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Fluid Dynamics Modeling for Per- and Polyfluoroalkyl Substances Removal in Legacy Fire Suppression Systems

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FLUID DYNAMICS MODELING FOR PER- AND POLYFLUOROALKYL SUBSTANCES REMOVAL IN LEGACY FIRE SUPPRESSION SYSTEMS

THESIS

Jacob G. Spaulding, Captain, USMC

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DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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Jacob G. Spaulding, BS

Captain, USMC

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Abstract

Legacy per- and polyfluoroalkyl substances (PFASs) exist in the form of aqueous film-forming foams within hangar fire suppression systems throughout the country, posing a threat to both surrounding environments as well as local populations. The United States (US) Department of Defense (DoD), in conjunction with the US Environmental Protection Agency (EPA), is investigating best practices to flush out existing contaminants prior to disposal and replacement with a less environmentally harmful replacement. While current procedures dictate a triple rinse of the entire system to yield contaminant levels acceptable to the DoD, the practice has never truly been tested. Designed as a tool to understand movement of drinking water within distribution systems, EPANET software can be used to model a contaminant's fate through a series of pipes reminiscent of a hangar fire suppression system and can thus simulate legacy PFAS transport from origin tank to expulsion emitters. Its hydraulic modeling and water quality modeling features make it ideal for this endeavor, and the results produced provide further support for the triple rinse's hypothesized six-log reduction of the chemical contaminant.

Acknowledgments

I would like to express my sincere appreciation to my academic and thesis advisor, Lt Col John Stubbs, for his guidance and support throughout the course of this thesis effort. The mentorship and advice garnered will carry me well beyond my time in the military. I would also like to thank my committee members, Dr. Eric Mbonimpa from the Air Force Institute of Technology (AFIT) and Dr. Jonathan Burkhardt from the Environmental Protection Agency (EPA), for both their unwavering support and latitude provided to me in this endeavor. Additionally, I would like to extend my gratitude to Dr. Matthew Magnuson and Dr. Terra Haxton from the EPA as well; the adaptability by all to make this happen during a global pandemic was truly a Herculean effort. Finally, I would like to thank the rest of the Environmental Engineering faculty at AFIT: Dr. Willie Harper, Dr. Jeremy Slagley, and Lt Col Casey Cooper. No doubt I prompted more than a few grey hairs to grow for most of you all during my time here, but I learned more than I could imagine about environmental engineering specifically and problem-solving in general, and for that I am truly grateful.

Jacob G. Spaulding

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FLUID DYNAMICS MODELING FOR PER- AND POLYFLUOROALKYL SUBSTANCES REMOVAL IN LEGACY FIRE SUPPRESSION SYSTEMS

I. Introduction

General Issue

Pollution is an inevitable byproduct of industry. From the manufacture and installation of wind farms and solar panels to the harvesting and compilation of rare metals and minerals to create powerful batteries, pollution in the 21st century is inescapable. One of the greatest concerns from a pollution standpoint is for that of our drinking water. While the earth is covered by roughly 70 percent water, only one percent of that is available for drinking. Therefore, any increase in the pollutant level of a drinking water source is of significant concern for both humans and the environment at large.

The United States (U.S.) Environmental Protection Agency (EPA), with the help of the Agency for Toxic Substances and Disease Registry (ATSDR), has identified a running list of chemical contaminants with potential negative impacts to both the environment and human populations. Having posted four Contaminant Candidate Lists (CCLs) since 1998 with a fifth one currently at the nomination phase, over 250 chemicals have been identified as harmful threats subject to governmental regulation (U.S. Environmental Protection Agency, 2020b). Prominent and most well-studied to date among these on CCL 4, announced November 17, 2016, are two contaminant subsets of per- and polyfluoroalkyl substances (PFASs), perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA). These two anthropogenic and suspected carcinogenic (U.S. Environmental Protection Agency, 2016b, 2017) compounds were common in everything from personal care products and nonstick cookware to stain- and water-resistant clothing and firefighting foams and are now ubiquitous in the environment (Dasu, Kempisty, & Mills, 2019; Kempisty, Xing, & Racz, 2019; U.S. Environmental Protection Agency, 2017).

While dermal and inhalation pathways of exposure to dangerous PFASs can be of concern (Haug, Huber, Becher, & Thomsen, 2011), ingestion of such chemicals via contaminated drinking water and food offers a much more likely route for humans (Agency for Toxic Substances and Disease Registry, 2020; Sunderland et al., 2019). Excessive levels of PFOS and PFOA found within drinking water is of primary concern, due in large part to persistence and mobility within both water and soil mediums (3M, 2000). Often times, perfluoroalkyls transport through the soil into groundwater, where they eventually find themselves in drinking water sources, land-locked surface waters, and eventually the oceans (Agency for Toxic Substances and Disease Registry, 2020; Minnesota Department of Health, 2019; U.S. Environmental Protection Agency, 2017). One of the primary means of entry into the natural environment’s soil and water is via aqueous film-forming foams (AFFF).

“As of July 2020, 2,230 locations in 49 states are known to have PFAS contamination” (Benesh & Lothspeich, 2019). As illustrated in Figure 1, 206 of these are military sites, and as such, host sizeable populations of dependents, contractors, other civilians, and servicemembers.

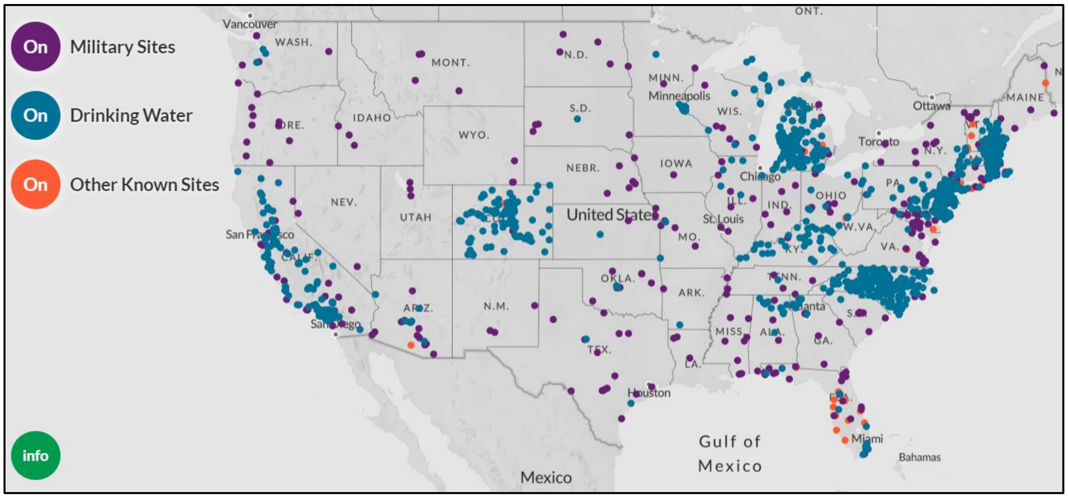


Figure 1: Map of PFAS contamination spread in the United States (Hayes & Faber, 2019)

The military's presence within the continental U.S. has grown exponentially in the last century (Chambers II, 2020), establishing over 400 bases in every corner of the country (Sherman, n.d.). Most of these have at least some type of hangar or maintenance bay to support aircraft either in transit or permanently housed there. With the modernization of fire suppression technologies, one can reasonably assume that the majority of these hangars house some type of foam generating system, such as the one seen in Figure 2. Couple those with the number of civilian hangars, firefighting training areas (FFTAs), and aircraft rescue and firefighting (ARFF) vehicles, and the number of past and potential leaks is astronomical in terms of likely human and environmental impact.

Figure 2: AFFF cleanup at Travis AFB, California, in 2013 (Wright, 2013)

In 2016, the EPA issued Lifetime Health Advisories (LHAs) of 70 parts per trillion (ppt) in drinking water and the Department of Defense (DoD) was quick to amend existing protocols to get ahead of the issue (Air Force Public Affairs, 2019; Headquarters United States Marine Corps, 2020; U.S. Environmental Protection Agency, 2016a). The various branches of the United States armed services since adopted 800 parts per billion (ppb) as its target military specification (MILSPEC) for both PFOS and PFOA, the most current level of detection at the time of publication (Naval Sea Systems Command, 2017; SERDP/ESTCP, 2019). In order to ensure compliance, the military has opted for the triple rinsing approach. Per Marine Corps Bulletin 11000: “The surfaces of all equipment shall be triple rinsed after removal of AFFF product, utilizing approved methodology by

Naval Facilities Engineering and Expeditionary Warfare Center (NAVFAC EXWC)" (Headquarters United States Marine Corps, 2020).

Research Objectives

This research will address the following questions:

1. How effective is the triple rinse technique in removing legacy PFAS from a hangar fire suppression system?
2. In modeling the system, can any specific/potential areas of adsorption be identified and/or mitigated?

This research serves to further understand the persistence of legacy contaminants within a Group I (Ozmun & Brown, 2020) DoD hangar fire suppression system through a fluid dynamics modeling effort utilizing EPANET software. In doing so, both the EPA and DoD will gain useful insight into the efficacy of existing flushing and rinsing protocols, how to optimize such efforts, and recommendations for future waste removal. The digital model will function as the precursor to a physical model, which will in turn be applied to the system itself. A brief economic analysis will aid in deciding between the cost effectiveness of cleaning versus that of replacing the system entirely.

Furthermore, the research effort serves to simulate the hydraulics of a Group I aircraft hangar fire suppression system with a known quantity of chemical introduced and traced until dilution and expulsion. Furthermore, potential areas of adsorption, or "hot spots," will be identified in the event a more rigorous cleaning solution needs to be applied. Upon analysis of the yielded results, varying methods of simulation and optimization are applied to deliver the most cost-effective means of successfully removing PFAS chemicals to non-detect (ND), or below the prescribed detection limit (DL). Additionally, the resulting wastewater can be removed or destroyed via different means, each with pros and cons associated with it. Detailed cost-effectiveness will not be included within this effort, but recommendations will be made based on rudimentary comparisons of open-source information.

Defining hypotheses for this effort are:

1. The triple rinse is an effective and efficient technique, comparable to its theoretical outcome.
2. There are areas of adsorption, but these are mitigated by continuous flushing.

The Strategic Environmental Research and Development Program (SERDP) is the military's environmental technology and science program ("About SERDP," 2019), while the Environmental Security Technology Certification Program (ESTCP) is their demonstration and validation program. Together, they frequently partner with both the US Department of Energy (DOE) and the EPA, amongst many other government and non-government organizations, to tackle current environmental issues facing the nation and world abroad (SERDP-ESTCP, 2021). Below is a list of present concerns regarding legacy PFAS contaminants as it pertains to fire suppression systems. While each of the eight points will be discussed to some extent within this paper, 5a is the primary objective and will serve as the basis for follow-on actions at the DoD and EPA levels in the future.

SERDP/ESTCP Initiatives (SERDP-ESTCP, 2021)

1. The two options for dealing with firefighting systems are decontamination to remove PFAS contaminants and/or replacement of contaminated components.
2. Decontamination (e.g., flushing) protocols exist but may not be sufficient to remove PFAS to the desired levels.

3. Replacement of components is intrusive and costly, but this can be minimized by understanding why components may be sources of PFAS and design decontamination strategies to better clean those without replacement.
4. Decontamination, if not performed thoughtfully, can generate large volumes of waste.
5. Decontamination protocols can be optimized (e.g., minimize waste volumes, strategically replacing highly contaminated components) by modeling: a) the hydraulics of piping systems and b) sorptive behaviors of PFAS to the firefighting systems.
6. If sampling protocols for verifying decontamination efficacy are not well designed, e.g., the system is sampled too soon after decontamination, this will lead to false assurance of cleanliness and, in turn, recontamination of the system.
7. A variety of designs and ages of firefighting systems are in use at DoD and civilian operations, so the proposed research will target the most common systems and develop an adaptive framework applicable more broadly.
8. Vendors and facility contractors can apply the research by developing system-specific decontamination procedures.

Methodology

This research is accomplished via a comprehensive examination of peer-reviewed literature and a modeling of the hydraulics and foam proportioning systems within a standard hangar fire suppression system utilizing EPANET software. Inputs for the system were provided by digital and hard-copy blueprints and technical manuals (TMs) of existing United States Air Force (USAF) hangars in addition to on-site visits and correspondence with various component manufacturers.

Assumptions/Limitations

Due to a gap in knowledge of particular dimensions and pipe diameters, various liberties were taken with some measurements. Still, the vast majority of the system modeled is based on provided blueprints, TMs from the manufacturers, and personal measurements taken at Hangar 4015, 445th Airlift Wing, Wright-Patterson Air Force Base (WPAFB), Ohio. It can also be assumed that flushing/rinsing the system was not the main priority for the designers; rather, optimal distribution of the foam suppressant was the objective. Still, EPANET software does not account for fouling, or accumulation, of substances on surface walls; therefore, the overall assumption of the model is perfect removal within the system.

The USMC, through NAVFAC EXWC, recommends a triple rinse of all products that come into contact with AFFF (Headquarters United States Marine Corps, 2020; Spence, Edwards, & Appleman, 2020). Of significance, the assumption by the EPA and DoD is that three rinses will result in roughly six-log reduction, or 99.9999% removal (U.S. Environmental Protection Agency, 2008). Therefore, if applied to a hangar fire suppression system, only 0.0001% of the concentrate should remain. However, due to the complexity of the actual system, variables unaccounted for, and a lack of information regarding PFAS adsorption into the system components themselves, the achievement of "zero detect" should not be taken at face value. This is further compounded by EPANET software's inability to feature certain unknowns such as an accumulation or decay rate throughout flushing. In essence, the model produced can be characterized as an ideal, continuous-flow stirred-tank reactor (CFSTR). Additionally, because the primary focus of this research is primarily on the system's piping, the assumption is that all PFAS exits the source bladder and enters the pipes before it is discharged.

Lastly, it is important to note that system hydraulics were designed with the primary function being distribution of the fire suppression foam from origin tanks to emitters.

Although it may be insignificant, pumps could potentially need to be adjusted slightly or swapped out entirely in order to flush the system with pure water.

Uncertainty

Various unaccounted for effects on the overall system—such as time between flushes, adsorption, gravity, corrosion, etc.—are unable to be simulated using EPANET. Still, theoretically, the model can be adopted and adjusted to fit any hangar once proper dimensions and settings are input.

II. Literature Review

Chapter Overview

The purpose of this chapter is to propose the necessity for modeling a hangar fire suppression system, understand PFAS and AFFF, and introduce the software EPANET.

The Need to Model the Hangar Fire Suppression System

Modern-day hangar fire suppression systems, while more advanced and environmentally friendlier than their predecessors, still present myriad problems to the DoD, not only through the contamination aspect but also through the cost of cleanup. Still, like in so many cases, a DoD problem can quickly morph into a local population and environmental issue. PFAS contamination and persistence within surrounding soil and groundwater is a major reason why the EPA has been working closely with both the DoD and private contractors.

While manufacturers of fire-fighting foams have been transitioning from other more harmful formulas since the turn of the century, legacy AFFF still remains aboard DoD and civilian installations, particularly in large scale fire suppression systems. Therefore, the need to accurately model and simulate the hydraulics of the system itself and established rinsing and flushing of legacy contaminants within is of major concern.

PFAS

A PFAS molecule, as seen in Figure 3, is comprised of two parts: a functional group head and a carbon chain tail. The functional group head can differ depending on the type of PFAS but is attracted to water, or hydrophilic. In the case of the PFOA molecule below, the functional group is comprised of a single hydrogen atom, two oxygen atoms, and a carbon atom. Conversely, the tail of the molecule is hydrophobic, or repulsed by water, and is primarily composed of strong carbon-fluorine bonds. Thus, the chemical combination of hydrophilic and hydrophobic qualities provides a useful suppressant to Class-B hydrocarbon fires at the air-liquid interface (Interstate Technology Regulatory Council, 2017).

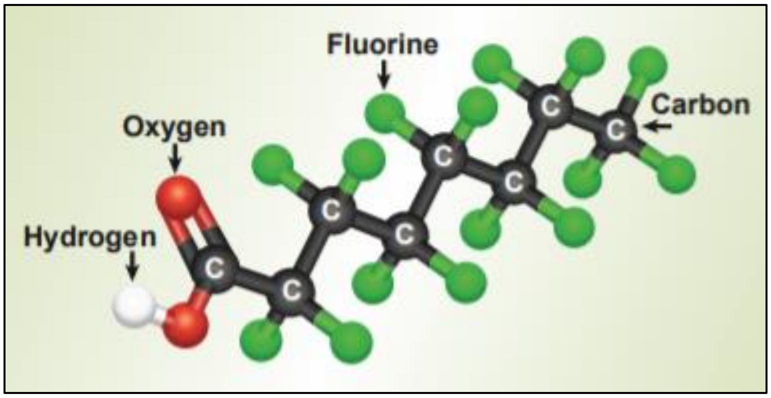


Figure 3: PFOA molecule (National Institute of Environmental Health Sciences, 2019)

PFAS chemicals can be classified by the number of carbons they possess. Long-chain PFAS, like PFOS and PFOA, are different from their short-chain counterparts largely because of their origin chemistry. “Within the perfluoroalkane sulfonate (PFSA) family, all substances with a carbon chain length greater than or equal to six are considered long chain. In contrast, within the perfluorocarboxylic acid (PFCA) family, all substances with a carbon chain length greater than or equal to eight are considered long chain” (Kempisty et al., 2019). Recently, long-chain PFAS have been classified by the United Nations (UN) as both persistent organic pollutants (POPs) and persistent, bioaccumulative, and toxic (PBT) substances (United Nations Environment Programme, 2009).

Due in large part to nearly unchecked mitigation for dozens of years following its introduction internationally, long- and short-chain PFAS were able to persist and accumulate in populations around the globe. Although many reports about the potential adverse health risks associated with long-chain perfluoroalkyl substances surfaced, it was not until efforts by Moody and Field (1999) that the environmental impact of such use begin to come under scrutiny from the national and international communities (Korzeniowski, Buck, Kempisty, & Pabon, 2019; Moody & Field, 1999).

While both short- and long-chain PFAS chemicals can be persistent in the environment, it is the latter that remains persistent in humans, thus posing the most significant threat (Rice, 2019). In addition to being persistent, multiple studies have indicated long-chain PFAS can be extremely bioaccumulative and toxic. According to the ATSDR, PFOA has a half-life of approximately 2-10 years while PFOS has a half-life of up to 27 years. PFAS can accumulate within the human body via many different exposure routes, including through inhalation of indoor air, outdoor air, and dust as well as ingestion of surface water and digestion of food (Agency for Toxic Substances and Disease Registry, 2018; Kempisty et al., 2019). In fact, a 2007 study found that some form of PFAS had been detected in serum samples of approximately 98 percent of the civilian, noninstitutionalized US population over the age of 12 (Calafat, Wong, Kuklenyik, Reidy, & Needham, 2007). It is also important to note that PFAS compounds with shorter chains tend to have shorter half-lives (Agency for Toxic Substances and Disease Registry, 2019). A 2017 study by Li et al. (2017) indicated a decrease in half-lives for PFAS amongst human populations, potentially due to the limited commercial and military use of long-chain PFAS in the preceding years (Li et al., 2017).

Many adverse health effects have been associated with exposure to PFAS, particularly among the most sensitive human populations. Multiple studies have indicated that exposure has impacted infant birth weights, effects on the immune system, cancer, and thyroid hormone disruption (Klein & Braun, 2019; U.S. Environmental Protection Agency, 2020a). Human epidemiology studies have also indicated an increased cholesterol level amongst exposed populations (U.S. Environmental Protection Agency, 2017).

Data concerning toxicity of PFAS has been mostly collected through animal studies, primarily of rats and monkeys (Hayes & Faber, 2019; Klein & Braun, 2019). As early as the 1980s, researchers have been aware of the harmful impacts of PFAS exposure poses to offspring, manifesting primarily in low birth weights. Additionally, though not a confirmed carcinogen, studies have linked chemical subsets of PFAS with an increased risk of cancer (Agency for Toxic Substances and Disease Registry, 2020). Still, it was not until 2015 that the military begin to transition from AFFF produced with PFOS and PFOA to a safer short-chain product (Hayes & Faber, 2019).

Although CCLs generated by the EPA through the Safe Drinking Water Act of 1974 seek to limit certain chemicals from being manufactured or imported into the U.S., the list itself is just the first step of many before any actual regulation can occur (Richichi, 2019; Via, 2019). In fact, many chemicals were either grandfathered in prior to the 1996 amendment or their health impacts have not been fully studied (Richichi, 2019).

Between 2000 and 2002, one of the largest manufacturers of PFAS, *3M*®, voluntarily began to phase out its production and import of PFOS. By December of 2002, nearly 100 PFAS chemicals were added to the EPA’s Significant New Use Rule (SNUR) under the Toxic Substances Control Act (TSCA), requiring notification to the EPA before any future manufacture or import. The SNUR still allowed for use of the substance for highly technical purposes in which there were no substitutes, and they would be used in low volume with low exposure and low releases. Ultimately, the EPA's SNURs over the next two decades encompassed PFOS and long-chain PFAS chemical substances (U.S. Environmental Protection Agency, 2020d), resulting in the total ban of PFOA and PFOS (Agency for Toxic Substances and Disease Registry, 2018). Still, more than 3,000 synthetic chemicals classified as PFAS exist today, the majority of which have very little corresponding data (Ross, 2019).

In addition to SNURs, the EPA can redirect around established regulation processes and publish emergency health advisories. In 2009, and again in 2016, the EPA issued provisional drinking water health advisories for both PFOA and PFOS, eventually settling on a health advisory level (HAL) of 0.07 μg/L or 70 ppt. The health advisory cited adverse short- and long-term health effects amongst sensitive subpopulations caused by long-chain PFAS as the reasoning. Although the EPA stated the level was informed by epidemiological studies of human populations exposed to PFAS, both the provisional and final advisories were primarily based on rodent studies (Agency for Toxic Substances and Disease Registry, 2019; U.S. Environmental Protection Agency, 2016a; Via, 2019). In other words, "[t]here is not a body of epidemiology sufficient to provide a basis for a health advisory" (Via, 2019).

The U.S. Congress has been heavily involved with oversight of PFAS production and importations since the early 2000s, and its most notable action to date was with the introduction of House Resolution (H.R.) 535 – PFAS Action Act of 2019. The legislation sought to allow the EPA greater power in regulating PFAS while circumventing previously established regulatory processes and bypassing other environmental laws

(House of Representatives, 2019). A largely partisan bill, H.R. 535 passed in the Democrat-held House of Representatives on 10 January 2020, but was understood as unlikely to pass a Republican-held Senate (Office of Management and Budget, 2020).

Meanwhile on the international stage, governments at the 9th Conference of the Parties (COP9) addressed growing concerns of PFOA. Prominent countries present agreed to a global ban; however, governments also included five-year exemptions for use in various industries (International Pollutants Elimination Network, 2019; Ross, 2019). Of note, China, Iran, and the European Union were granted additional exemptions. This ban comes a decade after nations restricted PFOS use with similar exemptions—exemptions COP9 sought to remove. Another deadline for PFOS production and use in firefighting foams was extended with no defined end in sight (International Pollutants Elimination Network, 2019).

AFFF

Firefighting foams have been utilized by the DoD since the 1960s. The United States Navy (USN), specifically, began development of the foams with the civilian company *3M*® before seeking a patent as early as 1963. However, it was not until four years later did the Navy make its use mandatory (Hayes & Faber, 2019; Korzeniowski et al., 2019).

On 29 July 1967, the USS *Forrestal* (CVA 59) was operating off the coast of Vietnam when an incident occurred that would forever change firefighting products and procedures for not only the military, but for the civilian sector as well. At approximately 11:00 a.m. local time, an F-4 Phantom fighter jet accidentally discharged a rocket prior to takeoff. The immediate aftermath would take the lives of 134 sailors, injure numerous others, and directly result in the modifications and implementations of a more effective firefighting foam, switching from the protein-based foams of the time and moving towards the perfluorinated and fluorine-free compounds widely used today (Kempisty et al., 2019; Ross, 2019; Stewart, 2004). However, within the following decade, questions began to rise concerning the environmental effects of using long-chain perfluoroalkyl substances (Hayes & Faber, 2019), eventually leading to a transition to short-chain use around the turn of the century (United Nations Environment Programme, 2009).

The incredibly strong carbon-fluorine bond coupled with the chemical composition of PFOS and PFOA create an ideal firefighting suppressant. The resulting aqueous film-forming foam (AFFF) has since been highly effective at extinguishing hydrocarbon and polar solvent fires (Interstate Technology Regulatory Council, 2017; Korzeniowski et al., 2019).

In a 2011 study completed by the Naval Research Laboratories, researchers found that AFFF agents extinguished fires "on average 77% faster for gasoline, 88% faster for methylcyclohexane (MCH), and 70% faster for heptane" than its fluorine-free foam counterparts. Furthermore, all gasoline and heptane fires were extinguished "in less than 30 seconds, the time required to pass the United States military specification." The same results were mirrored in multiple studies and tests which included suppression of other fires with different fuels. (Fire Fighting Foam Coalition, 2017). That said, the carbon-fluorine bond works in the opposite direction as well, creating an incredibly robust bond that is difficult to degrade (Wang & Liu, 2020).

It is through the manufacture, application, and resulting pollution of AFFF that most PFAS enter into soil and water sources, subsequentially being exposed to humans and the greater environment, as exemplified in Figure 3. Since AFFF is used to subdue aircraft fires, studies have found areas surrounding military and civilian hangars and training facilities witness a 35 percent increase in groundwater PFOS levels (Rice, 2019). Data collection surrounding industrial sites with a history of AFFF use and landfills also suggested movement of PFAS contaminants via groundwater (Hepburn et al., 2019). Furthermore, PFAS is just as persistent in food sources as it is in water sources, from fish downstream of a FFTA to the packaging paper of microwaveable popcorn (Agency for Toxic Substances and Disease Registry, 2018; Minnesota Department of Health, 2019).

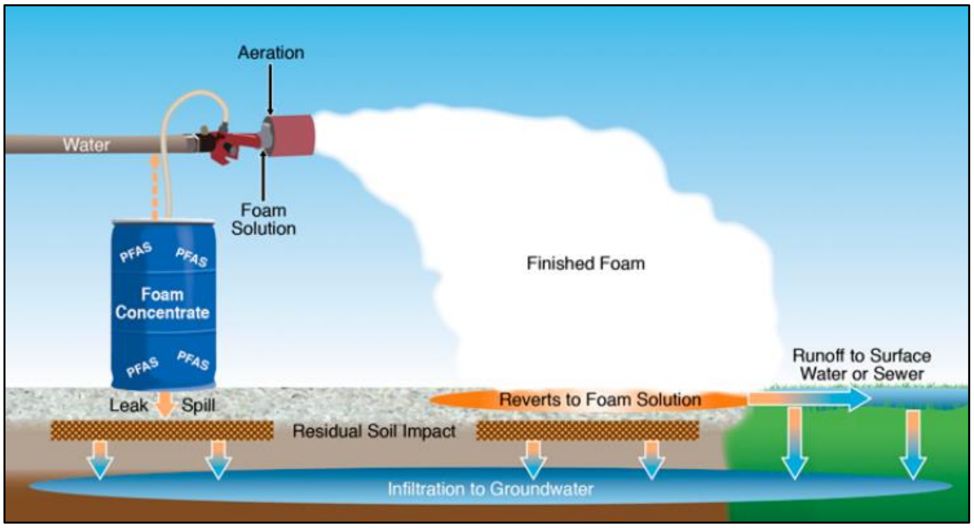


Figure 4: Release of firefighting foam into the environment (Hale, 2016)

Treatment of water and wastewater contaminated by PFAS chemicals is yet to be perfected (Dickenson & Verdugo, 2019). Currently, the most effective water treatment approaches for long-chain PFAS include filtration, sorption, biodegradation, thermal destruction, and advanced reduction (Merino et al., 2016). Sorbents, such as granular activated carbon (GAC), are amongst the most popular methods to achieve treatment of contaminated drinking water (Ross, 2019). The DoD has also experimented with a number of reduction and removal methods, including GAC, incineration, ion exchange, reverse osmosis and nano filtration, and solidification (Headquarters United States Marine Corps, 2020; Spence et al., 2020).

Hangar Fire Suppression System

Today's military aircraft hangars are designed and built with mission accomplishment, cost effectiveness, and environmental compliance in mind. The fire suppression system is one such component; many of the specifications and dimensions have been designed to both support operations and account for AFFF cleanup and removal.

The modern hangar fire suppression system utilizing AFFF agents is incredibly efficient at stopping fires. Hangars tend to house expensive aircraft and parts in addition to the personnel responsible for working on them. Therefore, the priority is to extinguish the fire before any permanent damage can be done, and recent hangar fire suppression systems do just that, especially with regards to the hydrocarbon, Class-B fires most common amongst aircraft. Still, there are many underlying problems with the use of AFFF.

For one, the environment and human populations are impacted in ways not entirely understood. Numerous studies and research efforts have been undertaken to identify the complete extent to which they are impacted from the release of harmful PFAS contaminants via foam escapes, but little is known apart from the potential health effects and persistence, particularly amongst long-chain PFASs.

Another disadvantage revolves around incidental discharges. Incidental discharges occur when the fire suppression system is triggered from something other than a fire within the hangar itself. Some causes include accidental releases by maintenance personnel, lightning strikes, and water leakage into heat detection systems. Consequences include damage to aircraft and equipment, costs associated with cleanup and removal, and even loss of life (Global Aerospace, 2019).

Relevant Flushing Research

Although limited experimentation has been done regarding rinsing solutions for AFFF contamination, fresh water is still the rinsate of choice, per governmental guidance. NAVFAC recommends the following for flushing and rinsing: "After completion of tests, flush all piping carrying AFFF concentrate and solution with fresh water. Piping normally containing AFFF concentrate when the system is in standby mode need not be flushed. Rinse with fresh water all equipment and building surfaces exposed to AFFF discharge" (Naval Facilities, 2020).

Triple rinsing is the standard for cleaning within the scientific community. "The logic behind a triple rinse is that in filling and emptying a vessel three times with water, each time you are diluting by 2 orders of magnitude" (Alconox Inc., 2020). Therefore, after three rinses, a six-order of magnitude reduction of most water-soluble residues should be observed; that is, 99.9999% of the target product should be removed (Alconox Inc., 2020; U.S. Environmental Protection Agency, 2008).

The DoD has adopted a triple rinsing standard for the cleaning of all components of the system that may come into contact with the AFFF foam concentrate (Spence et al., 2020). “Any equipment, piping, and apparatus that are used to remove AFFF products from systems and are identified as waste may be disposed as non-hazardous waste after completion of the triple-rinsing process unless future guidance or regulations impose more stringent requirements for disposal” (Headquarters United States Marine Corps, 2020).

Finally, while there is an abundance of research concerning flow patterns in piping, it is worth noting that very little has been published regarding AFFF movement from source to emitter. Still, previous work (Dewees, Chen, & Gustafsson, 2019) has highlighted that T-intersections, crosses, and other fittings can produce non-ideal flow patterns that may not be entirely captured in this work and act as potential fouling or difficult-to-flush areas.

EPANET

EPANET was the software selected for this particular modeling effort. Having been around in various forms the last several years, EPANET is a Windows-based program utilized to model water distribution systems. Originally designed as a tool to understand fate and movement of drinking water within distribution systems, “engineers and consultants use EPANET to design and size new water infrastructure, retrofit existing aging infrastructure, optimize operations of tanks and pumps, reduce energy usage, investigate water quality problems, and…model contamination threats” (U.S. Environmental Protection Agency, 2020c).

Two features in particular aided in the selection of this program: hydraulic modeling and water quality modeling. The first and major milestone for this effort centered upon a working hydraulic model. The program needed the flexibility to adjust and input various parameters to ensure a realistic simulation of the hangar fire suppression system. Upon establishment of a working hydraulic system, a chemical needed to be introduced in order to trace movement and flushing from origin to expulsion via emitters. Finally, the system needed to accurately portray time in order to analyze and record data accordingly. EPANET is able to provide all of these features and more (U.S. Environmental Protection Agency, 2020c).

III. Methodology

Chapter Overview

The purpose of this chapter is to design the model utilizing available resources via EPANET software, satisfying research objectives along the way. Upon completion of a comprehensive literature review, multiple sources including drawings, TMs, and onsite visits provide the framework for inputs within the program. The full table of inputs have been compiled in the appendices. Results for the simulation are then recorded for analysis and interpretation and can be viewed in Chapter IV.

Literature Review

Upon assignment to the topic, the first step of the methodology was a thorough and detailed review of the literature surrounding not only AFFF and its impacts to the environment, but also of hangars and their respective fire suppression systems. In doing so, a significant gap in research was identified: how much legacy PFAS is retained on fire suppression system components? Although a report was recently published by Naval Facilities Engineering Command in the spring of 2020, their research only examined the tanks housing the foam concentrate and not the pipes, valves, and emitters that comprise the bulk of the system. Still, enough information was obtained to move forward with the construction of the EPANET model.

Creation of the Model

Gathering the appropriate amount of information to model a realistic hangar was time-consuming and required extensive communication with various Air Force and civilian contacts in addition to numerous on-site visits to WPAFB. The first draft of the model was based solely on virtual blueprints of a generic Group I hangar provided by a Record Drawings representative at the Air Force Civil Engineer Center. Although the virtual drawings offered a solid baseline to construct an accurate model, significant information gaps propelled other means of information gathering.

Multiple on-site visits to the 445th Airlift Wing Hangar on WPAFB significantly reduced uncertainties, as physical measurements were taken and hard copies of the actual hangar blueprints were examined. Finally, correspondence with manufacturers and the TMs they provided allowed for a mostly complete picture and subsequent model to be built in EPANET. Outlying information regarding exact dimensions and diameters, particularly in the fire suppression source room, remained unspecified. As a result, and for the sake of simplicity, the intricacies of the source room were omitted to form a streamlined process for the sole purpose of mapping the remaining pipes and nodes. Additionally, the exact pipe lengths, diameters, number of elbows, and elevation of nodes are not entirely known; however, they are estimated to be within a reasonable degree of certainty.

Hydraulic Components

For this particular model, a 14-emitter hangar fire suppression system was selected. The number of foam generators can be solved for based on the rate of discharge (R) formula in Equation 1. Additionally, the number of emitters can be recommended by the manufacturer based on the type of foam concentrate utilized.

$$R = \left(\frac{V}{T} + R_S\right) * C_N * C_L \rightarrow \left(\frac{196{,}905\ ft^3}{4\ min} + 12{,}000\ \frac{ft^3}{min}\right) * 1.15 * 3 = 211{,}231\ \frac{ft^3}{min} \quad 1$$

V = Submergence Volume (ft^3)

T = Submergence Time (min)

R_S = Rate of foam Breakdown by Sprinkler (ft^3/min)

C_N = Compensation for Normal Foam Shrinkage

C_L = Compensation for Leakage

Based on the above calculation and provided blueprints, it was determined that 14 high expansion (HE) foam generators operating at a minimum of 50 psi and delivering at least 15,088 ft^3/min (CFM) of HE foam would suffice for this particular hangar. With the correct number of foam generators identified, the dischargers were then plotted as nodes on EPANET, as seen in Figure 5.

These parameters were thus set based on the example hangar assigned for this particular research. Initial conditions beyond the original inputs provided were used to, most significantly, ensure successful function.

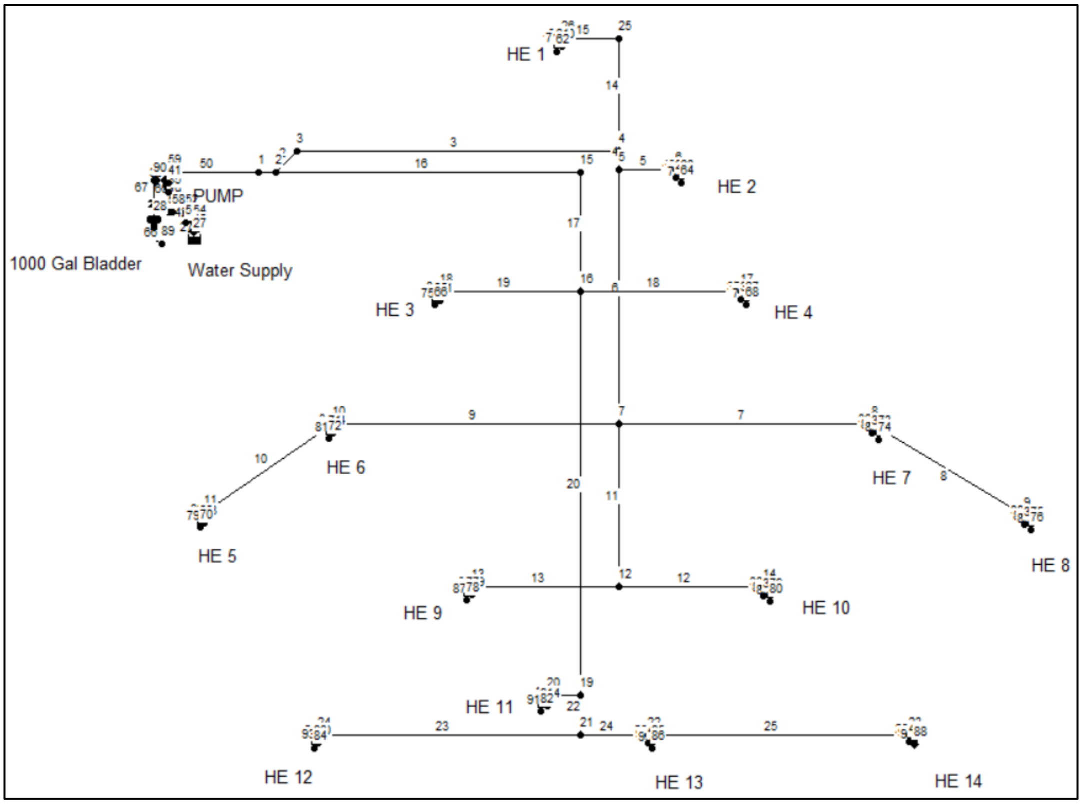


Figure 5: EPANET model prior to simulation

The default characteristics of the emitters within EPANET were left largely unadjusted. As a crucial portion of the system, the emitter’s flow rate can be satisfied via Equation 2. Base demands vary per manufacturer, with ANSUL® recommending 50 gpm for their JET-X High-Expansion Foam Generators (ANSUL, 2019). Of significance, the EPANET model is designed with this flow rate in mind, which may be different than pure water rinsate.

$$q = C\,p^{\gamma} \tag{2}$$

q = Flow Rate (gpm)

C = Discharge Coefficient (gpm/psi$^{0.5}$)

p = Pressure (psi)

γ = Pressure Exponent (0.5 for nozzles and sprinkler heads)

Finally, friction with the pipe walls causes hydraulic head lost and can be computed utilizing the equation below. Of note, EPANET recommends use of the Hazen-Williams headloss (h_L) formula, even though it cannot be used for liquids apart from water. Still, there is an insignificant difference in the density of AFFF (approximately 1.02 ± 0.02 g/ml) (ANSUL, 2015; CHEMGUARD, n.d.) and water (1.0 g/ml) (U.S. Geological Survey, n.d.). Additionally, this particular scenario utilizes a 2 ¾ percent concentrate, thereby accounting for a very minute portion of the total mixture.

$$h_L = Aq^B \tag{3}$$

h_L = Headloss (ft)

A = Resistance Coefficient

q = Flow Rate (gpm)

B = Flow Exponent

The Flow Exponent (B) for the Hazen-Williams formula is 1.852. The Hazen-Williams Resistance Coefficient (A) can be further represented by the following equation:

$$A = 4.727 * C^{-1.852} * d^{-4.871} * L \tag{4}$$

C = Hazen-Williams Roughness Coefficient

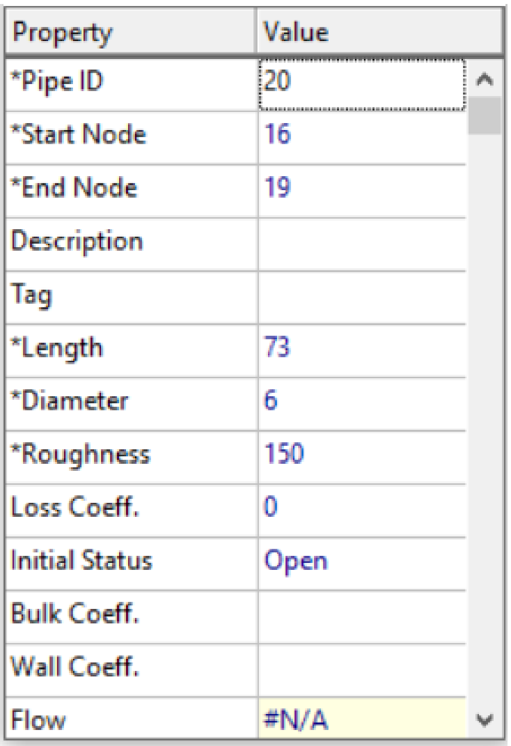
d = Pipe Diameter (ft)

L = Pipe Length (ft)

EPANET also recommends a Hazen-Williams Roughness Coefficient for steel piping at 140-150. Literature and manufacturer TMs recommend classification at the upper echelon of 150 (Building Code Resource Library, 2010; Rossman, 2000).

Physical Components

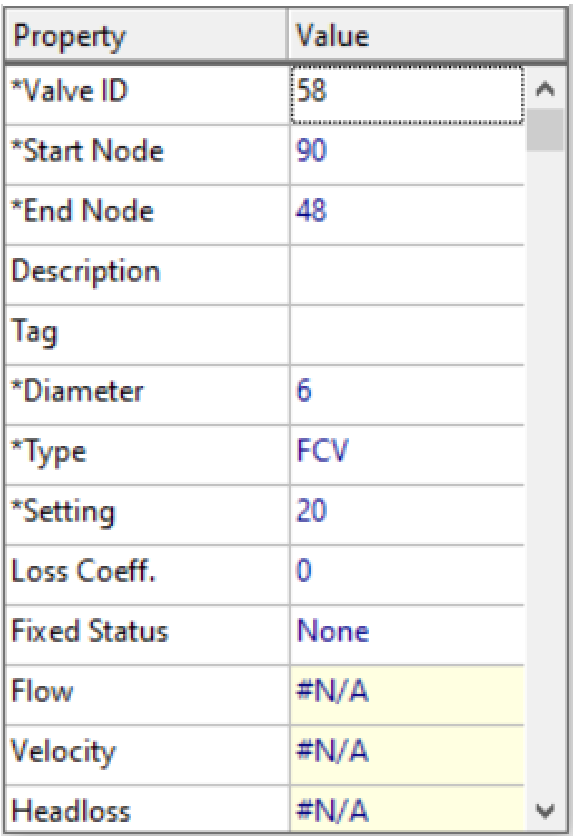
The overall model is comprised of several components, including 14 emitters, 80 pipes, two valves, a pump, a reservoir, and a single 1000-gallon tank for the AFFF concentrate. Pipes are what connects the plotted emitters to the rest of the system, or "links that convey water from one point in the network to another" (Rossman, 2000). Per manufacturer recommendation, and for the sake of simplifying the model, each pipe was classified as 304 stainless steel, thus yielding an overarching roughness coefficient of 150 (ANSUL, 2015). When simulating the model, EPANET considers pipes full at all times. Start and end nodes, length, diameter, and roughness coefficient are deemed principal hydraulic parameters for pipes. Additionally, EPANET allows the pipe's status parameters to be adjusted in order to simulate shutoff (gate) and check (non-return) valves. An example pipe from the model can be seen in Figure 6 below.



Property	Value
*Pipe ID	20
*Start Node	16
*End Node	19
Description	
Tag	
*Length	73
*Diameter	6
*Roughness	150
Loss Coeff.	0
Initial Status	Open
Bulk Coeff.	
Wall Coeff.	
Flow	#N/A

Figure 6: Pipe 20 from EPANET model

The model includes two defined valves, or “links that limit the pressure or flow at a specific point in the network” (Rossman, 2000). While EPANET allows for multiple different types of valves, this model only utilized Flow Control Valves (FCVs) to limit flow to a predetermined rate. Principal input parameters are very similar to those of pipes and include start and end nodes, diameter, setting, and status. For the sake of this research, it was assumed that all emitters must be operated together due to lack of isolation valves within the system. An example valve from the model can be seen in Figure 7 below.

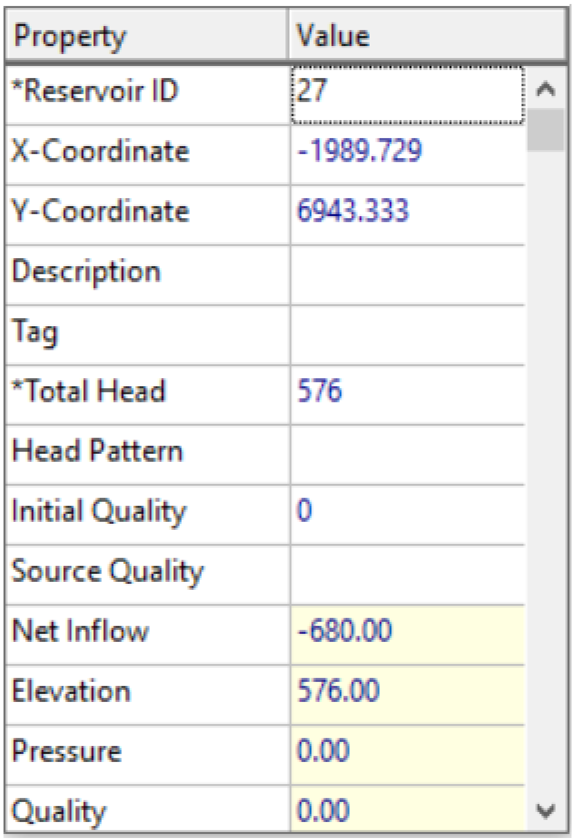


Property	Value
*Valve ID	58
*Start Node	90
*End Node	48
Description	
Tag	
*Diameter	6
*Type	FCV
*Setting	20
Loss Coeff.	0
Fixed Status	None
Flow	#N/A
Velocity	#N/A
Headloss	#N/A

Figure 7: Valve 58 from the EPANET model

EPANET defines pumps as “links that impart energy to a fluid thereby raising its hydraulic head” (Rossman, 2000). Parameter inputs for a pump include its start and end nodes and its pump curve. The pump curve is a mixture of heads and flows that the pump can yield. Of note, flow through the pump is unidirectional and is dictated by user inputs.

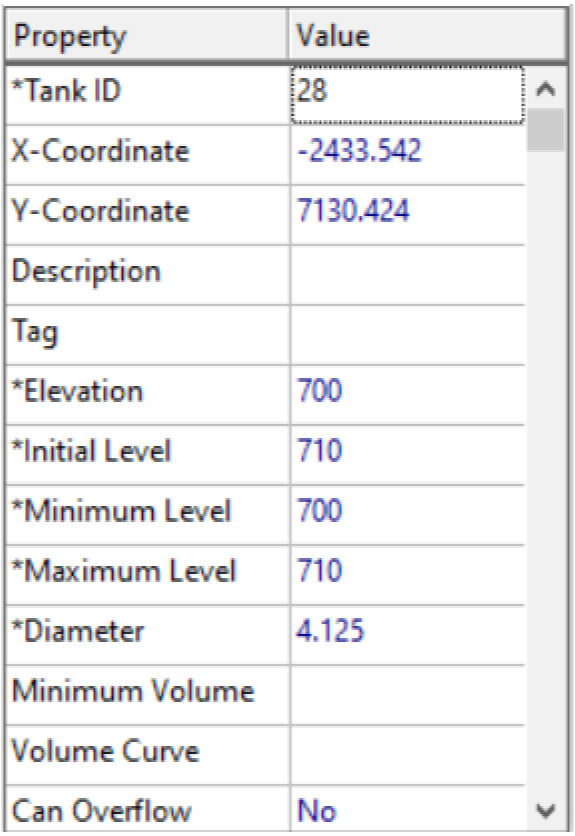
Reservoirs are “nodes that represent an infinite external source or sink of water to the network” (Rossman, 2000). Although hangars are not connected to an infinite source of water, it is useful to treat it as such for the sake of modeling flushing and rinsing until at the EPANET detection value of 0.0 μg/L. Primary inputs for a reservoir include its hydraulic head and its initial chemical quality. The reservoir from the model can be viewed in Figure 8 below.



Property	Value
*Reservoir ID	27
X-Coordinate	-1989.729
Y-Coordinate	6943.333
Description	
Tag	
*Total Head	576
Head Pattern	
Initial Quality	0
Source Quality	
Net Inflow	-680.00
Elevation	576.00
Pressure	0.00
Quality	0.00

Figure 8: Reservoir 27 from the EPANET model

The EPANET model features a single 1000-gallon tank. Tanks are defined within the program as “nodes with storage capacity, where the volume of stored water can vary with time during a simulation" (Rossman, 2000). Primary inputs include initial, minimum and maximum water levels; diameter; and initial water quality. Outputs, computed over time, are water quality and hydraulic head. Tank 28 from the model can be viewed in Figure 9 below.



Property	Value
*Tank ID	28
X-Coordinate	-2433.542
Y-Coordinate	7130.424
Description	
Tag	
*Elevation	700
*Initial Level	710
*Minimum Level	700
*Maximum Level	710
*Diameter	4.125
Minimum Volume	
Volume Curve	
Can Overflow	No

Figure 9: Tank 28 from the EPANET model

Governing Equations

The major impetus for use of the EPANET software was its water quality solver. Governing equations for it are dictated by reaction kinetics coupled with the principles of conservation of mass. Advective transport in pipes, that is "a dissolved substance will travel down the length of a pipe with the same average velocity as the carrier fluid while at the same time reacting (either growing or decaying) at some given rate" can be represented by the Equation 5. PFAS is environmentally stable and extremely difficult to breakdown; therefore, the reaction rate was set to 0.

$$\frac{dC_i}{dt} = -u_i \frac{dC_i}{dx} + r(C_i) \tag{5}$$

u_i = Flow Velocity (ft/sec) in Pipe *i*

C_i = Concentration (µg/L) in Pipe *i* as a Function of Distance *x* and time *t*

r = Rate of Reaction (µg/L/sec) as a Function of Concentration

Additionally, the flow velocity can further be described through the Bernoulli equation below, in which the total pressure is equal to the sum of the static pressure and dynamic pressure and is constant along a streamline. In this particular scenario, the elevations are considered negligible and thus zeroed out.

$$\frac{p_1}{\rho} + \frac{{u_1}^2}{2} + gz_1 = \frac{p_2}{\rho} + \frac{{u_2}^2}{2} + gz_2 + h_L \tag{6}$$

p = Pressure (psi)

ρ = Fluid Density (lb_m/ft^3)

u = Flow Velocity (ft/sec)

g = Gravity (32.2 ft/sec^2)

z = Elevation (ft)

h_L = Headloss (ft)

In terms of bulk flow reaction, the model uses first-order decay, exemplified by Equation 7. Of note, the reaction constant is unknown for this particular contaminant; therefore, the model assumed zero decay. This model utilizes an input of 0.00 for reaction rate.

$$r = kC^n \qquad 7$$

r = Rate of Reaction (µg/L/sec)

k = Reaction Constant (sec^{-1})

C = Concentration (µg/L)

n = Reaction Order (first order decay)

Based upon the given AFFF concentrate of 2 ¾ percent used in this particular scenario, an initial concentration, or quality, of the chemical throughout the system is determined to be approximately 2.86E07 µg/L. Concentration levels are monitored in timesteps of 10 seconds in order to trace the overall movement of the chemical and determine "hot spots" where potential accumulation of the chemical may occur.

Cost Modeling

Finally, a rudimentary cost comparison between rinsing and replacing can be made. While the cost to replace an entire system is largely dependent upon existing system type, components, and geographical location, generic system treatment prices can be made utilizing the following equation:

$$System\ cost = (flush\ volume) * (\$/gal) \qquad 8$$

Summary

This chapter details the process involved with creating the EPANET model and the scope of governing equations the software utilizes. Additionally, this chapter portrays the magnitude of inputs required to produce a useful model, from blueprints and TMs to onsite visits and email correspondence. Detailed tables of initial conditions can be found in Appendix A.

IV. Analysis and Results

Chapter Overview

This chapter reviews the results produced from the simulated model within EPANET and compares them to that of the theoretical triple rinse. Consideration is also given to the costs differences between rinsing or replacing an entire hangar fire suppression system.

Results of EPANET Simulation

It is important to note that the data to support an accurate simulation of adsorption and desorption of PFAS chemicals is currently unavailable and thus rendered negligible. Therefore, the program portrays perfect removal of the concentrate based on initial conditions and the hydraulics provided. Figure 10 depicts an EPANET snapshot at the roughly two-minute flush mark of the entire system. Predictably, the nodes farthest from the source are last to expel the contaminant. This is due to their distance from the source in addition to the various intersections the chemical encounters as it makes its way to the emitters. It is these intersections which may manifest as “hot spots” for the contaminant as it moves from its point of origin to point of expulsion. Still, continuous flushing, evidenced with the time series simulation, quickly expels contaminants at these potential chokepoints. Of significance, one of the closest emitters to the source, Node 62, is also one of the last to completely emit the chemical. This may be due to myriad reasons, including the various intersections the contaminant passes through prior to emission.

Applying the aforementioned initial conditions found within the Methodology section of this report, the chemical is fully expelled from the system within three minutes of flushing. Table 1 displays the chemical concentration over time for each emitter, and Figure 11 is a graphical representation of the tabulated data presented in Table 1.

When running the simulation over time, multiple potential fouling locations are identified. These include T-intersections, like the ones found at Nodes 16 and 7, and intersections and elbows where the pipe diameters decrease from six inches to two inches. Graphical depictions of each individual emitter can be found in Appendix B.

Fresh water flowing from the source room enters into the system at a rate of 680 gallons per minute (gpm). After approximately three minutes of flushing, the value for all emitter concentrations equals zero. Therefore, roughly 2,040 gallons of water has flowed through the system in order to reach that sum.

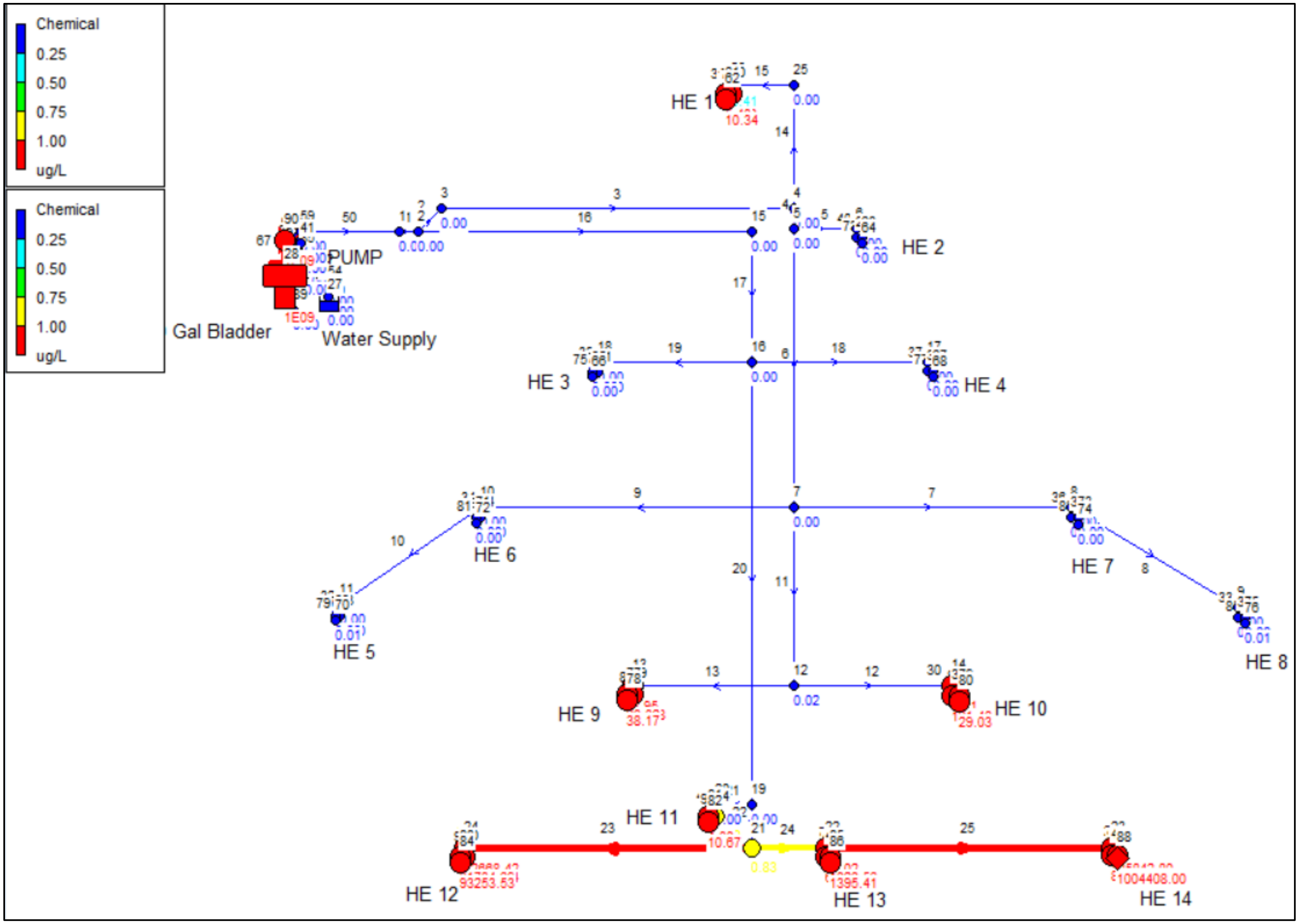


Figure 10: Simulated model at two-minute flush mark

Table 1: Chemical concentration for emitters at time 0:00:00 to 0:03:00

	Chemical Concentration (ug/L)													
Time (mins)	Node 62	Node 64	Node 66	Node 68	Node 70	Node 72	Node 74	Node 76	Node 78	Node 80	Node 82	Node 84	Node 86	Node 88
0:00:00	2.86E+07	2.86E+07	2.86E+07	2.86E+07	2.86E+07	2.86E+07	2.86E+07	2.86E+07	2.86E+07	2.86E+07	2.86E+07	2.86E+07	2.86E+07	2.86E+07
0:00:10	2.86E+07	2.86E+07	2.86E+07	2.86E+07	2.86E+07	2.86E+07	2.86E+07	2.86E+07	2.86E+07	2.86E+07	2.86E+07	2.86E+07	2.86E+07	2.86E+07
0:00:20	2.86E+07	1.69E+07	2.82E+07	2.83E+07	2.86E+07	2.86E+07	2.86E+07	2.86E+07	2.86E+07	2.86E+07	2.86E+07	2.86E+07	2.86E+07	2.86E+07
0:00:30	2.86E+07	5343994	2.34E+07	2.40E+07	2.83E+07	2.28E+07	2.23E+07	2.83E+07	2.86E+07	2.86E+07	2.86E+07	2.86E+07	2.86E+07	2.86E+07
0:00:40	2.86E+07	937018.7	1.08E+07	1.21E+07	2.23E+07	1.11E+07	1.06E+07	2.18E+07	2.86E+07	2.86E+07	2.86E+07	2.86E+07	2.86E+07	2.86E+07
0:00:50	2.86E+07	93999.33	1813753	2097407	1.08E+07	3112963	2943598	1.03E+07	2.54E+07	2.49E+07	2.84E+07	2.86E+07	2.86E+07	2.86E+07
0:01:00	2.36E+07	5416.31	112804.3	132191.3	3007782	508622.6	476494.2	2843960	1.62E+07	1.51E+07	2.56E+07	2.86E+07	2.84E+07	2.86E+07
0:01:10	1.16E+07	175.06	2698.83	3177.39	490054.9	48875.27	45517.42	459088.4	6570455	5756373	1.62E+07	2.84E+07	2.54E+07	2.86E+07
0:01:20	2973448	3.03	28.94	34.14	47012.1	2742.29	2544.3	43781.87	1630693	1359716	5280159	2.64E+07	1.58E+07	2.84E+07
0:01:30	388970.5	0.03	0.14	0.16	2635.06	87.21	80.72	2444.81	246321.5	197957	746692.6	1.88E+07	4882884	2.56E+07
0:01:40	24772.99	0	0	0	83.75	1.5	1.38	77.52	22516.79	17631.95	43216.57	7769701	697134.4	1.65E+07
0:01:50	712.08	0	0	0	1.44	0.01	0.01	1.33	1223.94	941.68	1007.19	1320860	45352.8	5696148
0:02:00	10.34	0	0	0	0.01	0	0	0.01	38.17	29.03	10.67	93262.38	1395.64	1004408
0:02:10	0.08	0	0	0	0	0	0	0	0.65	0.49	0.05	2975.63	22.13	91768.59
0:02:20	0	0	0	0	0	0	0	0	0.01	0	0	48.06	0.18	4423.62
0:02:30	0	0	0	0	0	0	0	0	0	0	0	0.4	0	119.81
0:02:40	0	0	0	0	0	0	0	0	0	0	0	0	0	1.87
0:02:50	0	0	0	0	0	0	0	0	0	0	0	0	0	0.02
0:03:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0

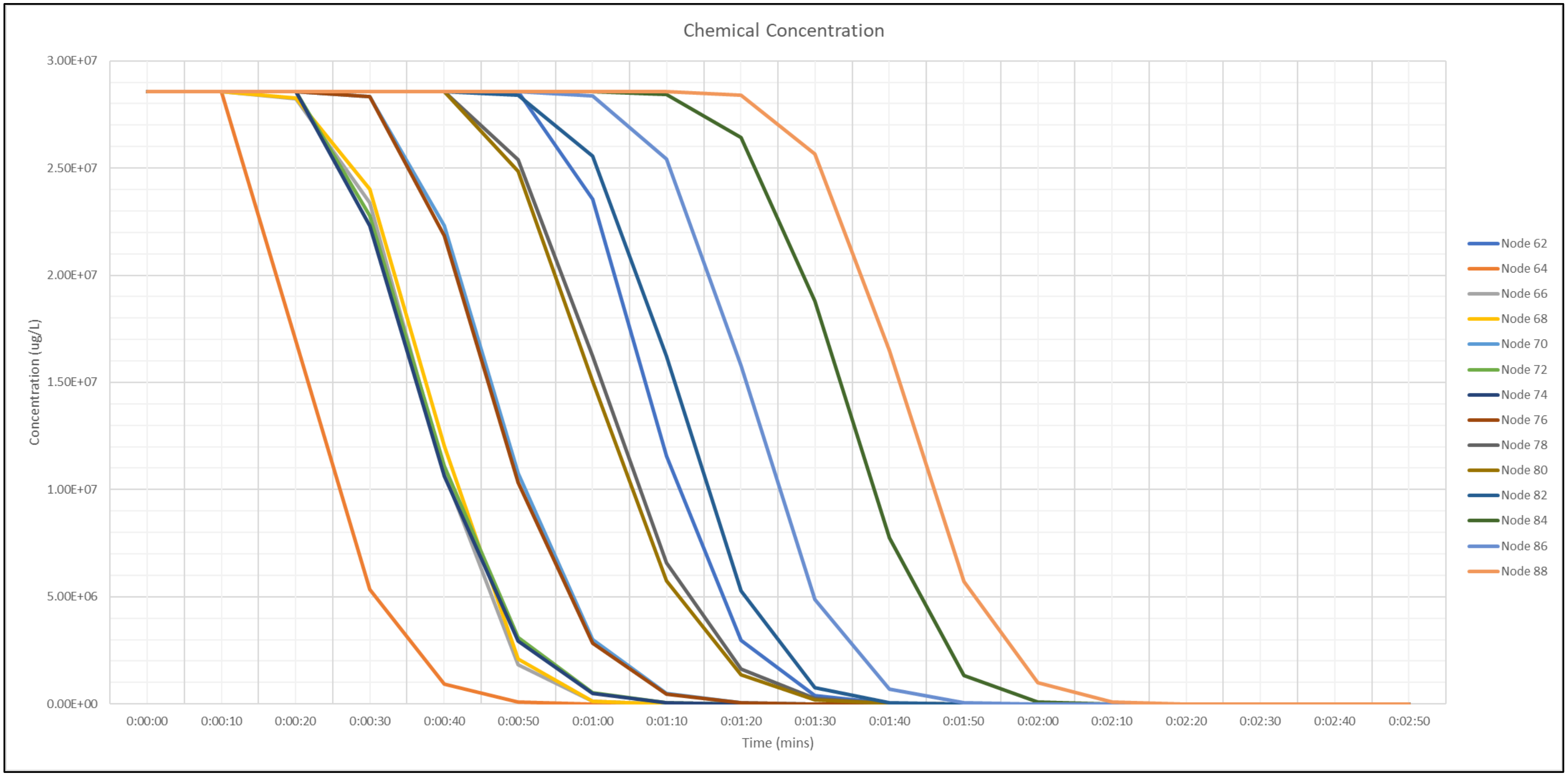


Figure 11: Total emitter chemical concentration vs time

Results of Theoretical Triple Rinse

Theoretically, a triple rinse should result in a six-log reduction of the initial concentration of the contaminant within the system, as seen in Equation 8 below.

$$C = (0.0001\%)(C_0) \qquad 8$$

C = Final Concentration (µg/L)

C_0 = Initial Concentration (µg/L)

For an initial concentration of 28,579,670 µg/L, the resulting six-log reduction, or 99.9999% removal, should yield a final concentration of 28.5797 µg/L or ppb. This is well below the 800 ppb the Navy is seeking to achieve but still several orders of magnitude larger than the 70 ppt LHA sought by the EPA.

A single rinse is defined as 100 percent of the piping volume, while a triple rinse is 300 percent. The overall volume of the piping, excepting the source room, is 68.177 ft^3, or approximately 510 gallons. Therefore, the total volume of the rinsate produced from a triple rinse is 1,530 gallons, or 510 gallons less than that of the EPANET model to fully expel the chemical from the system. At 680 gpm, it would take 2.25 minutes, or 00:02:15, in order to flush 1,530 gallons through the piping. As displayed in Table 1, the chemical concentrations are not zeroed out entirely for the 00:02:10 and 00:02:20 marks, particularly at the emitters farthest away from the source. Still, half the emitters have reached a concentration of 0.0 µg/L, while the remainder have approached the value calculated from the six-log reduction. Furthermore, an average of all emitter concentrations at 00:02:10 and 00:02:20 yields a concentration of 3,544.68 µg/L—quickly approaching the desired 800 ppb sought by the DoD.

Cost Analysis

The costs associated with rinsing hangar fire suppression systems varies by a multitude of factors, including but not limited to the disposal of wastewater and the replacement of AFFF. Some of the more popular treatment types and their associated costs can be seen in Table 2 below. According to the Engineering Manager responsible for all AFFF replacement projects at MSE Group®, a prominent international environmental, engineering, and construction firm, "Rough order costs for removal, disposal of AFFF and rinsate, and replacement with modern AFFF is roughly $40 - $50 per gallon for turn-key" (Bogert & Spaulding, 2021). Therefore, in order to successfully flush the modeled system with 2,040 gallons of fresh water, it would cost upwards of $102,000. "Solidification/landfill, which involves mixing the AFFF wastewater or concentrate with cement to make a solid mass to haul to a landfill, is another potential option, but can be expensive or restricted depending on state landfill requirements regarding PFAS" due to its susceptibility to leaching (Spence et al., 2020).

Table 2: Cost analysis for potential treatment types (Spence et al., 2020)

Treatment Type	Cost ($/gal)	Cost ($/System)	Pros	Cons
Incineration	$ 4.21	$ 8,588.40	No discharge limits. Cheap.	Geographical limitations.
Electro-chemical and ion-exchange	$ 1.20	$ 2,448.00	Below HAL. Cheap.	High volume of wastewater needed.
GAC	$ 0.13	$ 265.20	Effective at PPT or low PPB ranges.	Very expensive at high volumes. Geographical limitations.

Similar to the rinsing, a full replacement differs considerably depending on the system size and type in addition to aforementioned disposal/treatment methods. "Rough order of magnitude costs for the replacement of a two-tank bladder mechanical system would be approximately $150,000 to $250,000. This includes removal and disposal of existing AFFF (up to 1,000 gallons), rinsing of components, disposal of rinsate, installation of new tanks and proportioners, and filling the system with modern AFFF (or alternate product)" (Bogert & Spaulding, 2021). Replacement of the contaminated piping with new would incur a separate cost, about $36,500 for this example hangar based on current market prices. Testing and certification of the newly installed system would introduce still more costs, along with the removal and disposal of contaminated components. Consequently, the price to rinse legacy AFFF and to replace with a more environmental-friendly substitute is significantly lower than the price to fully replace all components of an existing hangar fire suppression system.

Summary

This chapter reviewed the results produced from the simulated EPANET model and compared to those of a theoretical triple rinse. Consideration was also given to economic impacts. While the model reached the hypothesized chemical levels sought, it took an additional 30-40 seconds and 510 gallons to do so. Still, the effects and associated costs of flushing the system an extra half-minute far outweigh the economic impacts of fully replacing all components within it.

V. Conclusions and Recommendations

Chapter Overview

This chapter serves to summarize findings for this paper and outline their significance. Recommendations for both follow-on actions and future research are presented.

Conclusions of Research

A digital model of a Group I aircraft hangar fire suppression system was constructed utilizing EPANET software. Inputs were gathered almost entirely from open-source resources and in-person measurements, while the remainder were fabricated to allow the model to run successfully and optimize efficiency for flushing.

Additionally, a simple cost analysis was conducted to compare rinsing and replacing prices. Based on limited information and the highly unique ramifications for each case, a generic comparison was made and found to significantly favor the side of rinsing.

The research served largely to answer the Research Objectives laid out in Chapter I and to confirm the hypotheses associated with each.

1. How effective is the triple rinse technique in removing legacy PFAS from a hangar fire suppression system?

Various shortcomings for utilization of the EPANET modeling system existed for the purpose of this research, and many assumptions were made to combat uncertainties. Most significant was the assumption of perfect removal of the contaminant occurred within the system due to flushing; additional research is needed to address whether PFAS adsorbs to stainless steel pipes to any significant degree.

The EPANET model resulted in a zero-detect concentration of the contaminant within three minutes of flushing the system with 2,040 gallons of water while the theoretical triple-rinse led to an average emitter concentration of approximately 29 ppb at the 00:02:15 mark after flushing with 1,530 gallons. With these results, it is probable that the current triple rinse standard operating procedure for the DoD is effective, both from an environmental and economic standpoint, providing support of the first hypothesis.

2. In modeling the system, can any specific/potential areas of adsorption be identified and/or mitigated?

The assumption of perfect removal from the outset of this research did not aid in definitively confirming areas of adsorption within the model. However, when running the simulation, potential "hot spots" were identified within the system. Namely, these included various elbows throughout, in addition to areas where two differing-diameter pipes intersected. Although a delay in chemical expulsion was expected at these junctions, continuous flushing ultimately proved to fully oust the contaminant from the system with little delay.

Significance of Research

PFAS, a contaminant known for decades to affect both the environment and humans, is still prominent in multiple facets of day-to-day life. Its more harmful inclusion in long-chain form within legacy fire-fighting foams creates a priority for removal from existing hangar fire suppression systems by both the DoD and EPA.

EPANET software has never been applied to model a hangar fire suppression system but serves to further confirm the effectiveness of the theorized triple rinse technique enforced by the DoD and its civilian counterparts. Still, there are some minor disparities between the results anticipated and the results produced, though lack of precise measurements and input details are likely to blame. Regardless, the DoD should invest in further experimentation similar to NAVFAC EXWC, except the focus should be on the system's piping rather than the system's bladder.

A very rudimentary cost analysis was applied as well, setting a foundation for follow-on research and investigation. As existing removal and treatment techniques become more efficient and cost-effective, and future technologies and solutions applied, detailed cost-benefit studies will need to be applied accordingly. For now, rinsing appears to be the most economical approach.

Recommendations for Action

A bench scale model should be constructed based on the EPANET model, and a chemical trace study should be conducted to confirm the results produced in this paper. Focus should be on both the success of the rinsing and effectiveness of the hydraulics. Then, separate tests for PFAS adsorption should be applied to various lengths, diameters, and sections of the fire suppression system's pipes.

Recommendations for Future Research

Future research surrounding adsorption of legacy AFFF contaminants on surfaces, specifically those utilized in hangar fire suppression systems, should be prioritized. Furthermore, methods comparable to those employed by NAVFAC EXWC could be applied to different segments of pipe rather than tanks to note effectiveness of cleaning techniques. Similarly, a complete hydraulics optimization profile should be conducted in order to cover all realistic and theoretical pump curves for the system. Then, the model can be adjusted accordingly, and more accurate results can be produced. Additionally, a thorough cost analysis for the various removal, treatment, and disposal techniques should be pursued. Consideration should be given to the volume of wastewater produced, concentration of wastewater, and geographical location.

Summary

PFAS is a chemical under scrutiny to environmentalists and industrialists alike. Its persistence in the environment and mobility within some mediums coupled with its bioaccumulative and toxic characteristics make it of chief concern within the air transportation and fire suppression communities. Triple rinsing a hangar fire suppression system, while effective on paper and within EPANET modeling, may not be the definitive answer. The DoD, in conjunction with the EPA, should continue pursuing further research on flushing techniques, adsorption, and costs encompassing legacy PFAS contaminants and hangar fire suppression systems.

Appendix A

Table 3: Initial conditions for pipe lengths and diameters

Link ID	Start Node	End Node	Length (ft)	Diameter (in)
1	1	2	10	6
2	2	3	4	6
3	3	4	53.5	6
4	4	5	2	6
5	5	6	14	2
6	5	7	43	6
7	7	8	48	2
8	8	9	49	2
9	7	10	52	2
10	10	11	49	2
11	7	12	29	6
12	12	14	15	2
13	12	13	20	2
14	4	25	26	6
15	25	26	16.5	2
16	2	15	53.5	6
17	15	16	29	6
18	16	17	26	2
19	16	18	22	2
20	16	19	73	6
21	19	20	14	2
22	19	21	15	6
23	21	24	76	2
24	21	22	18	2
25	22	23	62	2
26	40	24	3	2
28	42	22	3	2
29	43	23	3	2
30	38	14	3	2
31	39	13	3	2
32	33	11	3	2
33	37	9	3	2
34	34	10	3	2
36	36	8	3	2
37	32	17	3	2
38	31	18	3	2

39	26	30	.5	2
40	29	6	3	2
41	44	20	3	2
49	49	51	.5	6
51	52	53	1	6
52	53	54	1	6
61	51	58	.5	6
62	58	52	1	6
65	48	59	1	6
70	62	61	.5	2
71	61	30	.5	2
72	29	63	.5	2
73	63	64	.5	2
74	65	31	.5	2
75	65	66	.5	2
76	32	67	.5	2
77	67	68	.5	2
78	69	33	.5	2
79	69	70	.5	2
80	71	34	.5	2
81	71	72	.5	2
82	36	73	.5	2
83	73	74	.5	2
84	37	75	.5	2
85	75	76	.5	2
86	39	77	.5	2
87	77	78	.5	2
88	38	79	.5	2
89	79	80	.5	2
90	44	81	.5	2
91	81	82	.5	2
92	84	83	.5	2
93	83	40	.5	2
94	42	85	.5	2
95	85	86	.5	2
96	43	87	.5	2
97	87	88	.5	2
50	59	1	.5	4
60	49	35	10	6
63	41	48	1	6
66	89	28	1	4
67	28	90	10	6

27	27	45	2	10
35 Pump	35	41	#N/A	#N/A
58 Valve	90	48	#N/A	6
42 Valve	45	54	#N/A	12

Table 4: Initial conditions for demand, head, pressure, and quality

Node ID	Demand GPM	Head ft	Pressure psi	Quality ug/L
2	0.00	66.86	27.67	0.00
3	0.00	66.82	27.65	0.00
4	0.00	66.27	-1.62	0.00
5	0.00	66.25	-1.63	0.00
6	0.00	65.59	-1.91	0.00
7	0.00	65.99	-1.74	0.00
8	0.00	57.89	-0.92	0.00
9	0.00	55.60	0.69	0.00
10	0.00	57.21	-1.21	0.00
11	0.00	54.92	0.40	0.00
12	0.00	65.96	-1.75	0.00
13	0.00	65.03	0.45	0.00
14	0.00	65.26	0.55	0.00
15	0.00	66.54	-1.50	0.00
16	0.00	66.36	-1.58	0.00
17	0.00	65.14	0.50	0.00
18	0.00	65.33	0.58	0.00
19	0.00	66.15	-1.67	0.00
20	0.00	65.49	-1.95	0.00
21	0.00	66.12	-1.68	0.00
22	0.00	63.09	-3.00	0.00
23	0.00	60.19	0.08	0.00
24	0.00	62.57	1.11	0.00
25	0.00	66.26	-1.62	0.00
26	0.00	65.49	-1.95	0.00
29	0.00	65.45	-1.97	0.00
30	0.00	65.46	-1.97	0.00
31	0.00	65.19	0.52	0.00
32	0.00	65.00	0.44	0.00
33	0.00	54.78	0.34	0.00

34	0.00	57.07	-1.27	0.00
36	0.00	57.75	-0.98	0.00
37	0.00	55.46	0.63	0.00
38	0.00	65.12	0.49	0.00
39	0.00	64.89	0.38	0.00
40	0.00	62.43	1.05	0.00
42	0.00	62.95	-3.06	0.00
43	0.00	60.05	0.02	0.00
44	0.00	65.35	-2.01	0.00
48	0.00	67.29	27.86	0.00
49	0.00	-89.72	-40.17	0.00
51	0.00	-89.70	-40.17	0.00
52	0.00	-89.66	-40.15	0.00
53	0.00	-89.63	-40.14	0.00
54	0.00	-89.60	-40.13	0.00
58	0.00	-89.69	-40.16	0.00
59	0.00	67.26	27.85	0.00
61	0.00	65.44	-1.98	0.00
62	50.00	65.42	-1.99	0.00
63	0.00	65.43	-1.98	0.00
64	50.00	65.41	-1.99	0.00
65	0.00	65.17	0.51	0.00
66	50.00	65.14	0.50	0.00
67	0.00	64.98	0.43	0.00
68	50.00	64.96	0.41	0.00
69	0.00	54.76	0.33	0.00
70	50.00	54.73	0.32	0.00
71	0.00	57.05	-1.28	0.00
72	50.00	57.03	-1.29	0.00
73	0.00	57.72	-0.99	0.00
74	50.00	57.70	-1.00	0.00
75	0.00	55.43	0.62	0.00
76	50.00	55.41	0.61	0.00
77	0.00	64.86	0.37	0.00
78	50.00	64.84	0.36	0.00
79	0.00	65.10	0.48	0.00
80	50.00	65.07	0.47	0.00
81	0.00	65.33	-2.02	0.00
82	50.00	65.31	-2.03	0.00
83	0.00	62.41	1.04	0.00
84	50.00	62.38	1.03	0.00
85	0.00	62.92	-3.07	0.00

86	50.00	62.90	-3.08	0.00
87	0.00	60.02	0.01	0.00
88	50.01	60.00	0.00	0.00
35	0.00	-89.99	-40.29	0.00
41	0.00	67.32	27.87	0.00
89	0.00	1410.00	609.65	0.00
90	0.00	1410.00	609.65	0.00
45	0.00	576.00	249.58	0.00
27 Reservoir	-680.00	576.00	0.00	0.00
28	-20.01	1410.00	307.64	1E09 Tank

Table 5: Initial conditions for flow, velocity, and headloss

Link ID	Flow GPM	Velocity fps	Headloss ft/Kft	Status
1	700.01	7.94	29.39	Open
2	400.00	4.54	10.43	Open
3	400.00	4.54	10.43	Open
4	350.00	3.97	8.14	Open
5	50.00	5.11	46.74	Open
6	300.00	3.40	6.12	Open
7	100.00	10.21	168.73	Open
8	50.00	5.11	46.74	Open
9	100.00	10.21	168.73	Open
10	50.00	5.11	46.74	Open
11	100.00	1.13	0.80	Open
12	50.00	5.11	46.74	Open
13	50.00	5.11	46.74	Open
14	50.00	0.57	0.22	Open
15	50.00	5.11	46.74	Open
16	300.01	3.40	6.12	Open
17	300.01	3.40	6.12	Open
18	50.00	5.11	46.74	Open
19	50.00	5.11	46.74	Open
20	200.01	2.27	2.89	Open
21	50.00	5.11	46.74	Open
22	150.01	1.70	1.70	Open
23	50.00	5.11	46.74	Open
24	100.01	10.21	168.75	Open
25	50.01	5.11	46.75	Open
26	-50.00	5.11	46.74	Open

28	-50.00	5.11	46.74	Open
29	-50.01	5.11	46.75	Open
30	-50.00	5.11	46.74	Open
31	-50.00	5.11	46.74	Open
32	-50.00	5.11	46.74	Open
33	-50.00	5.11	46.74	Open
34	-50.00	5.11	46.74	Open
36	-50.00	5.11	46.74	Open
37	-50.00	5.11	46.74	Open
38	-50.00	5.11	46.74	Open
39	50.00	5.11	46.74	Open
40	-50.00	5.11	46.74	Open
41	-50.00	5.11	46.74	Open
49	-680.00	7.72	27.85	Open
51	-680.00	7.72	27.86	Open
52	-680.00	7.72	27.85	Open
61	-680.00	7.72	27.86	Open
62	-680.00	7.72	27.85	Open
65	700.01	7.94	29.40	Open
70	-50.00	5.11	46.75	Open
71	-50.00	5.11	46.74	Open
72	50.00	5.11	46.74	Open
73	50.00	5.11	46.74	Open
74	-50.00	5.11	46.74	Open
75	50.00	5.11	46.74	Open
76	50.00	5.11	46.74	Open
77	50.00	5.11	46.74	Open
78	-50.00	5.11	46.74	Open
79	50.00	5.11	46.74	Open
80	-50.00	5.11	46.74	Open
81	50.00	5.11	46.74	Open
82	50.00	5.11	46.74	Open
83	50.00	5.11	46.74	Open
84	50.00	5.11	46.74	Open
85	50.00	5.11	46.74	Open
86	50.00	5.11	46.74	Open
87	50.00	5.11	46.74	Open
88	50.00	5.11	46.74	Open
89	50.00	5.11	46.74	Open
90	50.00	5.11	46.74	Open
91	50.00	5.11	46.74	Open
92	-50.00	5.11	46.74	Open

93	-50.00	5.11	46.74	Open
94	50.00	5.11	46.74	Open
95	50.00	5.11	46.74	Open
96	50.01	5.11	46.75	Open
97	50.01	5.11	46.75	Open
50	700.01	17.87	211.82	Open
60	680.00	7.72	27.86	Open
63	680.00	7.72	27.85	Open
66	0.00	0.00	0.00	Open
67	20.01	0.23	0.04	Open
27	680.00	2.78	2.32	Open
35 Pump	680.00	0.00	-157.32	Open
58 Valve	20.01	0.23	1342.71	Active
42 Valve	680.00	1.93	665.60	Active

Appendix B

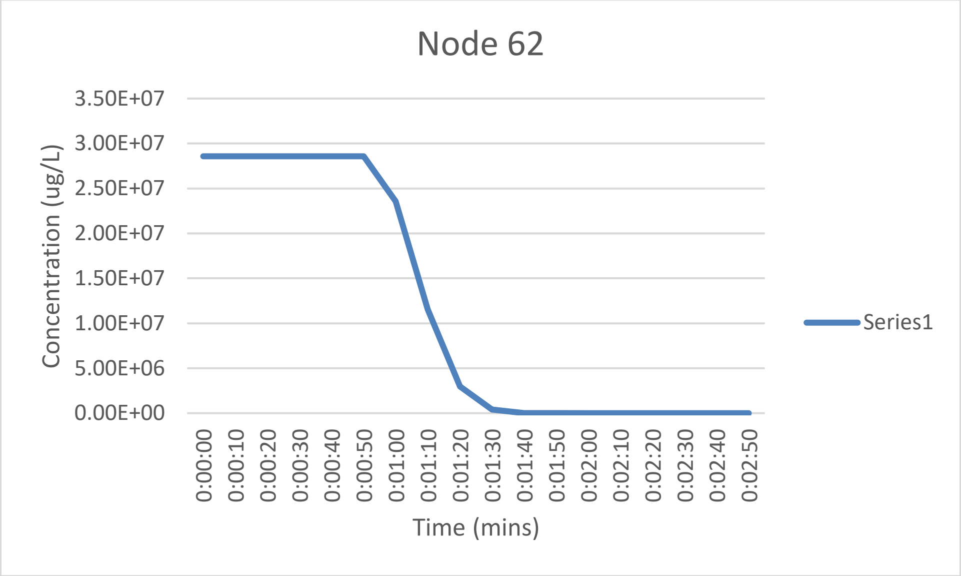


Figure 12: Emitter 62 concentration vs time

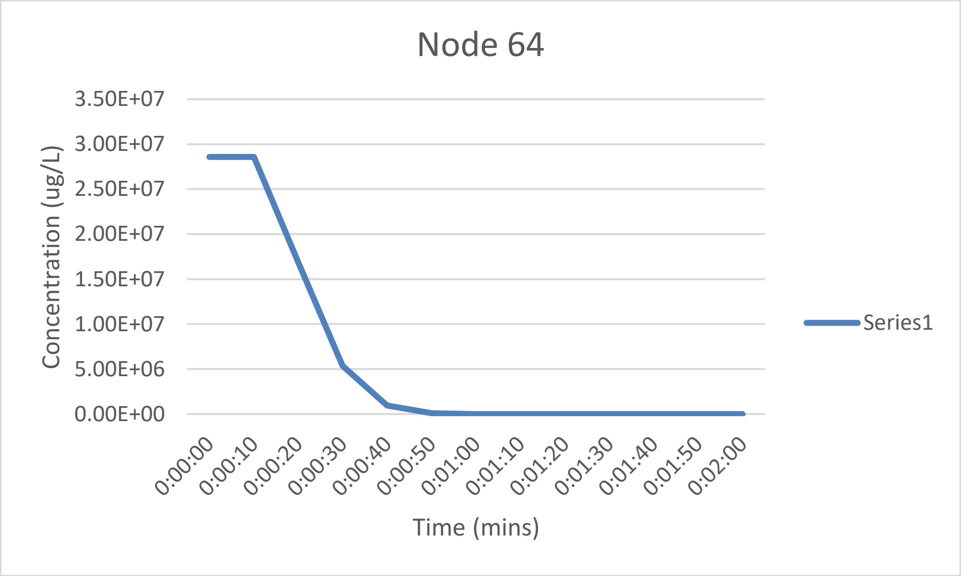


Figure 13: Emitter 64 concentration vs time

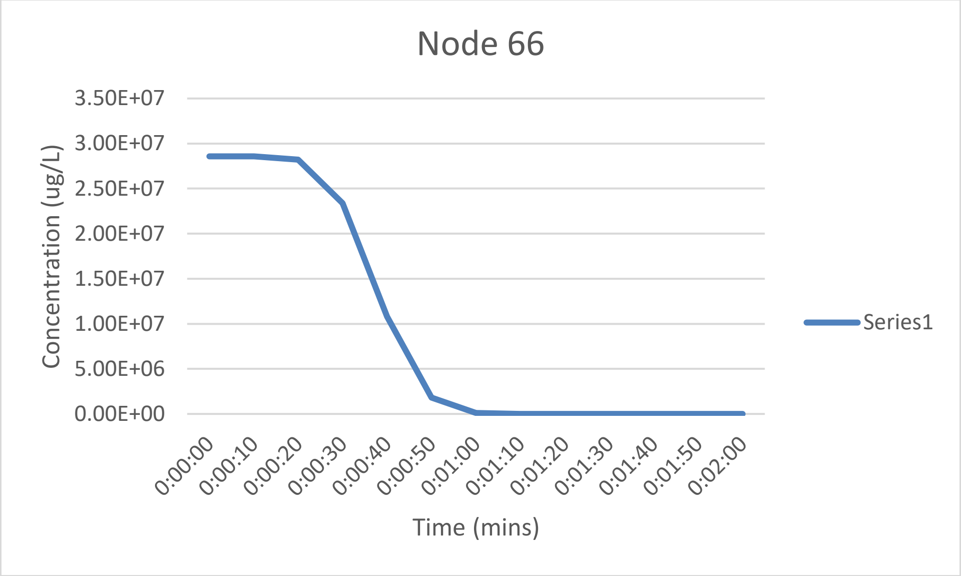


Figure 14: Emitter 66 concentration vs time

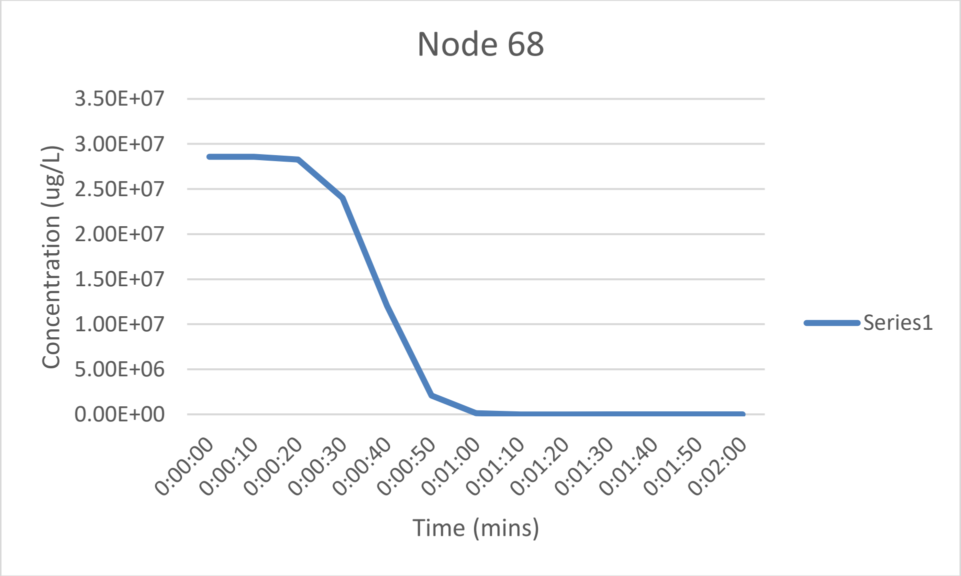


Figure 15: Emitter 68 concentration vs time

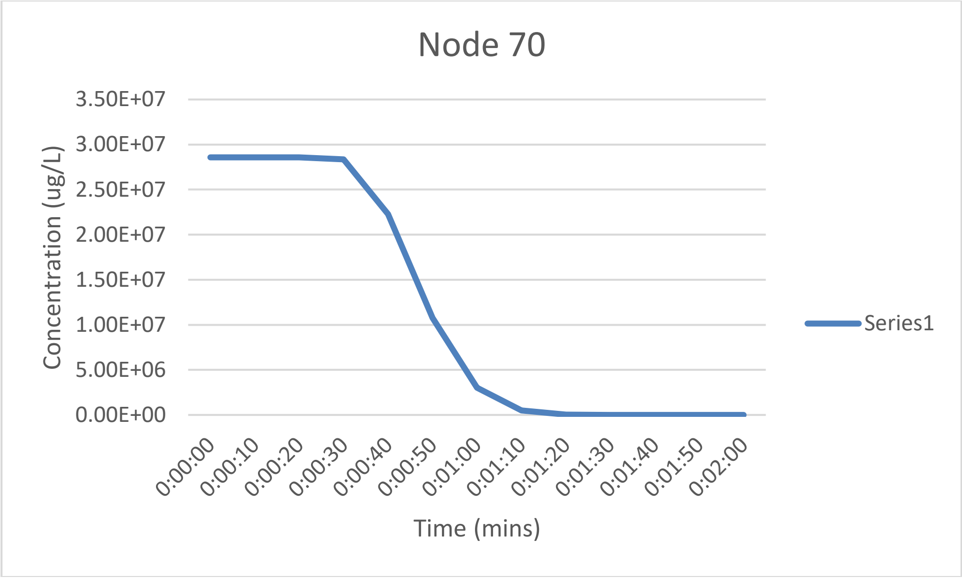


Figure 16: Emitter 70 concentration vs time

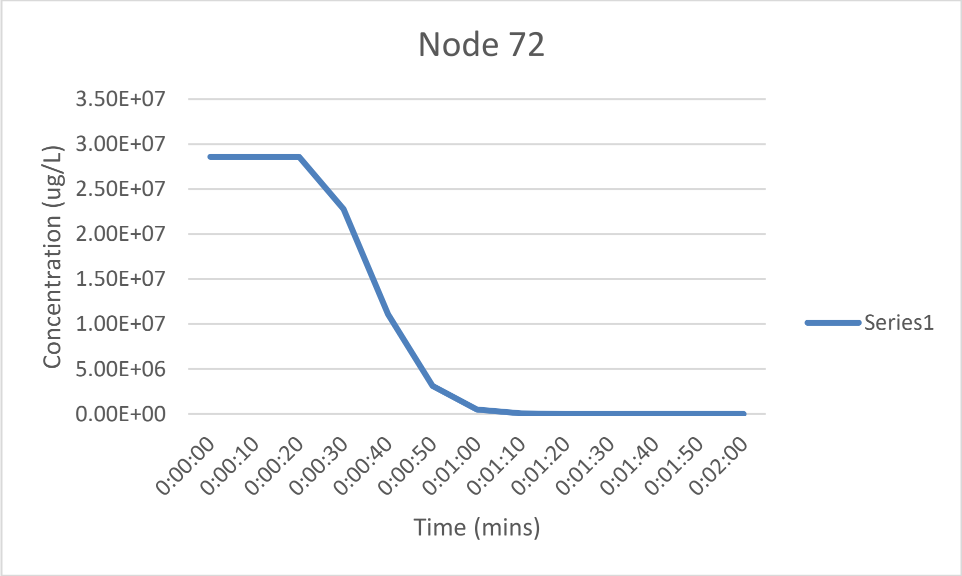


Figure 17: Emitter 72 concentration vs time

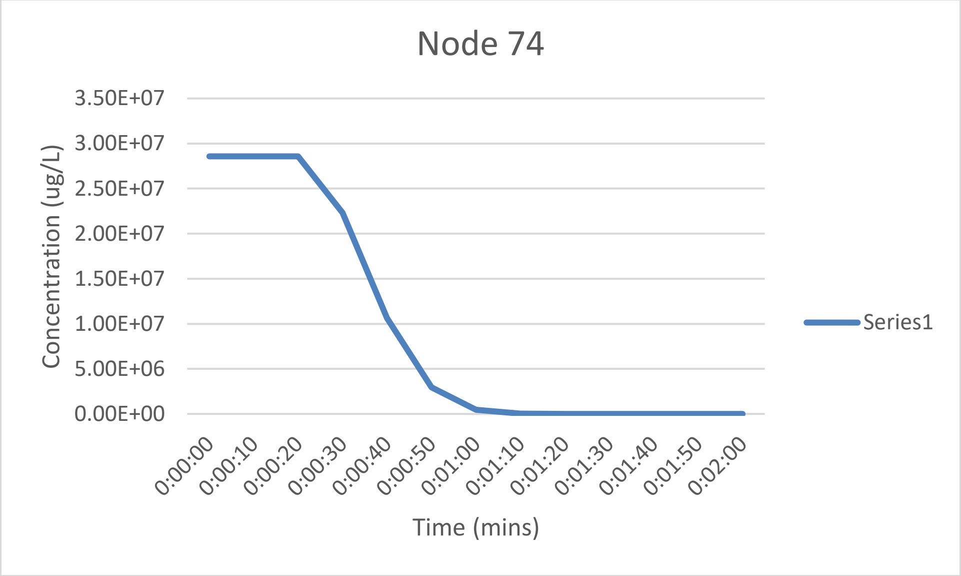


Figure 18: Emitter 74 concentration vs time

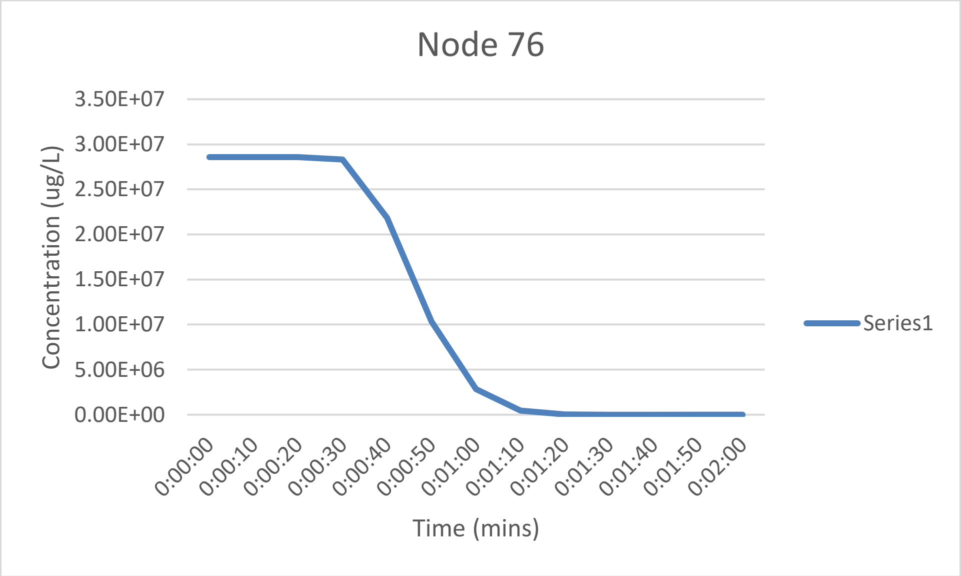


Figure 19: Emitter 76 concentration vs time

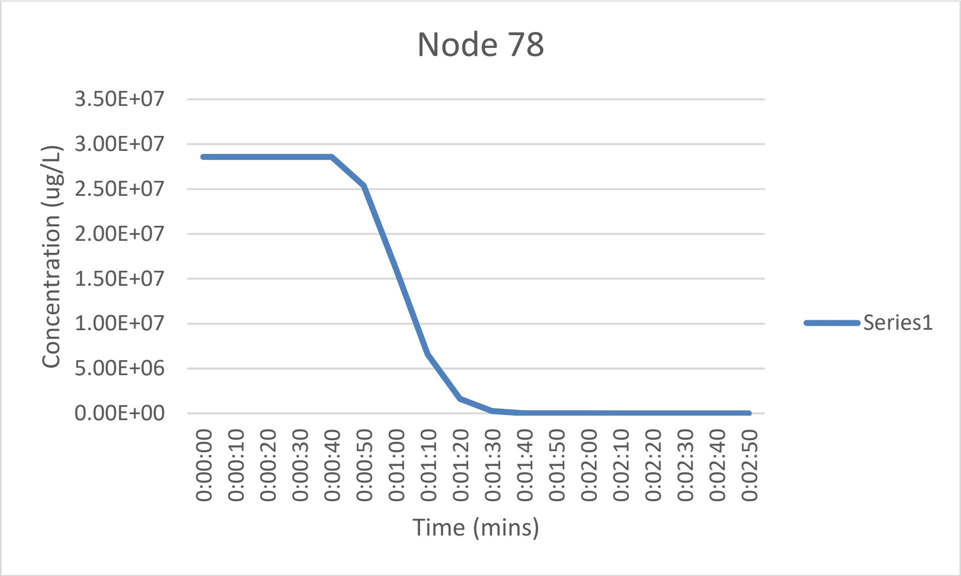


Figure 20: Emitter 78 concentration vs time

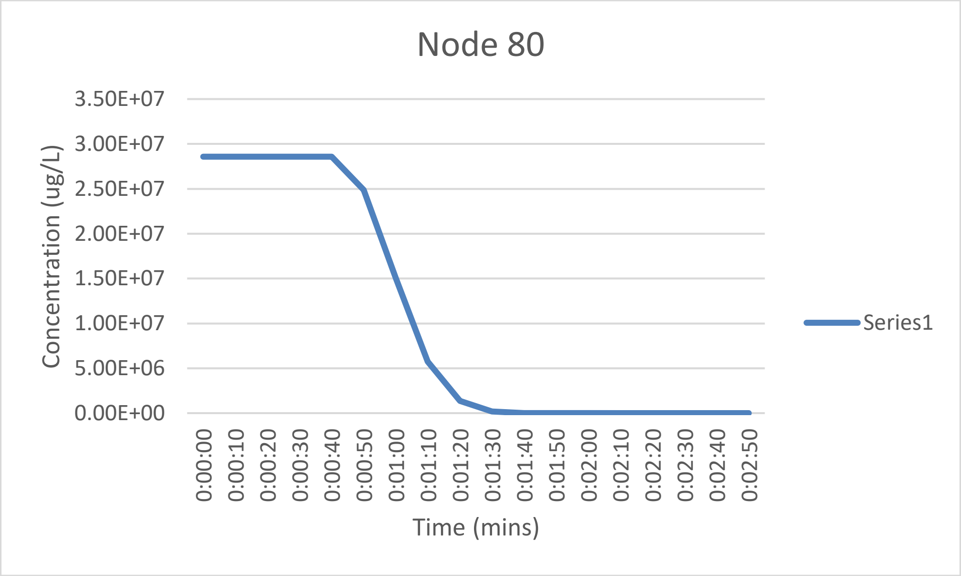


Figure 21: Emitter 80 concentration vs time

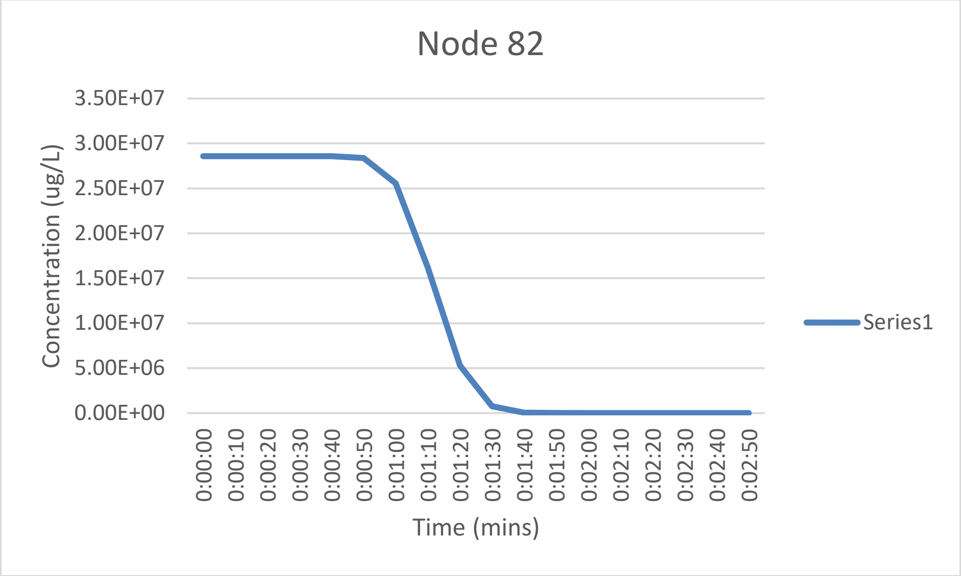


Figure 22: Emitter 82 concentration vs time

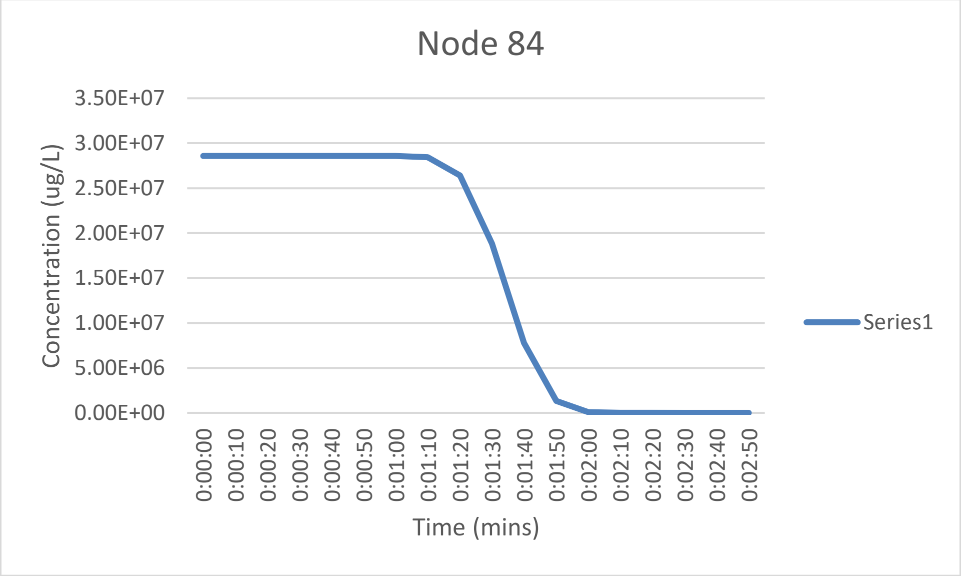


Figure 23: Emitter 84 concentration vs time

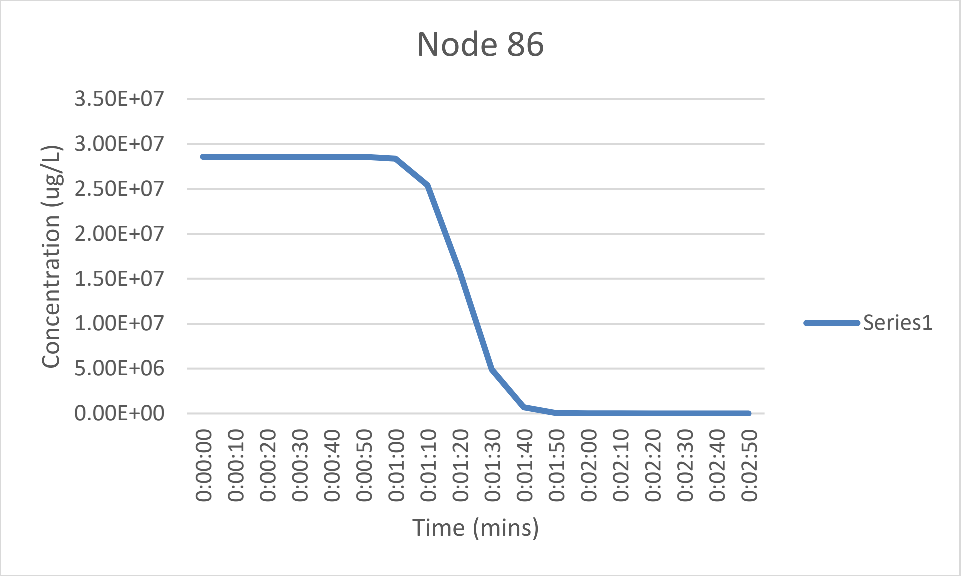


Figure 24: Emitter 86 concentration vs time

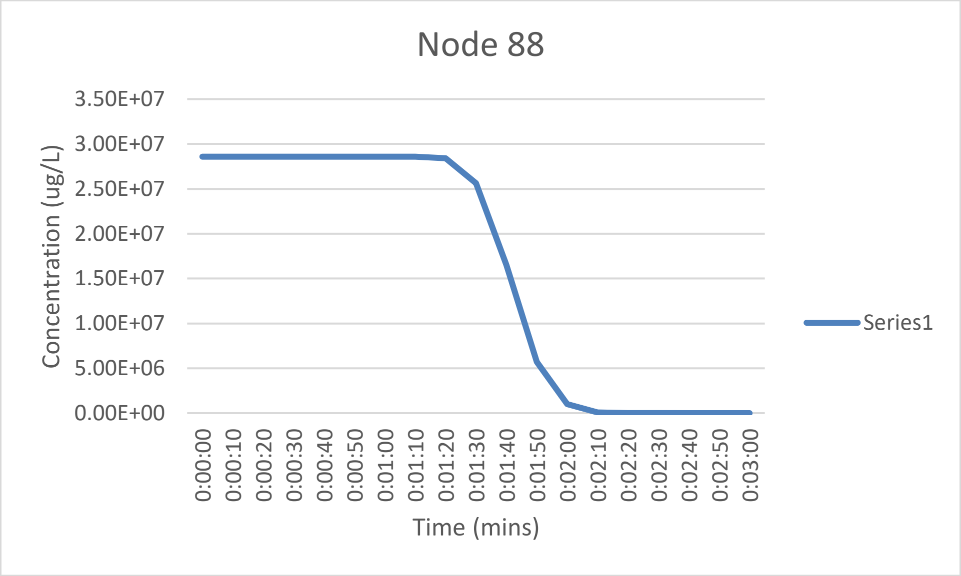


Figure 25: Emitter 88 concentration vs time

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14. ABSTRACT

Legacy per- and polyfluoroalkyl substances (PFASs) exist in the form of aqueous film-forming foams within hangar fire suppression systems throughout the country, posing a threat to both surrounding environments as well as local populations. The United States (US) Department of Defense (DoD), in conjunction with the US Environmental Protection Agency (EPA), is investigating best practices to flush out existing contaminants prior to disposal and replacement with a less environmentally harmful replacement. While current procedures dictate a triple rinse of the entire system to yield contaminant levels acceptable to the DoD, the practice has never truly been tested. Designed as a tool to understand movement of drinking water within distribution systems, EPANET software can be used to model a contaminant's fate through a series of pipes reminiscent of a hangar fire suppression system and can thus simulate legacy PFAS transport from origin tank to expulsion emitters. Its hydraulic modeling and water quality modeling features make it ideal for this endeavor, and the results produced provide further support for the triple rinse's hypothesized six-log reduction of the chemical contaminant.

15. SUBJECT TERMS
EPANET Model, PFAS, Aqueous Film-Forming Foams, Hangar, DoD, Hydraulics, Water Quality

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