOS_and_PFOA_of_a_Waste-to-Energy_incinerator

The text from the report below is clear in its appraisal that the facility is not capable of safely destroying PFAS:

“Essentially, 'small' emissions of PFOA from a steady state operational incinerator are just the tip of the iceberg when all the potential 'upset' conditions are considered. It conveys the impression that modern incinerators cannot fully destroy UPOPs like PCDD/F, PBB, PCB or even PFOA - even under optimal operating conditions. The interrupted sampling of UPOPs in flue gas indicate the real emissions are higher, in what degree more research is needed.”

In Australia, the Southern Australian EPA did a trial and study of a recently upgraded Veolia thermal destruction plant in Dry Creek Southern Australia. The facility was intended to destroy PFAS.¹⁷ In the plant its exhaust gasses were exposed to temperatures of 1,000 degrees C for over 2 seconds. The facility also had advanced technology such as carbon filters. The results of a trial test demonstrated the facility failed to safely destroy PFAS. A quote from the Australian EPA’s final report is below:

“Based on the waste ash and the quench water results, the trials were considered to have failed.

The quench waters from the trial have been removed to a site licensed to dispose of this water. In line with the Approved Trial Plans, the waste ash will also be removed to a site licensed to dispose of this waste.

Veolia has indicated that it will be requesting approval to undertake further trials to incinerate these types of low-level PFAS contaminated wastes. The company has proposed to engage a combustion specialist to assess and recommend incinerator settings to ensure complete combustion of waste, and to improve the destruction levels of the PFAS compounds.”

On behalf of the Swedish Environmental Protection Agency, Dr. Lisa Lundin and Dr. Stina Jansson at the Department of Chemistry, Umeå University, conducted a study to assess the capability of current technology in Advanced Solid Waste Incinerators (ASWI) to destroy PFAS and other toxins.¹⁸ The summary results are copied below in Figure 15:

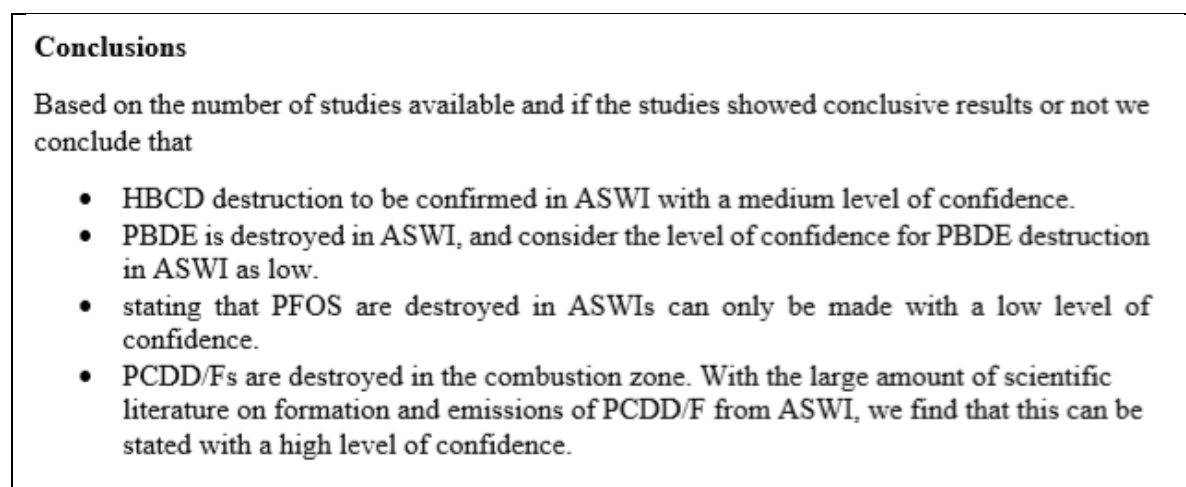


Figure 15. Lundin, Lisa; Jansson, Stina. "Destruction of Persistent Organic Compounds in Combustion Systems". Kemiska Institutionen, Umeå University, 2017, <https://www.diva-portal.org/smash/get/diva2:1155115/FULLTEXT01.pdf>

The data from around the world is consistent in pointing out that the use of thermal destruction of PFAS in the state-of-the-art incinerators is extremely challenged and essentially does not work to an acceptable level. Potential reasons for these failures and a deeper discussion of a better method using ultra-high temperature thermal destruction, will be covered in later sections of this paper.

The cost of getting it wrong

The data from around the world is pointing out that PFAS is not completely destroyed when it is processed in state-of-the-art incinerators. The test results showing failed destruction attempts are probably understating the problem since the data available has not quantified the levels of more than a handful of resultant PFAS compounds out of greater than 4,000 that could be present. No cumulative effects of multiple compounds on total toxicology were factored in either. The likelihood that many more contaminant PFAS compounds are present and being emitted from the destruction facility's exhaust stacks and ash byproducts is high. If the PFAS C-F bonds are not completely broken the probability of emitting shorter chained PFAS compounds is high. The possibility and risk of PFAS reformation in the incineration process is also not well understood at this time.

I am of the opinion that it is ludicrous to process concentrated PFAS wastes in a facility that in the end, re-distributes an unacceptable amount of the toxin in its air emissions and ash waste. Contaminating a large area and its population is an inevitable outcome of this process.

The real moral cost of contaminating living things cannot be assessed or quantified...it is too high. However, the current legal costs in the USA can be assessed. The following are examples of active or recent US legal actions¹⁹:

Minnesota

In February 2018, 3M settled a lawsuit for \$850 million related to contaminated drinking water in Minnesota.

New Jersey

Five New Jersey companies were declared to be financially responsible for statewide remediation of the chemicals in a directive from the New Jersey Department of Environmental Protection in March 2019. Among the companies accused were Arkema and Solvay in regard to a West Deptford Facility in Gloucester County, where Arkema manufactured PFAS, but Solvay claims to have never manufactured but only handled PFAs. The companies have denied liability and are contesting the directive.

Class Action Law Suits

In October 2018, a class action suit was filed by an Ohio firefighter against several producers of fluorosurfactants, including 3M and DuPont, on behalf of all US residents who may have adverse health effects from exposure to PFAS chemicals.^[63] Five New Jersey companies were declared to be financially responsible for statewide remediation of the chemicals in a directive from the New Jersey Department of Environmental Protection in March 2019.

In February 2017, DuPont and Chemours agreed to pay \$671 million to settle lawsuits arising from 3,550 personal injury claims related to releasing of PFAS chemicals from their Parkersburg, West Virginia plant, into the drinking water of several thousand residents. This was after a court-created independent scientific panel, "The C8 Science Panel", found a 'probable link' between C8 exposure and six illnesses: kidney and testicular cancer, ulcerative colitis, thyroid disease, pregnancy-induced hypertension and high cholesterol.

This story is told in the film *Dark Waters*, released in November 2019, produced by star Mark Ruffalo and directed by Todd Haynes.

It appears that in the US the legal community may in the end have the most pronounced effect in removing the PFAS threat to the US public unless US EPA standards are invoked. Unfortunately, this legal activity may not provide meaningful relief for the rest of the world. As mentioned, it would seem critical for the US EPA to accomplish its chartered duty and set appropriate air, water, soil and consumer product standards for PFAS. This will also make the legal efforts more efficient. Therefore it follows that since PFAS was developed in the US originally and put into large scale production in the US it is only rational that the US EPA should lead the effort in the world to clean up the toxicology problems associated with PFAS and set standards that the rest of the world can use to its advantage.

I was fortunate enough to have been involved in the re-write of a portion of the Clean Air Act specifically related to the transportation sections many decades ago. At the time I was working with the EPA in Ann Arbor Michigan and was a representative from industry. The process was effective and the groups worked well together. Modern diesel and gas fuel injection and automotive catalyst systems precipitated from the results. The balance of the world benefitted from the effort. Heavy duty and automotive products also benefitted from the more advanced technology required to meet the needed new emissions standards. In the end it became a triple win, 1) the EPA did its chartered job and set standards that helped to protect the US public, 2) the automotive and heavy-duty industry went through some trying times but, in the end, industry rose to the challenge and met the EPA's requirements, 3) industry developed a vastly superior product for consumers. To this day consumers are enjoying the

benefits of the new technology like fuel injection, which was developed primarily to meet the new emissions standards. The current performance and reliability of modern vehicles would not be possible without this technology.

It has always been on the EPA's radar (but not a requirement) to promulgate standards that are financially feasible for industry to achieve. In the end this financial judgement is a soft and difficult metric to balance. In the complicated world of developing a competent PFAS compliance program this financial goal may make the EPA's task nearly impossible. The hope is for history to repeat itself, as it is my experience and opinion the transportation section of the clean air act was established without knowing if industry could cost effectively meet the required new standards. Additionally, many of the major players of the auto industry were highly vocal in predicting that the new standards would cause major death and destruction to the industry and the consumer's ability to buy a reliable vehicle. But history has shown that industry was able to rise to the challenge and everybody won.

I am of the opinion that the EPA needs to focus on PFAS standards that will protect the public, independent of the cost. The PFAS material is too toxic, too long lasting, and too bioaccumulative to allow for compromise. Industry will again rise to the challenge and create clever solutions to accomplish the EPA's goals and consequently serve the public in a positive way.

A better path using Ultra-high Temperature Thermal Destruction

The following section builds on the experience of Plasma Power from over a decade of work in ultra-high temperature thermal destruction (UHTTD).

Thermal energy, independent of an oxidant, is a hammer which can be used to break down complicated molecules and substances into their basic elements. Used correctly in a complete process this hammer can convert toxic substances into safe components that do not affect living things in a negative way. It can render toxic substances into harmless by-products. Analyzed another way x -temperature times y -residence time will equal the reduction of any substance into its basic elements. This can render most any substance safe if the process is designed correctly. The two x and y coefficients are typically inversely related. In other words, very high temperatures need very short residence times to be effective and vice versa.

Progressing from the above simple concept, in Plasma Power's experience there are many challenges in a production real world setting to successfully achieve the desired outcome of breaking down complex molecules into inert and stable substances. Lab results many times show false positive outcomes in destroying toxic substances. Unfortunately, real-life large-scale production can show the opposite outcome. Plasma Power has spent over a decade using "better tools" than incineration to understand why this happens. The following is a summary of some of the results:

Temperature Distribution and Cold Spots

No matter what type of conventional incinerator is used it typically relies on burning or oxidizing a fuel to generate its thermal energy. It is useful to remember that PFAS is one of the best fire retardants known to man. Trying to burn a fire retardant is not an easy task or potentially even a good idea. Cold spots can occur. An example of cold spots is shown below.



The center of the incineration process is quite hot and full of thermal energy at 1400 degrees C. If the whole environment and production process could be maintained at this level it would be a significantly capable incineration process. Unfortunately, a graphic example of cold spots is shown by the existence of the surrounding snow closely coupled to the incinerating fire pit. This is a similar example of what occurs in many commercial incinerators (to a lesser extreme) even when burning less challenging feedstocks than PFAS. The occurrence of these cold spots in modern incinerators is well

documented. The test data from the many failed PFAS destruction examples in this paper confirms the problem.



This image shows other issues. The incinerator or fire pit on the left shows the accumulation of bottom ash. The contents of bottom ash are typically concentrated toxins that have not been completely broken down. The fire pit or incinerator on the right shows the aerodynamic effects of oxidizing a fuel. A significant mass flow needs to be added to the incineration process with an oxidant, in this case air, that can carry toxins into the exhaust stream. In this example the process is showing the escape of fly ash. Often fly ash does not

have the residence time at needed temperatures to be completely thermally processed and therefore contains significant toxins. The complex modeling required to understand the thermal transfer in the conditions of bottom ash and fly ash is formidable. The problem becomes even more impossible when you add the reactivity of the oxidant involved and the possibility of toxins reforming in a different state with all the different conditions that exist in the 2 pictures.

Note PFAS is often delivered to an incinerator in a non-homogenous form such as contaminated soils making this problem even more impossible to model and understand. Most models fail due to not considering the non-homogenous attributes of the feedstock, including multi-phase conditions that include latent heat sinks and radiation shields. At the temperatures required to safely complete the thermal destruction of PFAS most heat transfer is accomplished through radiation, not conduction. Inadvertent natural radiation heat shields are common problems in causing incomplete solids destruction.

In an ultra-high temperature thermal plasma process the heat energy or thermal energy is decoupled from oxidation. In other words, the process does not “burn” a fuel to make heat. The reality is no oxidant is needed to make heat. Thermal energy can be developed to any practical level in the absence of oxygen or air. Many thermal plasma processes run at temperatures hotter than the surface of the sun. This temperature is above the temperature that the surface of the earth was formed at. Any terrestrial material can be broken down to its basic elements at these ultra-high temperatures.

The lack of an oxidant also significantly reduces the mass flow of the destruction process. This can really help in reducing or eliminating fly ash and minimizing the reformation of toxins in the production process. This can also be an aid in increasing process residence time. Or said another way, it can extend the time the feedstock is being exposed to ultra-high thermal energy. The plasma process also runs hot enough to vitrify or make glass out of all the inorganics. There is no bottom ash in a correctly run high temperature thermal plasma process. There literally is no ash at all.

Ultra-high temperature thermal plasma also is a violent process that generates incredibly good mixing and a large content of aggressive free radicals that help in the process of reducing complicated compounds into their constituent elements at a very rapid rate.

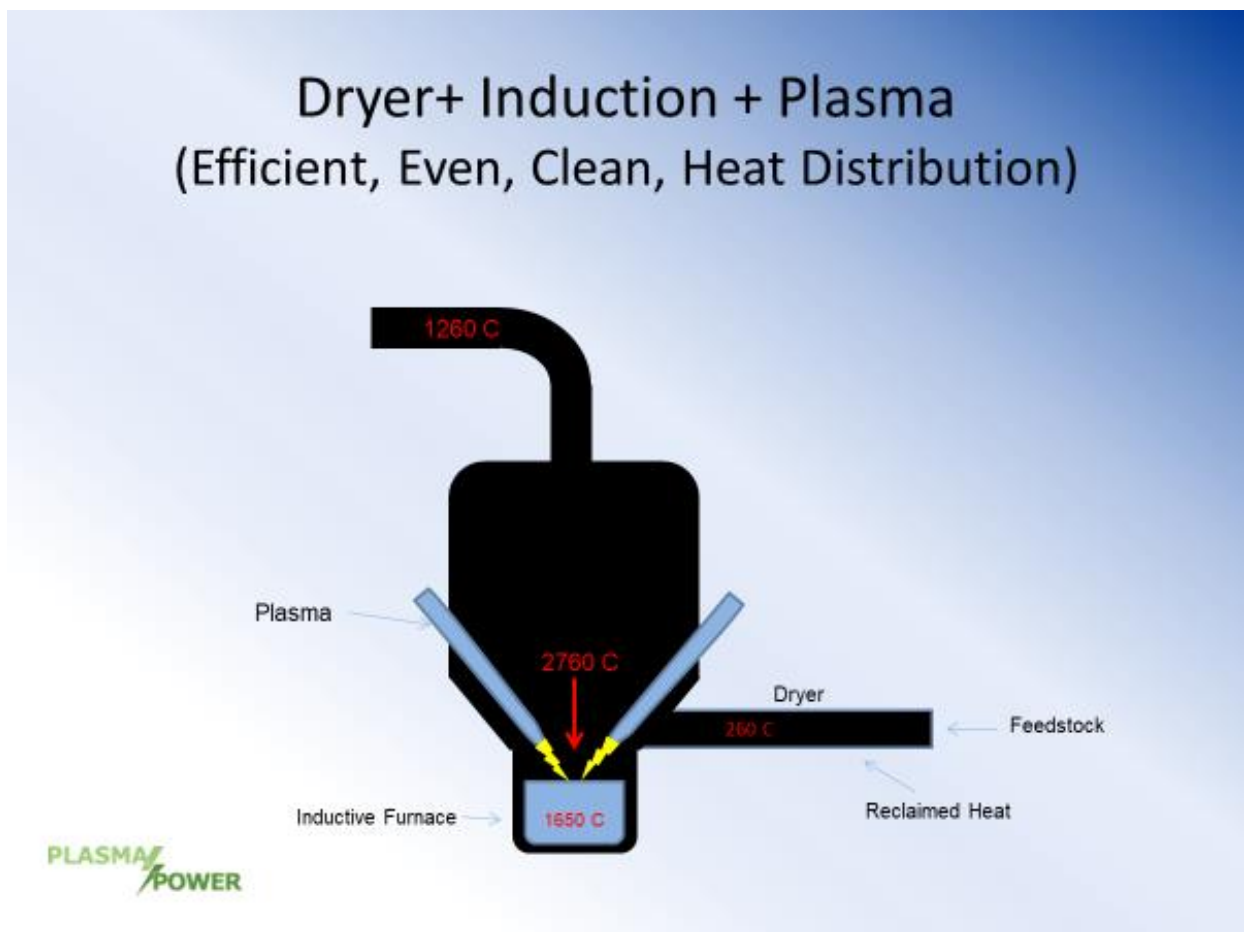
In Plasma Power’s design the plasma process is also always run under a vacuum. If there is a leak in the system the outside environment **leaks into** the process. This is a safe condition that does not exist in today’s conventional incinerators. They unfortunately leak toxins out into the surrounding environment. In a modern large-scale incinerator, it is very difficult if not impossible to accurately find and quantify system leaks. Nothing man has ever made does not eventually leak. Plasma Power’s systems are designed to “Fail Safe” if they leak.

Unfortunately, high temperature thermal plasma processes are not without their own challenges. Plasma energy by its very nature is extremely energy dense. In other words, it is intensely hot over a small area. The challenge is to distribute that intense thermal energy consistently over an area large enough to accomplish the safe and reliable thermal destruction of a feedstock. Many plasma companies have failed in achieving this goal. Their large-scale plasma production plants could not reliably expose the feedstock to the benefit of the high energy plasma. Plasma Power worked for many years to solve this problem.

Every feedstock material also has its own challenges. Non-homogeneous materials are always a challenge in any production process. The destruction of a non-homogeneous material in a PFAS destruction process is no exception. A contaminated soil of varying density, moisture level, PFAS contamination level, PFAS compound blends, clump size, feedstock shape and containing other thermally competing substances is very difficult to model for a successful destruction process and in real world production life difficult to deal with. The production process required to be successful has

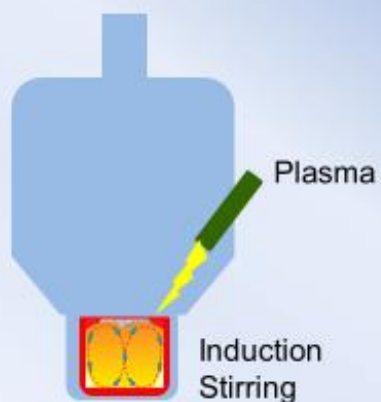
to be robust and operate without failure every time it is in operation. Unfortunately, with the high toxicity level of PFAS the destruction process has to succeed 100% of the time.

In order to achieve a consistent ultra-high temperature environment with no cold spots Plasma Power developed a production process where the ultra-high temperature thermal plasma is distributed over a broader area by projecting the plasma energy into a constantly mixed and pre-heated metal pool. The liquid metal pool is the coldest element in the immediate thermal destruction process. The image below shows the highlights of the production process:



The metal pool is maintained at a constant temperature of approximately 1,650 degrees C using inductive energy. The thermal plasma is projected into this inductively stirred metal pool to produce a very dynamic production area at approximately 2,760 degrees C. This compares to incineration temperatures in conventional systems that struggle to achieve a peak temperature of 1,200 degrees C. The production area is constantly stirred due to the principals of induction energy transfer and the tangentially projected plasma. An image showing the effect is included below:

Temperature Distribution



PLASMA
POWER

The result is a production environment that can be maintained at a high and consistent temperature for extended feedstock residence time.



The image shows this extreme environment while the plasma system is in the production process of destroying contaminated soils. The contaminated soils are being vaporized as seen in the left-hand side of the viewing window (the bright area). The soil is continuously fed into the thermal process. The coldest spot in the process is the wall of the chamber on the far side of the viewing window. The wall is at approximately 1,640 degrees C.

If more residence time is required at a higher temperature Plasma Power has operated its short run production facility with the addition of another stage of thermal plasma. It is shown in the image below:

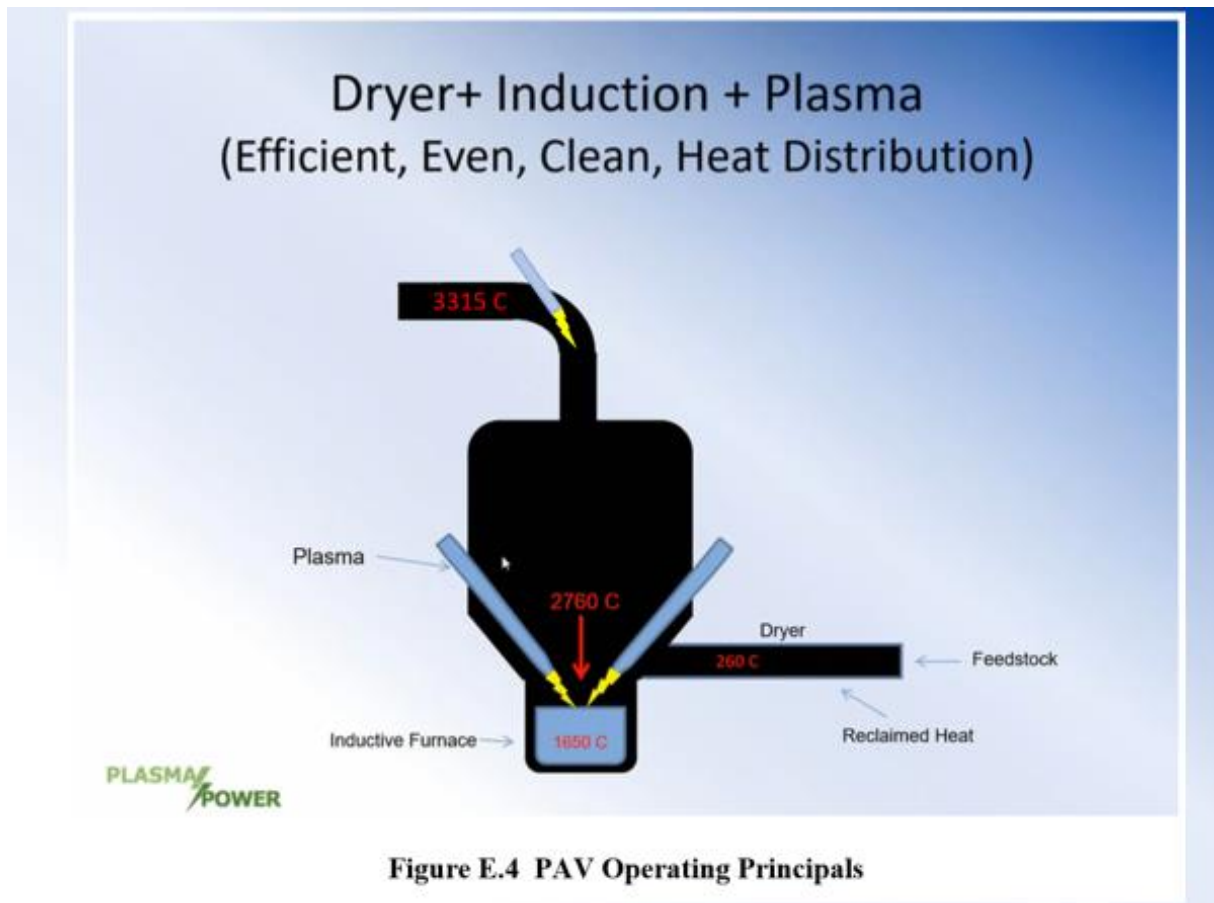


Figure E.4 PAV Operating Principals

It is expected that this ultra-high level of thermal energy and residence time in the extra down draft stage is most likely more than is required to reliably destroy PFAS.

The Development of a Reliable PFAS Destruction Process

To the extent that is known, Plasma Power has the largest short run plasma production plant in the world. The plant can process up to 30 tons per day of feedstock depending on the energy required to process the specific feedstock.

A reliable production process, learned from 30-years of experience of developing many production processes, always starts with the process being applied at a conservative rate. The rate should be well below the capability of the plant. Available data shows this condition has never happened in the destruction of PFAS in conventional incinerators. They lack excess capability. The reality is they lack even adequate capability^{15,16,17}.

Ideally, if additional production capability exists the production process then is typically ramped up to find its limits of reliability. The process at that point can either be improved to eliminate the choke points or cut back to provide a significant factory of safety and assure a reliable process even with upsets that undoubtedly will occur in the real world. Again, with conventional incinerators operating “on the edge” or more realistically below the threshold required to perform their charted task they will never be capable of these safe “factors of safety” operating levels. Production upsets are inevitable in the real world which makes the contamination of the public with PFAS inevitable when it is processed in today’s conventional incinerators.

A solid metric to measure success is always needed in developing a reliable production process. It is believed that the only reliable metric, given the possible plethora of PFAS derivatives including short chain PFAS, is a full fluorine mass balance across the complete production process. In other words, the measurement technique needs to account for every C-F bond that goes into the destruction process. An accounting should show all the available fluorine and fluoride that went into the process is captured in the process and rendered harmless. It is believed that, although difficult to measure, this C-F mass balance task is possible to accomplish with today’s measurement tools. Once x -temperature times y -residence time is established in a non-homogeneous feedstock under worse case conditions the world will finally have a reliable PFAS destruction metric. The metric can then be optimized to build in the required “factor of safety” and established a process that will finally be reliable. Additionally, it is believed that a secondary independent belt and suspenders fluorine capture program downstream of the PFAS destruction primary production process should be included to assure the production process keeps the surrounding public safe.

To be complete, the reforming or “reformation” mechanics and principals of PFAS need to be understood and documented to fully eliminate the possibility of continued contamination by short chain PFAS. The US EPA has an ideal test bed to accomplish this very challenging task. Figure 16 below shows the “Rainbow” furnace resident at the US EPA’s development center:

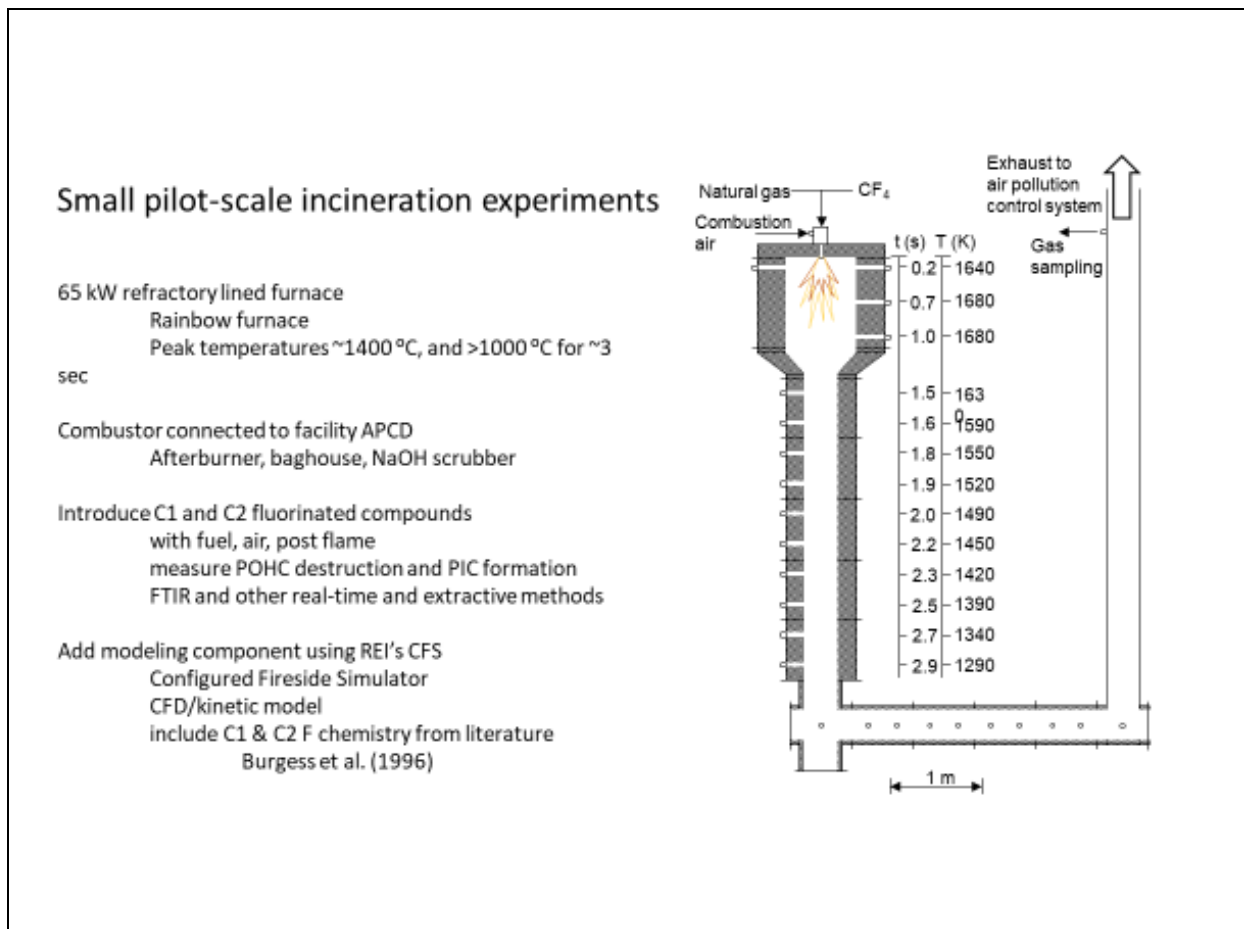


Figure 16. US EPA “Rainbow” furnace resident at the US EPA’s development center

In the above test bed environment residence time, temperature and chemical constituents could be studied to establish the conditions that control PFAS reformation in gases. It is recommended that a reformation study program should be run in parallel to an Ultra-high Temperature PFAS destruction program. Both of the above programs will require a solid plan to be executed correctly. The next section will show an example of how this could be done.

The Development of a Safe PFAS Destruction Process

Experience demonstrates that most complex programs fail in the beginning before they ever start. There typically is not enough engineering and planning invested to make certain the program will succeed and meet its intended goals in the end. To minimize this condition Plasma Power has established a structured “Design of Experiment” (DOE) methodology to execute complex programs. Each major stage of a program uses this tool. An example of a basic DOE to establish a safe production process for PFAS destruction (not including reformation) under real world conditions including production upsets is listed below. It is only a simple example. Real executable DOEs require significant engineering effort to be valid. The simple example is:

1. Establish the limits of feedstock for the production process
 - a. Will it be soil
 - i. To what level will the soil be pre-conditioned
 - b. Will it only be Granulated Activated Charcoal (GAC) material
 - i. To what level will the GAC material be pre-conditioned
 - c. Will it be a mix of consumer products that contain high levels of PFAS such as carpet?
 - i. To what level will the consumer products be pre-conditioned
 - d. Will feedstocks be mixed
2. Establish the measurement metric to define complete PFAS destruction. As previously noted in this paper, it is recommended to use the metric of a fluorine mass balance for the full system as the ultimate metric for success in establishing the PFAS destruction production process. This is not an easy task. The task is complicated in the fact that typical high temperature refractory absorbs fluorine. A benefit of this absorption characteristic is the fact that eventually the refractory will age to a saturated condition. The refractory could also be "pre-seasoned" with high levels of fluorine. If the test is long enough fluorine saturation for the refractory could occur on its own. In any case the refractory will at some point in the mass balance need to be dissected and accounted for its fluorine content in the mass balance.
3. Establish the appropriate handling standards for the feedstock. It is recommended that an automated vacuum-controlled feedstock handling system to assure no fugitive PFAS compounds are released to the surrounding environment or workers. The resultant vacuum media (air potentially laden with PFAS) would need to be processed in the PFAS destruction process.
4. Implement a portion of the destruction process that can capture the fluorine in a stable form to help minimize the possibility of reformation of PFAS into new toxic compounds. It is then recommended to develop the process to convert the PFAS back into hydrofluoric acid. In many cases PFAS was originally made from hydrofluoric acid. Returning it to this stable substance is logical. The acid can also be handled as a commodity if the correct safety standards are followed.
5. Standardize the feedstock into a known condition to establish a process baseline. An example if soil was chosen as the feedstock would be to start with a manufactured sample of known soil content and characteristics spiked at a known density with a known PFAS chemical content.
6. Operate the process at an energy level well above the thought to be needed x temperature times y residence time.
7. Look for break through PFAS and any fluorine compounds downstream of the hydrofluoric acid accumulation section using a modified method V impinger system in stack air samples potentially using mass spectrometer, gas chromatometer and FTIR. A secondary fluorine "sponge" potentially an enhanced aqueous scrubber needs to be in place downstream of the hydrofluoric acid production stage and the modified method V sampler to assure there is no PFAS break through to the surrounding environment.
8. If no fluorine is found in the modified impinger sample the process can be ratcheted back to find its limits until breakthrough is detected.
9. An appropriate factor of safety could be established under the idealized conditions of a known feedstock accounting for the extra energy required to handle real world feedstocks.
10. Real world feedstocks could be processed at the newly established "factor of safety" production process limits and the system would be monitored for breakthrough.

- a. If no breakthrough occurs reduce the process constraints until break through occurs.
 - b. Re-establish desired factor of safety production process conditions using real world feedstocks
11. Shut down the system and replace the refractory
 12. Run the system at the proposed production operating conditions with a known feedstock configured for a worse case production requirement.
 13. Complete a fluorine mass balance including the parameters of PFAS in, fluorine captured in the hydrofluoric acid, fluorine captured in the refractory which will need to be extracted at the completion of the run and analyzed.
 - a. Analyze air emissions to make certain break through does not occur
 - b. Analyze vitrified slag to verify no fluorine content
 - c. Analyze the extra downstream aqueous PFAS sponge to make certain no PFAS breakthrough occurred. PFAS measurement technology has advanced rapidly and many tools exist such as; Total Oxidizable Precursor (TOP) and Total Organic Fluorine (TOF) assay, FTIR, and LC-MS/MS processes. Many of these methods employ the use of advanced spectroscopy techniques which allow for the screening of unknown or non-targeted substances. These advanced spectroscopy techniques also include liquid chromatography quadrupole time of flight mass spectroscopy (LC-QToF-MS) and particle-induced gamma emission (PIGE) spectroscopy. It would seem more than enough measurement technology now exists to measure nearly all fluorine content in a system at least under a controlled environment such as a DOE. As part of the full DOE the invested parties should establish what specific methods will be utilized to assure a reliable and trusted fluorine mass balance measurement. Once done this should assure all long and short chain PFAS have been destroyed and are accounted for.
 14. Once the mass balance has been performed asses the confidence level of the mass balance results. Is the confidence level high in the mass balance results?
 - a. If not check for "lost fluorine sinks"
 - b. If no fluorine sinks exist re-run the production process variables to a more aggressive level and repeat the mass balance exercise

At the completion of an acceptable DOE result a capable and safe PFAS destruction production process for the world would be developed. That would be a major step forward for the world and finally assure the safe destruction of existing PFAS.

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