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EVALUATION OF NEWTONIAN AND NON-NEWTONIAN PFAS FREE FOAMS IN AN AIRCRAFT HANGAR AFF FIRE SUPPRESSION SYSTEM

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1. SUMMARY

The USAF is investing in research, development, testing and evaluation (RDT&E) of alternatives to aqueous film forming foam (AFFF) that contain poly-, perfluoroalkyl substances (PFAS) for aircraft hangar and airport firefighting rescue operations. Several companies have developed PFAS free fire suppression foams (PFFs) that are being applied internationally for aviation fire protection and promoted as alternatives to legacy AFFF. The PFF concentrates fall within two distinct types of fluids; Newtonian and non-Newtonian.

The objective of this work was to develop a database compiling test results using Newtonian or non-Newtonian PFF concentrates in existing AFFF fire suppression systems. The information may be used by—Air Force Civil Engineer Center/Operations Directorate Engineers (AFCEC/COS), the DoD Fire Protection Engineering Working Group, and the DoD PFAS Task Force to guide decisions on modifications to the installed fire suppression system hardware. PFF concentrates were applied through the existing fire suppression system in an Air Force hangar on Tyndall AFB, FL. The system was designed for AFFF and charged with those formulations (ca. 20 years). Specific aims of this work were to (1) assess whether residual PFAS were released from a legacy AFFF installed suppression system—when rinsed with water, and when PFF were discharged from the system; (2) test and assess performance of PFF in a low-level nozzle system and closed-head foam-water sprinkler system; (3) determine—application rate, agent proportioning, and foam quality, and (4) determine the suitability of Newtonian and non-Newtonian PFF concentrates as direct drop-in replacement for the AFFF (C-8 and C-6 formulations, are both Newtonian fluids).

There is concern that materials and equipment previously contacting AFFF may retain residual PFAS that would contaminate water and PFF if systems are re-used rather than replaced. Samples were collected from a rinse series and all discharge tests and then analyzed for presence of representative PFAS. The first water discharge and AFFF discharge samples showed detectable quantities of PFHxA and PFOA. After triple rinsing the foam concentrate tank then flushing the system with two, one-minute, water-only system discharges, low levels of PFHxA were detected. No other representative PFAS were detected. The samples analyzed from PFF trials did not reveal any of the analytes. The present results suggest triple rinsing the bladder tank and flushing water through piped system reduced the representative PFAS below detectable levels in subsequent uses of the system. The present test was not exhaustive, longer residence time and liquid contact with the fire suppression system components may dissolve residue in interstitial spaces and release PFAS into liquid.

A series of quantitative assessments of the discharge and mixing operations showed generally good compatibility of the PFF with the existing system. Agent application rates were 0.11-0.12 gpm/ft² for all AFFF and all PFF tests with the exception of tests with the PC-50 nozzle. The lower k-factor of the PC-50 nozzle decreased application rate to 0.09 gpm/ft² in the four tests that it was used. The floor monitor proportioning delivered concentrate and mixed with water acceptably. All tests showed mixed agents were 3.0-3.9%, matching targeted values and recommended concentrations. The results using the original facility proportioner and nozzle were comparable to the alternative proportioners and nozzles specified by the manufacturer for three of the four PFF tested. The Solberg non-Newtonian foam was actually closer to the target 3%

with the original facility proportioner and nozzle than with the manufacturer-specified components. The closed-head sprinkler proportioning simulations and evaluations were less consistent. Only two of the eight proportioning samples were within the acceptable concentration range (3.0-3.9%), one from a low flow test and one from a high flow test. None of the wide range proportioners accurately metered and mixed PFF at both extremes of low and high flow sprinkler discharge rates.

The foam quality (i.e., expansion ratio and 25% drain times) were determined following floor monitor discharge and compared. Direct comparisons of the AFFF and PFF using the existing system (drop-in) showed 3 of 4 PFF had higher expansion ratios. The drain times for Newtonian foams were comparable and the thick, non-Newtonian foams drain times were much longer. The foam quality characteristics for PFF tested using a manufacturer specified non-air aspirated nozzle were comparable to the drop-in test except the expansion and drain time for the non-Newtonian Solberg foam was higher. The air-aspirated nozzle tests differed, three of the four PFF had statistically lower expansion ratios than with the non-air aspirated nozzles and drop-in tests; the drain times were comparable to the drop-in test for 3 of 4 foams. Again, the drain time for the Solberg PFF increased markedly compared to the drop-in test hardware. The foam quality results for sprinkler heads were largely irrelevant because the nozzles were too close to the floor and the proportion of foam concentrates were not within proper working range. For example the proportioning system mixed the non-Newtonian Fomtec agent to 12.2%; the 25% drain time of the resulting foam was 19,800 seconds, more than 8-fold longer than the test with drop-in floor monitors.

Butyl carbitol is commonly used in AFFF and PFF and excess exposure has negative health consequences. Personnel exposure was monitored during tests and operation activities using commercial sampling badges. The badge material effectively compiles volatile butyl carbitol but are fouled if exposed to any liquid. The valid materials (those that remained dry throughout use), showed TWA exposure to butyl carbitol <0.5 ppm for all tests. That level is well below the formal risk regulation, the TLV of 10 ppm.

The tests results provided a series of preliminary conclusions. The floor monitor system tested appeared amenable to use of PFF. The Newtonian and non-Newtonian concentrates were—proportioned appropriately, delivered at set rates, and the foam structure (with respect to ER and drain times) met requirements. The overhead sprinkler system, however, was not as suitable in the tests. The PFF were not mixed to proper proportions. It is unclear presently what hardware will be needed for proportioning foams at the low flow and high flow sprinkler discharges. The proposed switch to PFF may mitigate potential environmental and health risks. Minimal to imperceptible concentration of PFAS were measured after flushing system and shifting to PFF use. There was no evidence for significant exposure to toxic butyl carbitol from the use of AFFF or PFF in the discharge tests.

2. INTRODUCTION

The fire protection systems currently approved for installation in USAF maintenance aircraft hangars are designed for a worst-case fire threat, e.g., hundreds of gallons of liquid fuel spilled, pooled, and subsequently ignited near an aircraft. Fire suppression systems typically found in modern USAF aircraft hangars include the use of AFFF containing PFAS-based surfactants and high expansion (Hi-Ex) foaming agents. As AFFF is under increased scrutiny for its adverse health effects, the USAF is investing in research, development, testing and evaluation (RDT&E) of alternatives. Several companies have developed fluorine free fire suppression foams, and while they do not meet the stringent standards of MIL-PRF-24385 (MIL-SPEC) (1), Underwriters' Laboratories (UL), and International Civil Aviation Organization (ICAO) standards for firefighting foams, they are being applied internationally for aviation fire protection and promoted as alternative to legacy AFFF.

The PFF fire suppression concentrates fall within two distinct types of fluids. Newtonian liquids, which have properties similar to water and viscosities that are essentially constant (the current Military Specification AFFFs are Newtonian fluids). Non-Newtonian liquids, are similar to syrups or gels, their viscosities change when force is applied and mechanical pumping can be difficult. Accordingly, direct replacement of AFFF with other Newtonian fluids may be relatively straightforward compared to replacement with non-Newtonian fluids. Recent tests by the Naval Research Laboratory identified several Newtonian and Non-Newtonian liquid foam concentrates with encouraging fire extinguishment and burn back resistance performance, the products may be candidate to replace AFFF in shore-based installed fire suppression systems (2) as the use of PFAS-containing products is eliminated.

The vast majority of installed AFFF fire suppression systems in the Department of Defense are used in hangars to protect valuable aircraft assets. It is necessary to determine the degree of modification required to install either Newtonian or non-Newtonian replacement concentrates in these existing systems to provide decision makers measurable data to evaluate various replacement investment options. The direction and choices are uncertain today; there will undoubtedly be application and performance tradeoffs for all options.

3. METHODS, ASSUMPTIONS, AND PROCEDURES

The objective of this work was to develop a database from evaluation of alternative fire control agents in existing AFFF fire suppression systems. The information can be used by AFCEC/COS, the DoD Fire Protection Engineering Working Group, and the DoD PFAS Task Force to inform choices and minimize modifications to the installed fire suppression system hardware. PFAS-free concentrates were applied through the installed AFFF suppression system in an existing Air Force hangar on Tyndall AFB, FL. The goals were to collect and analyze data to determine the impact and cost of switching from military specification AFFF to a fluorine free concentrate that meets commercial standards such as UL 162, ICAO standards, or other recognized listing/approval standard for class B fire suppression.

The following specific aims were identified and addressed in these evaluations:

1. Conduct low-level nozzle system and closed-head foam-water sprinkler system discharge and assess the residual PFAS released from the legacy AFFF suppression system with historic exposure to C-8 AFFF and C-6 AFFF concentrates.
 - a. Determine PFAS “wash-out” from fire suppression system prior to PFF substitution.
 - b. Assess whether PFAS is released during PFF discharge.
2. Test and assess compatibility of PFF in low-level nozzle system and closed-head foam-water sprinkler systems.
3. Test and assess performance of floor monitor discharge nozzles for PFF delivery (estimate agent application rate in gallons per minute per square foot).
4. Evaluate low-level nozzle system and closed-head foam-water sprinkler system discharge for agent proportioning.
5. Evaluate foam quality (expansion and 25% drain time) of PFF after discharge from low-level nozzle system.
6. Determine the suitability of Newtonian and non-Newtonian PFF concentrates to be used as a direct drop-in replacements for existing Newtonian C-8 and C-6 AFFF concentrates from an infrastructure dynamic perspective.

3.1. TEST METHODS

3.1.1. FACILITY AND FIRE SUPPRESSION SYSTEM

Building 295 on Tyndall AFB has two aircraft hangars and was selected as the representative test site. The hangar mechanical room includes two foam/water deluge risers and a single 200 gallon bladder tank for the foam concentrates. Each deluge system riser and proportioning system dispenses firefighting agent solution to a single underwing floor monitor nozzle in the open hangar bay, one on the North side and one on the South side of the facility. This facility does not include a closed-head, foam-water system riser, so the effect was simulated manually by directing the foam-water sprinkler flow through the deluge system test header.

Fire suppression water is supplied from a central pump house to a 12-in. diameter manifold for the facility fire suppression system risers (see Appendix A, Figure A- 1). The foam/water deluge riser was 4-in. diameter with foam concentrates proportionally pumped in from the bladder tank

(see Figure 1). Water was provided to the foam concentrate bladder tank through a 2.5-in. pipe from the fire suppression water manifold. The foam concentrate line from the bladder tank to the riser was changed from test-to-test depending on the recommendations of the manufacturer for each proportioner. The original 1.5-in. diameter foam concentrate line was used for all AFFF and water discharge tests and for all PFF agent drop-in tests. For all other tests this pipe was either 2- or 2.5-in. diameter to match the foam concentrate inlet on the proportioner recommended for each PFF test. The bladder in the bladder tank was replaced with a new bladder in September of 2018 when the prior AFFF agent was replaced with 3% Ansulite C-6 (AFC-3MS-C, lot# MS 31840). Although the bladder was replaced, the tank's internal PVC pipes were most likely reused, there was no record that those plumbing materials were replaced. The same bladder tank was used for all tests conducted in the project.



Figure 1. Foam/Water Deluge Riser (left) and Bladder Tank (right)

The South hangar bay of Bldg 295 was used for testing. The hangar is 65- wide by 75-ft from the back wall to the floor drain that spans the width of the floor. Fire suppression water/foam enters the hangar through a 4" pipe and there are two test header valves and an isolation OS&Y valve before the discharge monitor as shown in Figure 2. Agent is discharged into the hangar through a Spectrum Manufacturing, Inc., medium flow model 4 oscillating monitor (see Appendix A, Figure A- 2). The Spectrum monitor has a 3-in. internal flow path and is designed for flows from 150-750 gallons per minute (gpm). The monitor was configured for this test series for manual oscillation, and an operator controlled the discharge direction for each test. A Williams Fire and Hazard Control, Inc. brass, non-air aspirated, fog-to-straight stream nozzle was installed on this monitor when the system was originally installed in the facility. The test header valves were used for high flow 800 gpm sprinkler tests (see Appendix A, Figure A- 4). A 2-in. branch pipe was added from the 4-in. pipe for the low flow 64 gpm sprinkler test (see Appendix A, Figure A- 3). The hangar bay exterior doors were previously removed, and in order to ensure that discharged foam was contained in the facility, a 65- wide by 8-ft high wall was assembled across the door opening. In the corner near the foam collection backboards, the wall was extended higher to

contain foam/water spray. Plastic sheeting was installed 8 ft and higher on most walls around the perimeter of the hangar bay to contain foam/water spray.



Figure 2. Hangar Bay Fire Suppression Floor Monitor and Valves

3.1.2. PFF AND RECOMMENDED HARDWARE

Before testing began, PFF manufacturers were contacted and asked to recommend the optimum non-air aspirated nozzle, air-aspirated nozzle, and a proportioner for their agent for the low-level nozzle tests. For sprinkler tests, the manufacturers were asked to recommend a wide-range proportioner. If a nozzle or wide-range proportioner was not specified by the manufacturer, the following standard equipment was used.

- Non-air aspirated nozzle: Williams Fire and Hazard Control, Inc. fog-to-straight stream nozzle.
- Air-aspirated nozzle: National Foam PC-50
- 3% wide-range proportioner: Ansul FLOWMAX CL variable range. (The Ansul proportioner specification states a minimum and maximum flow rate of 49 and 3,122 gpm, respectively.)

Four PFF concentrates were evaluated in this program. AFCEC/COS specified the candidate agents that were used in the present hangar tests. Products chosen for the tests were commercially available and had been previously evaluated for effectiveness against MIL-F-24385 by both AFCEC and NRL. The PFF tested were:

- Solberg Re-Healing™ RF3, 3% Foam Concentrate
- BIOEx Ecopol A 3% Fluorine Free
- Fomtec ENVIRO USP 3%
- National Foam Avio Green KHC 3%

The Solberg and Fomtec products are non-Newtonian liquids, the BIOEx and National Foam products are Newtonian liquids

3.1.2.1. SOLBERG RE-HEALING™ RF3 RECOMMENDED HARDWARE

Perimeter Solutions was contacted for recommended nozzles, ratio controller proportioner, and wide-range proportioner.

- The recommended non-air aspirated nozzle was a Task Force Tips (TFT) 2.5-in. ZN Industrial model.
- The air-aspirated nozzle recommendation was the same nozzle with a TFT multi-expansion aspirating attachment (type MX-FOAMJET MAX FJ-MX-MD).
- The recommended turret discharge ratio controller was the Rehealing RF3, 3%, 3.0 in. between flange proportioner that has a 1.25-in. NPT foam concentrate inlet.
- The recommended wide-range proportioner was the 6-in. variable range RF3 proportioner. The wide-range proportioner specification states a minimum and maximum flow rate of 115 and 1,700 gpm.

3.1.2.2. BIOEX ECOPOL A RECOMMENDED HARDWARE

Tempest Technology Corp. was contacted for recommended nozzles, ratio controller proportioner, and wide-range proportioner. There were no recommended hardware nozzles or proportioners specified outside of the replacement hardware listed in Section 3.1.2. As a result, the two drop-in tests had the same hardware as the two planned tests with the manufacturer's recommended non-air aspirated nozzle and ratio controller, so these tests were not repeated and two total tests were conducted with this hardware.

3.1.2.3. FOMTEC ENVIRO USP RECOMMENDED HARDWARE

Dafo Fomtec AB was contacted for recommended nozzles, ratio controller proportioner, and wide-range proportioner.

- The recommended non-air aspirated nozzle was a KNN500NA 500 gpm nozzle manufactured by K.C. Antincendi S.R.L. (KCA).
- Since no air-aspirated nozzle was recommended, the National Foam PC-50 specified in Section 3.1.2 was used.
- The recommended turret discharge proportioner was the KCA KFP114NL, 4-in. ratio controller – with a 2-in. foam concentrate inlet.
- The recommended wide-range proportioner was the KCA KNR063L, 6-in. with a 2.5-in. foam inlet. The wide-range proportioner specification states a minimum and maximum flow rate of 50 and 1,800 gpm, respectively.

3.1.2.4. NATIONAL FOAM AVIO GREEN KHC RECOMMENDED HARDWARE

National Foam was contacted for recommended nozzles, ratio controller proportioner, and wide-range proportioner.

- The recommended non-air aspirated and air-aspirated nozzle was the National Foam Gladiator 500.
- The recommended turret discharge ratio controller was the National Foam 4-in. RCW 3% protein, wafer style (between flanges) that has a 1.5 in. foam concentrate inlet.

- National Foam recommended the Avio Green agent for aircraft rescue firefighting (ARFF) applications, such as the turret discharge planned for these tests. The AVIO Green, however, had not been previously tested for sprinkler applications and therefore, there was no data available for National Foam to make wide-range proportioner determination. National Foam eventually recommended the National Foam LFP-6-3-BT-GR wide-range proportioner with a 2-in. foam inlet for this sprinkler testing. The wide-range proportioner specification states a minimum and maximum flow rate of 23 and 3,093 gpm.

Table 1 summarizes the hardware that each manufacture recommended for non-air aspirated and air-aspirated monitor nozzles and the proportioning hardware recommended to yield monitor flow and sprinkler flow.

Table 1. Manufacturer Recommended Hardware for Monitor and Sprinkler Flow

Manufacturer Recommended	Solberg	BioEx	Fomtec	National Foam
Non-Air Aspirated Nozzle	Task Force Tips ZN Industrial 2.5", 500 gpm	NR	KCA KNN500NA 500 gpm	Gladiator 500
Air-Aspirated Nozzle	FJ-MX-MD TFT Nozzle Attachment	NR	NR	Gladiator 500
Proportioner (Ratio Controller)	3.0", Between Flange RE-HEALING RF3, 3%	NR	KCA KFP114NL 4" Ratio Controller	RCW-3% 4" Ratio Controller
Wide Range Proportioner	6" Variable Range Proportioner RF3-UL Version	NR	KCA KNR063L 6" Wide Range Controller	Wide Range Proportioner, LFP-6

NR = No Recommendation

3.1.3. FLOOR MONITOR FLOW TESTS

Two floor monitor flow tests were originally planned for each test scenario. There were three floor monitor scenarios for each PFF agent for a total of 6 tests: 1) As a drop-in agent using the original system hardware, 2) Using a manufacturer specified ratio controller proportioner and a non-air aspirated nozzle, and 3) Using a manufacturer specified ratio controller proportioner and an air-aspirated nozzle. Since scenarios 1 and 2 had the same hardware specified for the BioEx agent, only one set of two flow tests were conducted with this hardware.

For AFFF, there was only one test scenario with two planned tests: 1) using the original sprinkler system hardware. During the first AFFF test, foam from the floor flowed into the collection

cylinders along with the foam from the backboard. Due to the contamination of the backboard foam sample, a third AFFF discharge was conducted.

3.1.4. SIMULATED SPRINKLER FLOW TESTS

Two sprinkler flow rates were planned for testing, low flow at 64 gpm and high flow at 800 gpm. One test was conducted with each PFF.

To accomplish the low flow, new 2-inch pipe was installed from the test header to the center of the facility near the East wall. A sprinkler head was installed 6 feet above floor at this location. The sprinkler head was a Viking VK302 upright K5.6 foam-water sprinkler that is FM approved and UL listed for closed head and open head configurations. This sprinkler resulted in flow rates of ~64 gpm with the facility fire suppression system pressure. The bulb was removed from the sprinkler before testing began.

For high flow simulated sprinkler system tests, two Guardian model 9415 flowmeter stands (see Figure 3) with 500 gpm capacity were installed in the hangar and attached to the two test header valves using 2.5-in. fire hose. These test devices each included a Venturi type flow meter, pressure gauge, and a full flow gate valve that was adjusted each test to achieve approximately 400 gpm through each device for a total of approximately 800 gpm flow. The discharge of these devices was aimed toward the floor with no good method of collecting samples from the discharge for foam expansion, drain time, or PFAS measurements. PFAS measurements were instead collected as described in Section 3.1.5.1.



Figure 3. Guardian Flowmeter Stands Discharging Foam

3.1.5. DATA COLLECTION

3.1.5.1. FOAM CONCENTRATE PROPORTIONING

Agent concentration in the discharge solution was measured to evaluate the ability of each proportioning system to correctly inject foam concentrate into the suppression system. Immediately before the end of each test, discharged solution was collected from a hose connected to the floor monitor discharge adjacent to the test header valves (see Appendix A, Figure A- 2, Figure A- 3, and Figure A- 4). Solution flowed through this hose throughout the duration of the test to ensure what was collected at the end of the test was the same as the foam solution that was collected through the floor monitor for expansion and PFAS measurements.

The samples collected were analyzed for foam concentration in the AFCEC Research & Development (R&D), Requirements, and Acquisitions Division (CXAE) laboratory using a Hach HQ440D multi-parameter meter with an Intellical CDC401 conductivity probe. For each foam concentrate tested, solution standards of 2%, 3%, and 4% were mixed in the laboratory, as per NFPA 11, Annex D (3), using foam concentrate from the bladder tank and water from the riser manifold test header. The three standards' conductivity results were plotted in Microsoft Excel and a curve fit formula was calculated. Conductivity of each sample collected was measured three times and averaged. This average was used with the formula generated for each foam concentrate to determine the sample proportioned percentage.

3.1.5.2. FOAM QUALITY

Foam quality equipment and procedures are described in NFPA 11, Annex D (3). These procedures were followed for measurements of foam expansion and 25% drain time. Two foam sample collector backboards (see Figure 4) were installed side-by-side in the facility near the opposite corner of the aircraft hangar from the monitor discharge and facing the monitor. Water and foam flow was initiated in the system with the turret directed away from the collection devices. After the system reached steady state flow plus 15 seconds, the discharge stream was then directed so that foam fell on the collection backboards. A foam sample was collected in ~1,600 mL sample containers from each backboard and measured for expansion and 25% drain time as described in the NFPA 11 (3) procedures.



Figure 4. Foam Collector Backboards, Sample Containers, and Bucket

NFPA 11 (3) does not specify acceptable results for foam expansion or 25% drain time. A similar foam quality test is described in NFPA 412 (4). In Section 5.1 of that standard, the acceptable non-air aspirated expansion is 3:1 or greater with a drain time of 45 s or greater. For an air-aspirated nozzle, the acceptable expansion is 5:1 or greater with a drain time of 135 s or greater. MIL-PRF-24385F (1) describes using an air-aspirated nozzle and lists the minimal acceptable AFFF results as expansion of 5:1 with a drain time of 150 s.

The test plan did not call for measurement of expansion and drain time during the simulated sprinkler discharge testing since sprinkler heads were not going to be installed at typical spacing and ceiling height, and the foam wouldn't have time to interact with air before impacting the floor to allow an accurate measurement. As described in Section 3.1.4, a single sprinkler head was installed 6 ft above the floor to accomplish the required 64 gpm flow rate. After testing began, the decision was made to collect a foam sample for drainage and expansion during the low flow tests with the understanding that the result would not be representative of a typical installation and would only be relative to other similar measurements. The backboard device was kept away from the foam discharge area until approximately 60 seconds after foam was first visibly detected at the sprinkler head. At that time, the collection device was positioned (see Figure 5) in the sprinkler discharge area. The collection cup was removed when it was filled and expansion and drain time were measured. Foam quality was not measured during 800 gpm simulated sprinkler tests.



Figure 5. NFPA 11 (3) Foam Collection Device Being Positioned in the Sprinkler Discharge

3.1.5.3. PFAS

Samples of discharged foam were collected in each test to measure the PFAS discharged through the system. The samples were sent to Battelle Norwell Operations for analysis of PFAS by liquid chromatography and tandem mass spectrometry (LC-MS/MS). The results of this analysis provided the detectable quantities of perfluoro-n-hexanoic acid (PFHxA), perfluoro-n-octanoic acid (PFOA), perfluoro-1-hexanesulfonate (PFHxS), and perfluoro-1-octanesulfonate (PFOS). To eliminate the possibility of contamination, these samples were collected from the foam discharge before the solution impacted a surface. In all turret discharge tests and low flow sprinkler discharge tests, the samples were collected in an unused plastic 5 gallon bucket. All results are in Section 4.1.

Before testing began and to ensure no contamination from sample collection, an unused bucket was evaluated to ensure that no PFAS was present on the bucket surface from the manufacturing process. For turret discharge tests, a bucket was placed adjacent to the foam quality collection backboards (see Figure 4) in a stand designed to keep the bucket from moving when impacted by the foam spray. For low flow sprinkler tests, the bucket to collect a sample was placed on the floor adjacent to the backboard when the backboard was positioned under the sprinkler discharge (see Figure 5). For high flow simulated sprinkler flow tests, PFAS measurements were collected from the hose described in Section 3.1.5.1 that was connected to the floor monitor discharge adjacent to the test header valves.

3.1.5.4. FLOW RATE

Flow rate through the turret nozzle was measured with a Tornatech model GT-FluxFP, 4"/DN 100 orifice flow meter installed in the 4-in. line in the hangar. The flow meter appeared to work properly until the last 8 turret discharge tests. During that time, the flow meter readings were not consistent with visible observations, the pressure data recorded, and prior tests. The meter appeared to have debris and a higher-than-water viscosity fluid in the sight glass. Attempts were made to flush out the flow meter, however, flow measurements continued to not match the recorded pressures. As a result, the flow values from these tests were estimated based on pressure measurements, nozzle K factors, and prior test results.

3.1.5.5. PRESSURE

Fire suppression system pressure was measured at multiple locations. A pressure gauge was installed in the standpipe in the hangar adjacent to the turret location. This pressure gauge was monitored during all tests and is the pressure measurement used for verifying flow data. A pressure gauge was installed at the facility fire suppression system manifold and recorded for all but four tests. The pressure differences between these two readings were due to friction losses in the system piping. During some of the tests, the operators in the pump house reported the pressure at the pump house while the pumps were operating.

3.1.5.6. BUTYL CARBITOL

Personal exposure monitoring was conducted during five days of the testing; one day for each foam concentrate. The intent of the monitoring was to determine personal exposure concentration of butyl carbitol (diethylene glycol monobutyl ether, CAS 112-34-5) from AFFF and the four fluorine foam concentrates. Activities involving potential exposure to butyl carbitol consisted of collecting foam samples from the foam collection backboards, dispersal of foams from the floor monitor, measuring the foam expansion and drain times, as well as cleaning the facility after testing. The percentage of butyl carbitol reported by the manufacturer in each respective product concentrate are found in Table 2, below.

Table 2. Firefighting foams tested and Respective Butyl Carbitol Concentrations

Foam Concentrate	Reported Butyl Carbitol Content
Ansulite 3% AFFF	10-30%
Solberg Re-Healing Foam RF 3%	<20%
BioEx Ecopol-A	10-25%
Fomtec Enviro USP	5-9%
National Foam Avio Green KHC 3%	10-30%

Three personnel were monitored for exposure on the five test days. Two of the personnel had the highest potential exposure as they were in the discharge spray collecting the foam quality samples from the backboard. The third person was in the hangar bay during the test, but not directly exposed to the foam discharge. The two sample collection personnel wore personal protective equipment while performing tasks with potential exposure consisting of a full face respirator equipped with organic vapor/acid gas cartridges, chemical resistant suits with an integrated hood, water-proof boots, and chemical resistant (industrial thickness nitrile) gloves. All three personnel were involved with measuring the foam quality and assisting with cleaning the facility. Due to the nature of the testing, badges were exposed to the facility atmosphere for different amounts of time for each day and each person; however, the results of each sample were adjusted to an 8 hour time weighted average.

Butyl carbitol samples were collected using an AssayTech personal passive TraceAirII Monitor for Organic Vapors badge with an average flow rate of approximately 30 to 90 milliliters/minute. The sampler was hung within the breathing zone for the duration of the operations described above. After completion of the monitoring, all sampling media were sealed and shipped according to analytical laboratory instructions. The laboratory used was SGS Galson Laboratory, in East Syracuse, New York. SGS Galson is an American Industrial Hygiene Association accredited laboratory (AIHA-LAP, LLC – IHLAP, ELLAP, EMLAP, Accredited Laboratory ID 100324).

3.2. TEST PROCEDURES

Water/foam discharge tests conducted with the facility fire suppression system included water only discharge, AFFF discharge, and PFF discharge tests from the floor monitor and PFF discharge tests through simulated sprinkler flows. System hardware components including nozzles and proportioning valves were changed for different test scenarios as described in Section 3.1.2. Following is a general chronology of the testing conducted:

1. Water flow rate and leak check evaluations through the floor monitor and simulated sprinkler devices.
2. Floor monitor discharge proportioning tests with 3% C6 Mil-Spec AFFF in the foam concentrate tank.
3. Drain AFFF concentrate from the bladder tank, triple rinse the tank with water, refill the tank with water.
4. Floor monitor discharges of water with no proportioning.

5. Drop-in floor monitor discharge proportioning tests with water in the foam concentrate tank.
6. Drain and fill the bladder tank with Solberg Re-Healing™ RF3.
7. All Solberg Re-Healing™ RF3 floor monitor and simulated sprinkler discharges.
8. Drain, rinse with water, and fill the bladder tank with BioEx Ecopol A.
9. All BioEx Ecopol A floor monitor and simulated sprinkler discharges.
10. Drain, rinse with water, and fill the bladder tank with Fomtec ENVIRO USP.
11. All Fomtec ENVIRO USP floor monitor and simulated sprinkler discharges.
12. Drain, rinse with water, and fill the bladder tank with National Foam AVIO Green KHC.
13. All National Foam AVIO Green KHC floor monitor and simulated sprinkler discharges.

For each of the PFF (line items 7, 9, 11, 13 above), the following tests were planned (Note: When testing Solberg Re-Healing™ RF3 and Fomtec ENVIRO USP agents, the drop-in tests occurred as the last two tests instead of the first two tests):

- A. Two drop-in floor monitor discharge proportioning tests with the original system hardware.
- B. Two non-air aspirated floor monitor discharge tests with the manufacture specified nozzle and proportioner (see Sections 3.1.1 and 3.1.2).
- C. Two air-aspirated floor monitor discharge tests with the manufacture specified nozzle and proportioner (see Sections 3.1.1 and 3.1.2).
- D. A low flow (64 gpm) simulated sprinkler test with the manufacture specified wide-range proportioner (see Sections 3.1.1 and 3.1.2).
- E. A high flow (800 gpm) simulated sprinkler test with the manufacture specified wide-range proportioner (see Sections 3.1.1 and 3.1.2).

3.2.1. DISCHARGE TEST PROCEDURES

Floor Monitor Discharge Procedures

Following are the step-by-step procedures conducted for deluge low-level nozzle system discharge tests.

1. Confirm that the correct agent concentrate is in the bladder tank, the correct proportioner is installed, and the correct floor monitor nozzle is installed.
2. Close the OS&Y valve adjacent to the floor monitor.
3. Verify that 325th CES/JJOU personnel are monitoring the fire pump operation.
4. Open the foam/water riser OS&Y valve to pressurize the system to the floor monitor OS&Y valve. (Note: The riser deluge valve was not reset and remained open throughout all testing.)
5. Personnel collecting foam quality samples don PPE.
6. Start video cameras.
7. Aim the turret away from the foam collection device.
8. Initiate discharge by opening the OS&Y valve adjacent to the floor monitor.
9. Open the foam concentrate proportioner ball valve to initiate flow into the riser from the bladder tank.

10. Discharge away from the foam collection device until foam is visible in the discharge, then discharge for an additional 15 seconds.
11. Manually aim the turret toward and above the collection backboards so that foam lands on the backboards and doesn't discharge out the open door.
12. Move the turret discharge away from the foam collection backboards after the collection cups are filled and collected.
13. Collect foam/water solution from the sample hose for proportioning analysis.
14. Close the foam concentrate proportioner ball valve.
15. Close the OS&Y valve adjacent to the floor monitor to stop flow into the hangar bay.
16. Complete NFPA 11 (3) foam quality analysis measurements.
17. Transport samples collected to the laboratory.
18. Clean the facility.

Low Flow (64 gpm) Simulated Sprinkler Discharge Procedures

Following are the step-by-step procedures conducted for discharge tests through the Viking VK302 upright K5.6 foam-water sprinkler.

1. Confirm that the correct agent concentrate is in the bladder tank and the correct proportioner is installed.
2. Close the OS&Y valve adjacent to the floor monitor.
3. Verify that 325th CES/JJOU personnel are monitoring the fire pump operation.
4. Open the foam/water riser OS&Y valve to pressurize the system to the floor monitor OS&Y valve. (Note: The riser deluge valve was not reset and remained open throughout all testing.)
5. Personnel collecting foam quality sample dons PPE.
6. Position a foam collection backboard and a PFAS sample collection bucket outside of the sprinkler discharge pattern.
7. Start video cameras.
8. Initiate discharge by opening the 2-in. ball valve to the sprinkler.
9. Open the foam concentrate proportioner ball valve to initiate flow into the riser from the bladder tank.
10. Once foam is visible in the discharge, then discharge for an additional 60 seconds.
11. Manually position the collection backboard and bucket into the sprinkler discharge pattern.
12. Collect foam/water solution from the sample hose for proportioning analysis.
13. Once all samples are collected, close the foam concentrate proportioner ball valve.
14. Close the 2-in. ball valve to the sprinkler to stop flow into the hangar bay.
15. Complete NFPA 11 (3) foam quality analysis measurements.
16. Transport samples collected to the laboratory.
17. Clean the facility.

High Flow (800 gpm) Simulated Sprinkler Discharge Procedures

Following are the step-by-step procedures conducted for high flow simulated sprinkler discharge tests.

1. Confirm that the correct agent concentrate is in the bladder tank and the correct proportioner is installed.
2. Close the OS&Y valve adjacent to the floor monitor.
3. Verify that 325th CES/JJOU personnel are monitoring the fire pump operation.
4. Open the foam/water riser OS&Y valve to pressurize the system to the floor monitor OS&Y valve. (Note: The riser deluge valve was not reset and remained open throughout all testing.)
5. Open the two test header valves to pressurize the 2.5-in. hoses to the flowmeter stands.
6. Start video cameras.
7. Initiate discharge by opening and adjusting each full flow gate valve to achieve approximately 400 gpm through each device.
8. Open the foam concentrate proportioner ball valve to initiate flow into the riser from the bladder tank.
9. Once foam is visible in the discharge and the flow stabilizes at 800 gpm, then discharge for an additional 15 seconds.
10. Collect foam/water solution from the sample hose for proportioning analysis.
11. Collect foam/water solution from the sample hose for PFAS analysis.
12. Once all samples are collected, close the foam concentrate proportioner ball valve.
13. Close the flowmeter stands' full flow gate valves to stop flow into the hangar bay.
14. Transport samples collected to the laboratory.
15. Clean the facility.

4. RESULTS AND DISCUSSION

4.1. PFAS

Samples of discharged foam/water were collected in each planned test to measure the PFAS discharged through the system and from the bladder tank immediately after the triple rinse. The samples were analyzed for perfluoro-n-hexanoic acid (PFHxA), perfluoro-n-octanoic acid (PFOA), perfluoro-1-hexanesulfonate (PFHxS), and perfluoro-1-octanesulfonate (PFOS) as described in Section 3.1.5.3.

Before any of the planned foam discharge tests were conducted in building 295, the suppression system was evaluated for leaks, discharge throw distance, and general operation to determine if any system repairs were needed. Water was discharged through the floor monitor, through the single sprinkler head, and through the two 500 gpm flowmeter stands. No problems were found with the suppression system during these evaluations. Water flow through the single sprinkler head was captured for analysis of the system background PFAS level.

Table 3 lists the PFAS analysis results in parts per trillion (ppt or ng/L) from this initial system flow test and lists all sample analysis results in chronological order of the sample collection. Results not detected or detected below the instrument detection limit are listed as ND in the table. The instrument detection threshold varied from test-to-test but was below 16 ppt for all but one of the discharge tests. PFHxS and PFOS were not detected in any samples. All data collected are listed in the table in Appendix B.

Table 3. PFAS Analysis Results (ppt)

Test Conducted	PFHxA	PFOA	PFHxS	PFOS
Prior To Testing, Initial Water Flow Through Sprinkler	783	80	ND	ND
1 st 3% AFFF Floor Monitor Discharge	5370	136	ND	ND
2 nd 3% AFFF Floor Monitor Discharge	3050	187	ND	ND
3 rd 3% AFFF Floor Monitor Discharge	6190	135	ND	ND
Water Sample From Bladder Tank (After Triple Rinse)	27	ND	ND	ND
1 st Water Floor Monitor Discharge with No Proportioning	29	ND	ND	ND
2 nd Water Floor Monitor Discharge with Proportioning	18	ND	ND	ND
All PFF Tests	ND	ND	ND	ND

ND = not detected (concentration below analytical threshold)

Before planned testing began, the initial PFAS measurement with water only flowing through the existing suppression system resulted in a background level of 783 ppt PFHxA and 90 ppt PFOA. The three floor monitor discharge tests of AFFF proportioned at 3% and flowing ~550 gpm resulted in elevated PFAS measurements as compared to the initial water flow test, with an average of 4,870 ($\pm 1,629$) ppt PFHxA and 153 (± 30) ppt PFOA. The variable concentrations for PFHxA and PFOA (standard deviation of ca. 33 and 20%, respectively) for the three AFFF discharge tests is likely due to interference from other chemical constituents in the samples. The additional constituents lead to inconsistent quantitation (e.g., the PFHxA levels in lines 2-4, Table 3). The phenomenon is often referred to as “matrix effects” and is especially common for LC-MS-MS analysis (5). Additional pre-processing of the samples can reduce variance. The conclusion in present work, however, is evident, the water flush and subsequent PFF tests showed minimal levels of the representative PFAS compared to AFFF trials.

After draining the AFFF concentrate from the bladder tank and triple rinsing the tank, the tank was filled with water again for the two water flow floor monitor discharge tests. A sample of this water was taken from the bladder tank resulting in a PFHxA value of 27 ppt and no detectable PFOA. Immediately following this sample collection, water was discharged through the floor monitor at 520 gpm and the proportioning valve from the bladder tank remained closed. This test resulted in a PFHxA value of 29 ppt and no detectable PFOA. The proportioning valve from the bladder tank (that was filled with water) was opened for the next floor monitor water discharge. Water flow was measured at 515 gpm and the PFHxA was measured at 18 ppt and no detectable PFOA.

The remaining system discharges were conducted with PFF concentrate proportioned into the system from the bladder tank. No detectable quantities of PFAS were collected in any PFF testing including all low-level nozzle system and closed-head foam-water simulated sprinkler system discharge tests. The hypothesis from this result is that the ability for any remaining PFAS in the fire suppression system after the bladder tank triple rinse and water flushing through the piping was not enough to contaminate the high velocity flowing water through the system to a level that is detectable. There is still the possibility that with longer residence time of liquid contact with the fire suppression system components that detectable levels of PFAS may be found in those liquids. This is more likely in the bladder tank where long term storage of foam concentrate in a potentially contaminated bladder may release PFAS into the foam concentrate.

4.2. LOW-LEVEL NOZZLE SUPPRESSION SYSTEM

4.2.1. AGENT APPLICATION RATE

The flow rate through the floor monitor is a product of the water pressure at the pump house, pressure losses in the system between the pump house and the nozzle, and the characteristics of the nozzles used in the test. Reasons for system pressure losses include restrictions such as valves, orifices, nozzles, pipe size decreases, and friction losses between the water and the pipe surface which increase with increased velocity of the water, or flow, in the pipe.

Pump house pressure was not planned to be recorded during these tests, however, the pressure was noted during several tests. During all floor monitor and large flow simulated sprinkler tests

where flow rates were between 435-830 gpm, the jockey pump could not maintain system pressure and a single diesel engine pump automatically came on to maintain pressure. The pump house pressure was between 152-162 psi in these tests. During the low flow sprinkler tests, the jockey pump maintained pump house pressure at 138-140 psi and the large diesel pumps never automatically activated at this flow rate.

The range of flow rates measured during all floor monitor tests with all nozzles except the PC-50 nozzle were 515 – 580 gpm. All data collected are listed in the table in Appendix B. For the four tests with the PC-50 nozzle, the measured flow was 335-340 gpm. The foam/water pressure measured in the hangar bay adjacent to the floor monitor ranged from 112-138 psi in all of these tests. From these measured flows and pressures, the nozzle k-factor was calculated for each test from the formula:

$$\text{K-factor} = \text{Flow} / (\text{pressure})^{0.5}$$

During the planning of this testing, the original non-air aspirated floor monitor nozzle was thought to have a k-factor of 39 based on facility records and from speaking to industry experts. However, during 14 discharge tests with this nozzle, the calculated k-factor averaged 50. The three nozzles recommended by the PFF manufacturers (Task Force Tips ZN Industrial 2.5”, KCA KNN500NA, and Gladiator 500) all had stated k-factors of 50 and measured values averaged 51 (TFT) and 47 (KCA). The flow meter malfunctioned during tests with the Gladiator 500 nozzle and no k-factor was calculated. The PC-50 nozzle was expected to have a k-factor of 40 and the measured values were 37. Figure 6 shows a floor monitor discharge test with the TFT nozzle and the air-aspirated attachment.



Figure 6. TFT Nozzle Discharge with Air-Aspirated Attachment

Figure 7 shows the average flow rates with error bars for each agent discharged through the floor monitor. The figure includes data with the facility original non-air aspirated nozzle and for the other manufacturer specified or default non-air aspirated and air-aspirated nozzles tested. Water only and AFFF discharge tests were only conducted with the original nozzle so there are no results included for the air-aspirated or non-air aspirated nozzles. BioEx did not specify a non-air

aspirated nozzle different from the original nozzle, resulting in no plotted data for the non-air aspirated nozzle with this agent, although data is plotted for the original nozzle with this agent.

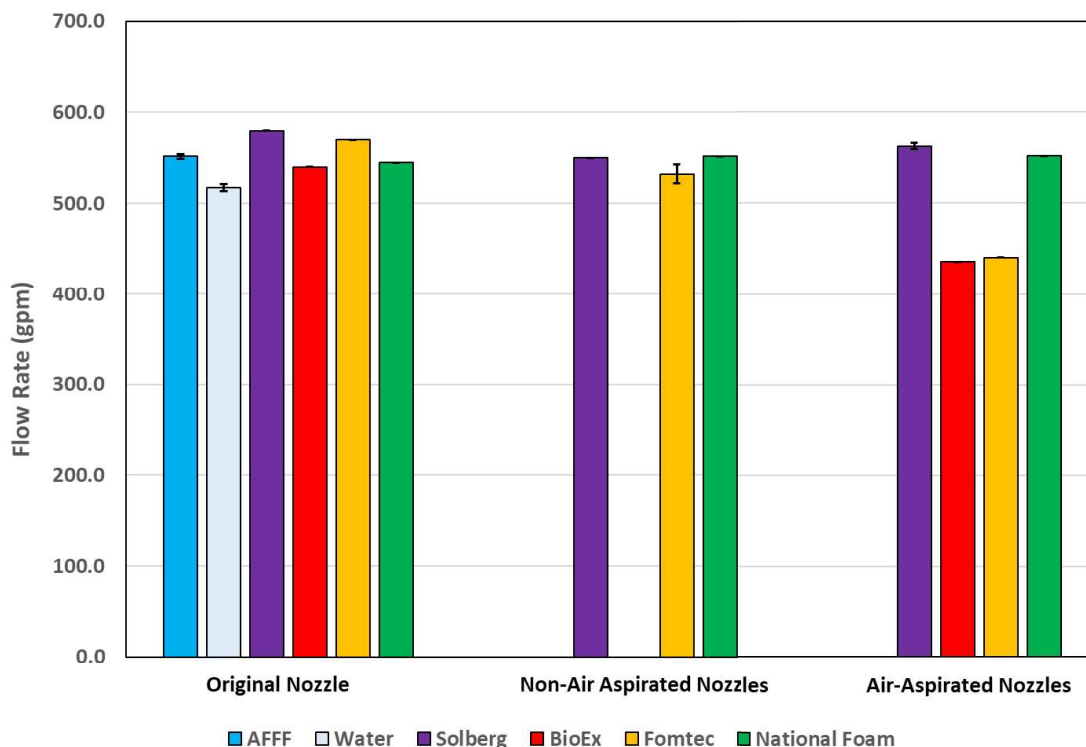


Figure 7. Average Floor Monitor Flow Rates for Each Agent and Nozzle Type

Application rate of the foam/water discharge is calculated using the measured flow rate and the floor area (listed in Section 3.1.1 as 65- by 75-ft). The resulting calculations were an application rate of 0.11-0.12 gpm/ft² for all AFFF and all PFF with the exception of tests with the PC-50 nozzle. The lower k-factor of the air-aspirated PC-50 nozzle resulted in a lower flow rate than other tests (see Figure 7) and an application rate of 0.09 gpm/ft² for the two tests each conducted with BioEx Ecopol-A and Fomtec Enviro USP. The Newtonian and non-Newtonian nature of the concentrates were not factors in these reduced flow rates.

4.2.2. AGENT PROPORTIONING

Foam concentrate proportioning is important in foam/water systems to ensure that the agent reaching the fire is the approved and proven mixture for optimum fire suppression. NFPA 11 Annex D, Section D.2 (3) discusses collecting and analyzing the concentration of foam solutions discharged from a suppression system. Two methods are described for analyzing the collected foam/water sample, the refractive index method and the conductivity method. Laboratory analysis was conducted before testing began and the conductivity method provided the best accuracy for foam concentration analysis, so this method was used in all testing. Section 3.1.5.1 describes the procedures for collection and analyzing the foam/water samples. NFPA 11, Section 11.6.4 (3) says, “The foam concentrate induction rate of a proportioner... shall be within minus 0 percent to plus 30 percent of the manufacturer’s listed concentrations.” Thus, for 3% foam concentrate the acceptable range of results is 3.0-3.9%.

In tests with AFFF and the original system proportioning valve, AFFF concentration was measured at a remarkably precise 3.00-3.02% in all three tests. Figure 8 shows this result and the average results (with data uncertainty error bars) for all tests. From Figure 8 it can be seen that the proportioning for all agents was within the acceptable range of 3-3.9% when the data uncertainty was considered. The individual tests results that were measured outside of the acceptable range were with Fomtec and Solberg agents, but with each of these agents, other test results were within the acceptable range resulting in the larger error bars shown in Figure 8.

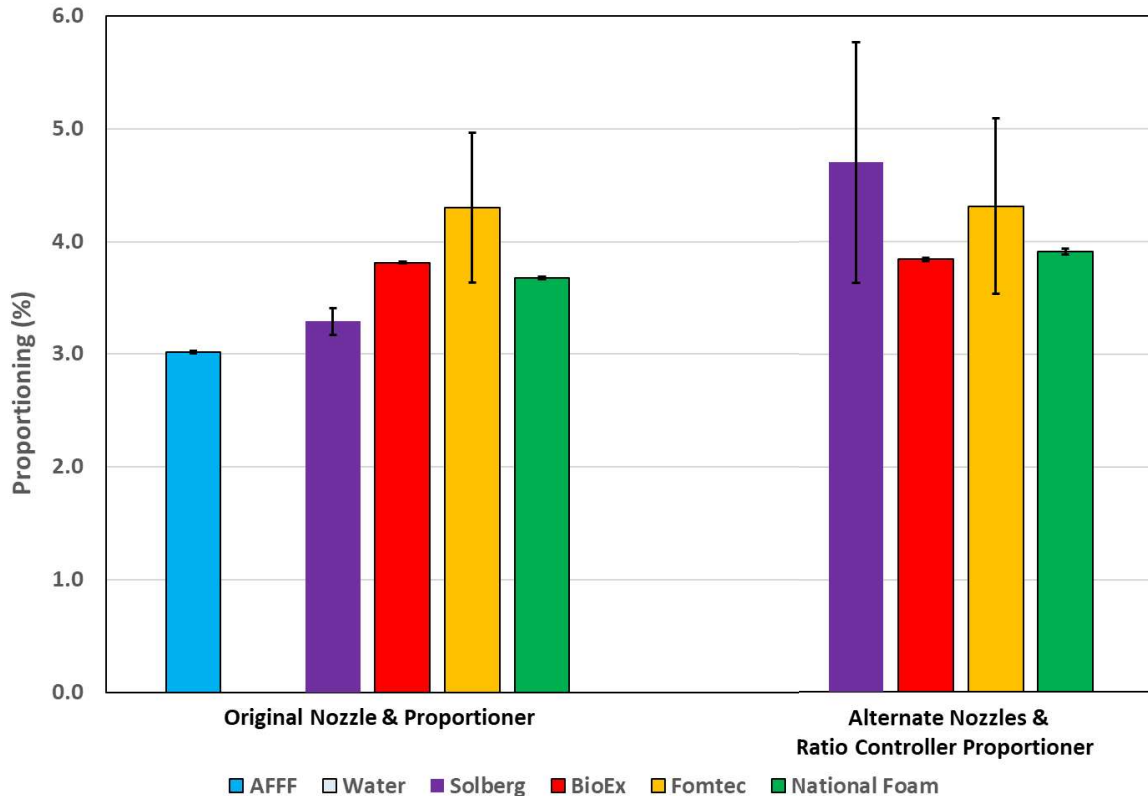


Figure 8. Average Foam Concentrate Proportioning for Each Agent and Nozzle/Proportioner Type

From Figure 8, BioEx, Fomtec, and National Foam had similar results with the original facility proportioner/nozzle as they did with manufacturer specified or replacement proportioners/nozzles. Solberg foam results were closer to 3% when using the original facility proportioner and nozzle.

Including all nozzles and proportioners tested with the floor monitor discharge, the Solberg agent was proportioned between 3.2-5.32%; the BioEx was proportioned between 3.81-3.85%; Fomtec was proportioned between 3.83-5.46%; and the National Foam was proportioned between 3.67-3.92%. Additional proportioning charts are shown in Appendix B.

4.2.3. FOAM QUALITY

NFPA 11, Annex D (3) procedures were followed for collection and measurements of foam expansion and drain time as described in Section 3.1.5.2. Two NFPA foam collection backboards were used to collect samples for foam quality during each floor monitor discharge test. Since each test was repeated twice, there were four foam quality samples collected for each turret discharge scenario. Discharge tests included drop-in with the original facility proportioner and nozzle, and non-air aspirated and air-aspirated with manufacturer specified or replacement proportioners/nozzles. All data collected are listed in the table in Appendix B.

4.2.3.1. DROP IN TESTS

Drop-in results for AFFF and all PFF are plotted with foam expansion versus drain times in Figure 9. All expansion ratios exceeded 11:1 with the non-Newtonian foams (Solberg and Fomtec) having the highest expansion ratios. All Newtonian foams (AFFF, BioEx, and National Foam) had similar expansion and 25% drain times. The non-Newtonian agents exhibited much higher 25% drain times than the Newtonian agents. Drain times for the Newtonian agents were equal to or greater than the AFFF drain time.

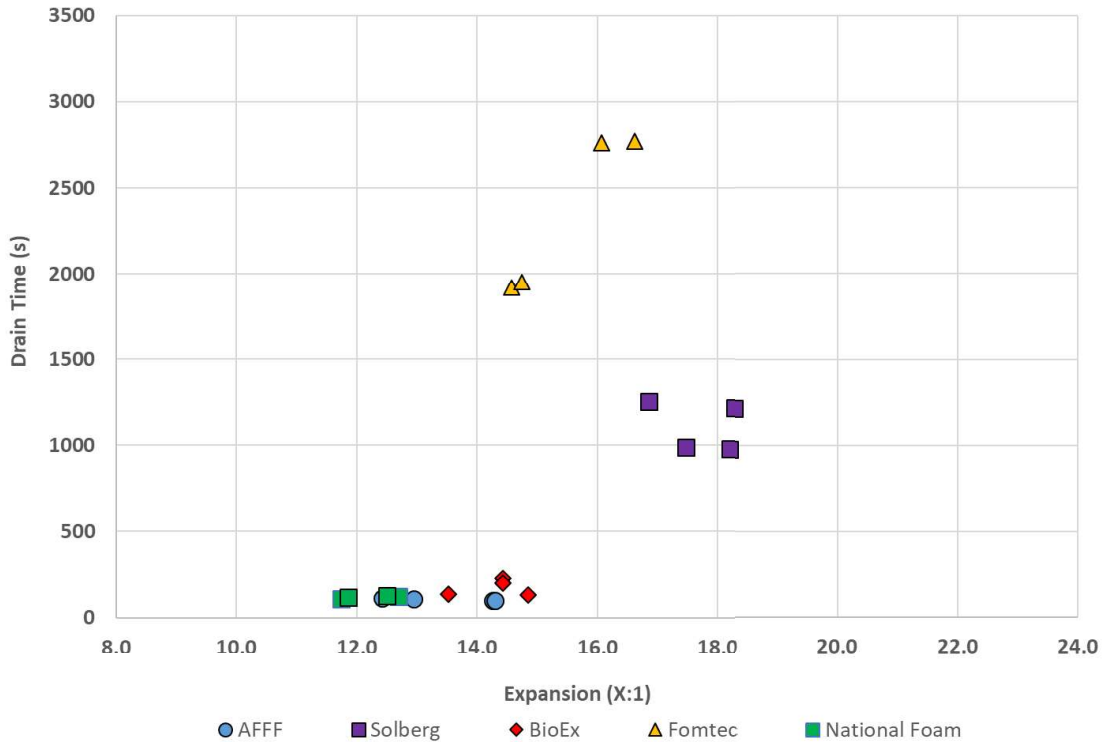


Figure 9. Measured Foam Expansion and Drain Time in Drop-In Tests

4.2.3.2. MANUFACTURER SPECIFIED HARDWARE TESTS

Results for the manufacturer specified or replacement proportioners/nozzles are in the following figures. Figure 10 has the results for the manufacturer specified or replacement non-air aspirated nozzles and ratio controller proportioners. Figure 11 has the results for the manufacturer specified or replacement air-aspirated nozzles and ratio controller proportioners. Since the

manufacturer did not specify a non-air aspirated turret or a replacement ratio controller proportioner, the plots for BioEx in Figure 9 and Figure 10 are the same data.

From Figure 9 and Figure 10, there was negligible difference in foam expansion as a result of switching from the drop-in hardware to the manufacturer specified proportioners and non-air aspirated nozzles. Only one of the non-Newtonian agents exhibited a higher 25% drain time with this switch. From Figure 10 and Figure 11, the average foam expansion measurements for the air-aspirated nozzles was lower than the non-air aspirated nozzles for three of the four PFF, one Newtonian foam was the exception. Drain times for the Non-Newtonian agents appear slightly higher with the air-aspirated nozzle, however the differences did not fall outside of the data uncertainty. Drain times were slightly lower for both Newtonian agents.

Table 4 lists the average foam expansion and drain time for each of the test scenarios and includes the variability for the averages. A discussion of acceptable foam quality results is in Section 3.1.5.2. While NFPA 11 does not specify minimal acceptable results, NFPA 412 (4) and MIL-PRF-24385F (1) do. All floor monitor expansion ratios measured exceeded those minimal acceptable levels, however a few measured Newtonian agent 25% drain times were below NFPA 412 (4) or MIL-PRF-24385F (1) levels for non-air aspirated or air-aspirated nozzles.

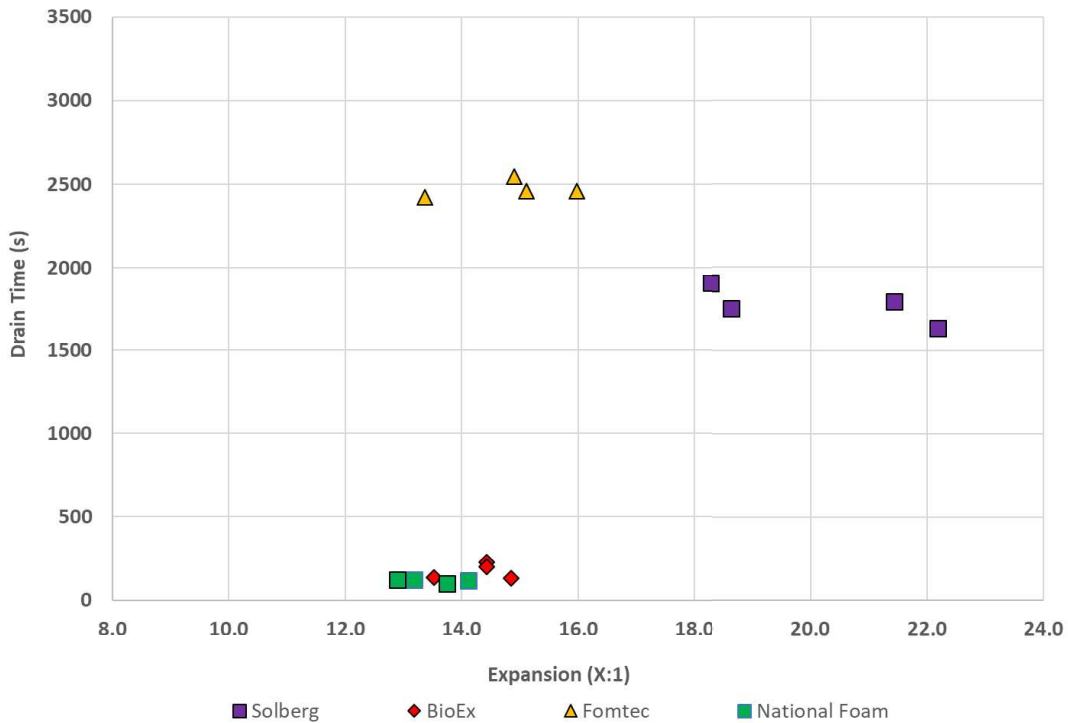


Figure 10. Measured Foam Expansion and Drain Time in Non-Air Aspirated Tests

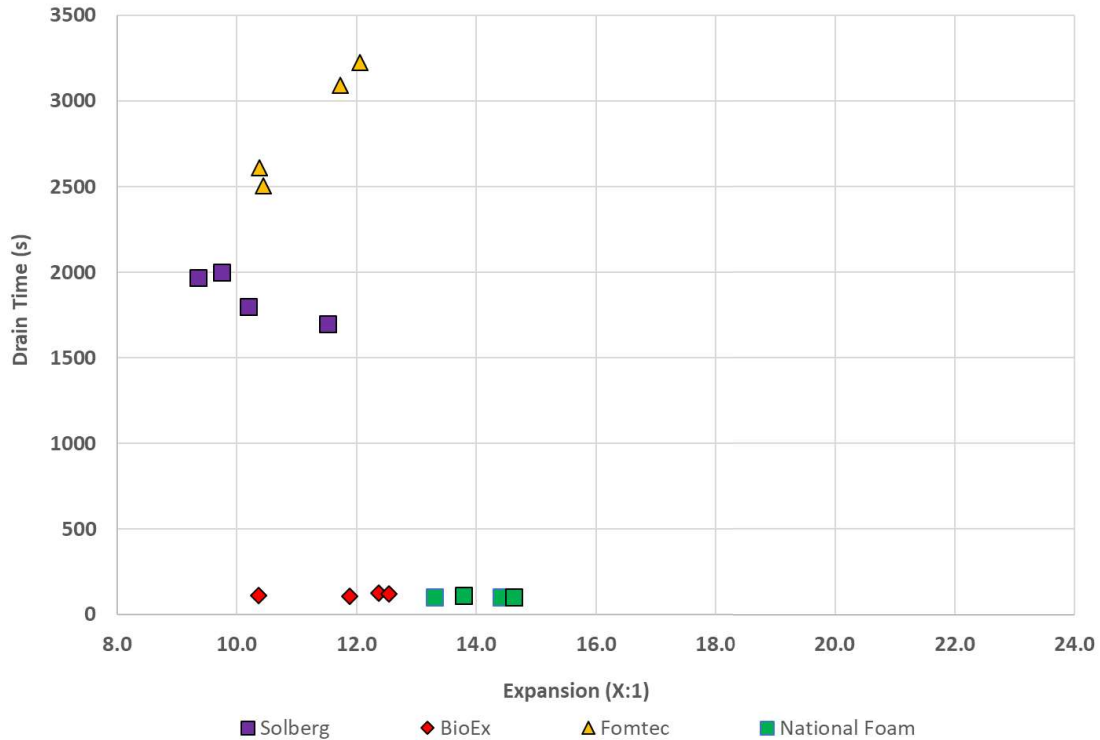


Figure 11. Measured Foam Expansion and Drain Time in Air-Aspirated Tests

Table 4. Average Foam Quality Results for Turret Discharge Tests

Nozzle Type	AFFF		Solberg		BioEx		Fomtec		National Foam	
	Exp. Ratio (X:1)	Drain Time (s)	Exp. Ratio (X:1)	Drain Time (s)	Exp. Ratio (X:1)	Drain Time (s)	Exp. Ratio (X:1)	Drain Time (s)	Exp. Ratio (X:1)	Drain Time (s)
Drop In	13.5 ±0.9	106 ±6.4	17.7 ±0.7	1,110 ±147	14.3 ±0.6	174 ±47	15.5 ±1.0	2,349 ±479	12.2 ±0.5	119 ±7.5
Non-Air Aspirated	n/a	n/a	20.1 ±2.0	1,770 ±112	14.3* ±0.6	174* ±47	14.8 ±1.1	2,472 ±51	13.5 ±0.6	115 ±11
Air-Aspirated	n/a	n/a	10.2 ±0.9	1,867 ±143	11.8 ±1.0	114 ±9.3	11.2 ±0.9	2,856 ±354	14.0 ±0.6	102 ±4.3

* Same hardware as Drop-In tests. Tests were not repeated.

4.3. CLOSED-HEAD FOAM-WATER SPRINKLER SYSTEM

Section 3.1.4 describes the planned low flow 64 gpm and high flow 800 gpm sprinkler flow tests, and diagrams of the test setup are in Appendix A, Figure A- 3, and Figure A- 4. This description includes the specific sprinkler head used in all low flow discharges and the valves and flow meters specific to the high flow tests. Test procedures are described in Section 3.2.

Since no foam proportioning sprinkler system was installed in the test facility, simulated sprinkler discharge was conducted using the floor monitor suppression system with the agent discharge through a single sprinkler for low flow and through the test headers for the high flow tests. These two flow rates evaluated the extremes of the sprinkler proportioning system for the scenarios of either a single sprinkler or multiple sprinklers operating.

Before collecting samples from low flow tests, the system was allowed to discharge for 60 seconds after the first indication of foam exiting the nozzle to ensure the piping was fully flushed from the proportioner and an accurate representation of the agent proportioning was obtained. For the high flow tests, the system was allowed to flow for 15 seconds after the first indication of foam exiting the nozzles before sampling for the same reason.

For all sprinkler tests a wide-range proportioner valve was used to proportion the foam concentrate into the suppression system. Section 3.1.2 describes the proportioner hardware used and their minimum/maximum flow range specifications for each agent. No sprinkler tests were planned with AFFF foam concentrate. All data collected are listed in the table in Appendix B.

4.3.1. AGENT PROPORTIONING

Agent proportioning samples were collected from the same location as in the floor monitor discharge tests and analyzed using the conductivity method for foam proportioning as described in Sections 4.2.2 and 3.1.5.1 for turret discharge tests. NFPA 11 Annex D, Section D.2 (2) discusses collecting and analyzing the concentration of foam solutions discharged from a suppression system. NFPA 11, Section 11.6.4 (2) says, “The foam concentrate induction rate of a proportioner... shall be within minus 0 percent to plus 30 percent of the manufacturer’s listed concentrations.” Thus, for 3% foam concentrate the acceptable range of results is 3.0-3.9%.

Table 5 has the results from all low flow and high flow tests. Flow rate was measured at 63-64 gpm for all low flow tests. High flow tests measured flow was 800 gpm for three tests and 830 gpm for the other test. The higher 830 gpm was due to an incorrect valve adjustment. Only two of the eight proportioning samples collected fell within the acceptable limits of 3.0-3.9%, one low flow and one high flow. No combination of tested wide-range proportioner and PFF agents at the two flow extremes proportioned within the acceptable percentage.

Only one of the eight tests fell outside of the flow ranges specified by the proportioner manufacturers. That test was the low flow test of the Solberg wide-range proportioner. The flow rate measured was 63 gpm and the proportioner specifications list a minimum flow rate of 115 gpm. All other wide-range proportioners listed minimum flow rates below the measured 64 gpm. Proportioning charts for individual agents are in Appendix B.

Table 5. Flow Rate and Foam Proportioning for Low and High Flow Sprinkler Tests

Nozzle Type	Solberg		BioEx		Fomtec		National Foam	
	Flow Rate (gpm)	Prop. %	Flow Rate (gpm)	Prop. %	Flow Rate (gpm)	Prop. %	Flow Rate (gpm)	Prop. %
Low Flow	63	6.34	64	3.9	64	12.21	64	0.26
High Flow	800	3.67	830	4.46	800	8.32	800	4.8

The Solberg agent along with the 6-in, variable range proportioner produced the only acceptable high flow result. The low flow result was high and the flow rate being less than the proportioner minimum may have factored into this measurement outside of the acceptable range.

BioEx did not specify a wide-range proportioner, so the Ansul FLOWMAX CL variable range proportioner was used as specified in the test plan. The low flow proportioning result was at the high end of the acceptable limits (3.9%) and was the only acceptable low flow result of the four agents tested. The high flow proportioning was high.

The Fomtec agent along with the manufacturer specified 6-in, wide range proportioner produced more than twice the proportioning in the high flow test and more than three times in the low flow test. The resulting low flow foam quality results may have been affected by this high proportioning rate.

National Foam reported that their agent was not recommended for sprinkler applications and had not previously been evaluated in a sprinkler system. As a result, prior to recommending a wide range proportioner, the manufacturer stated that there was no test data to use to select an appropriate proportioner. The proportioning at low flow was almost non-existent based on three conductivity tests of the sample collected and was the only measured result under the target 3%. Nonetheless, a foam blanket formed on the floor during the low flow discharge as with other products (Figure 13).

4.3.2. FOAM QUALITY

As discussed in Section 3.1.5.2, foam quality was not originally planned to be measured during sprinkler flow tests since sprinkler heads were not going to be installed at typical spacing and ceiling height. After testing began, the decision was made to collect a foam sample for drainage and expansion during the low flow tests with the understanding that the result would not be representative of a typical installation and would only be relative to other similar measurements. There were also no plans for AFFF sprinkler discharge tests. As a result, there were four total foam quality samples collected, one for each of the PFF agents.

The test results are in Figure 12 and Table 6. Expansion ratios for three of the four agents were lower than in the floor monitor testing. This was expected since the sprinkler head was close to the floor and there was not much air interaction with the foam concentrate solution to develop the foam. Both non-Newtonian agents had the higher measured expansion ratios, however, for one of the non-Newtonian agents, Fomtec, the expansion was much higher than the others. It was also surprising that National Foam expansion was as high as 4.6:1 when the agent was only proportioned at 0.26%. The non-Newtonian foams also had much higher 25% drain times in the sprinkler tests than the Newtonian foams, as might be expected with the foam properties and the higher expansion ratio numbers. The non-Newtonian agent Fomtec produced a remarkable 25% drain time of 5.5 hours. It's difficult to determine what test conditions led to this long drain time, but as discussed in Section 4.3.1, this agent was proportioned at 12.2%, which may have been a factor in the high expansion and drain time of this agent.

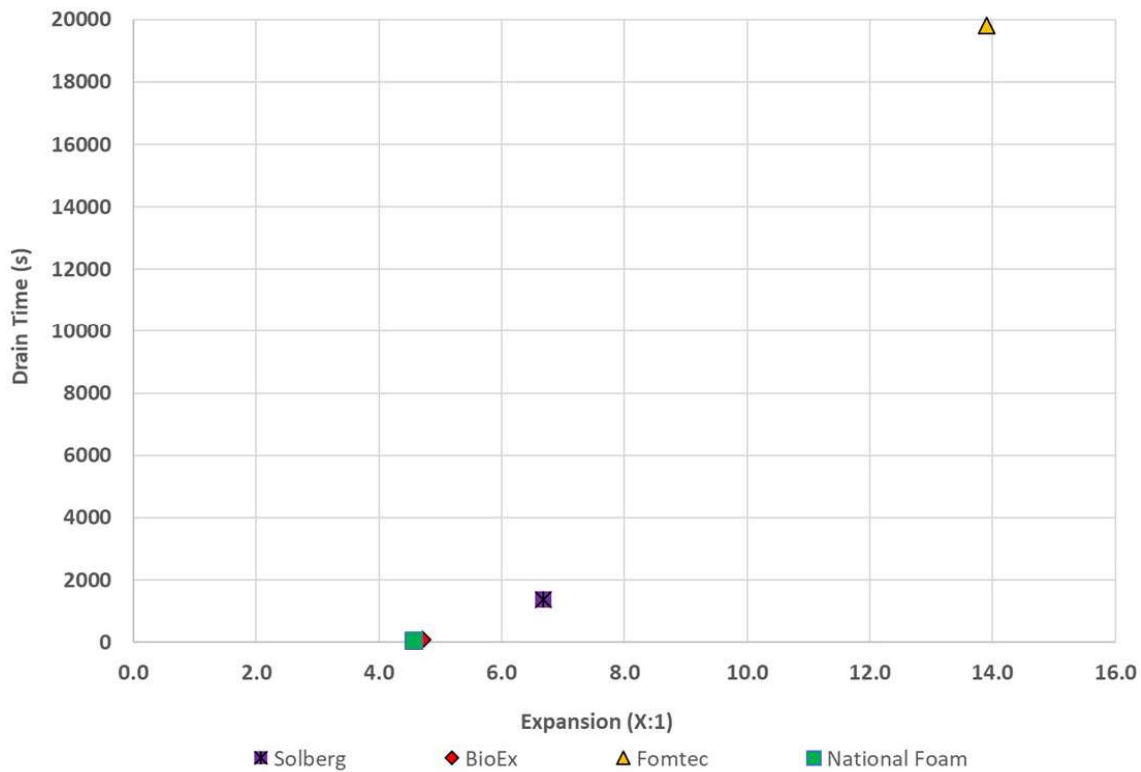


Figure 12. Measured Foam Expansion and Drain Time in Low Flow Sprinkler Tests

Table 6. Foam Quality Results for Low Flow Sprinkler Discharge Tests

Nozzle Type	Solberg		BioEx		Fomtec		National Foam	
	Exp. Ratio (X:1)	Drain Time (s)	Exp. Ratio (X:1)	Drain Time (s)	Exp. Ratio (X:1)	Drain Time (s)	Exp. Ratio (X:1)	Drain Time (s)
Low Flow	6.7	1,379	4.7	< 90	13.9	19,800*	4.6	69

* 25% Drain Time for the Fomtec sprinkler test was remarkable (5.5 hours). Concentrate proportioning was high at 12.2% and expansion was also higher than for other foams.

Video still shots of the four sprinkler discharges are shown in Figure 13. This images were taken immediately before the foam quality samples were collected, approximately 60 seconds after the first indication of foam exiting the sprinkler.



Figure 13. Sprinkler Discharge with all Agents: Solberg (top left), BioEx (top right), Fomtec (bottom left), and National Foam (bottom right)

4.4. MONITORING FOR BUTYL CARBITOL EXPOSURE

As described in Section 3.1.5.6, three personnel wore AssayTech personal passive TraceAirII Monitor for Organic Vapors badges during a day of testing each foam concentrate for a total of 5 days and 15 total samples collected. Multiple floor monitor discharge tests were conducted each day badges were worn. Two of the personnel were responsible for collecting foam samples at the moment the collection devices filled, requiring them to step into the foam spray. The third support person was also in the hangar bay, but did not approach the foam spray. Except for the few minutes of sample collection throughout the day, the three personnel basically performed the same functions.

Instructions for using the badges included that the badges should remain dry during exposure. The badges are intended to absorb butyl carbitol from air contact and may absorb higher levels from liquid contact. An attempt was made to keep the badges away from the foam spray by placing the badges under the chin of the collection personnel. Despite the precaution, the collection personnel were not successful in efforts to keep the badges dry while keeping them in the vicinity of their breathing air intake. Therefore we have reason to believe that this liquid contact affected the results of the collection personnel badges, and we have no reason to doubt the analytical results of the badge testing laboratory. Since the badges from the support person did not come in contact with liquid, these results should be more representative to the exposure of someone in the hangar during a floor monitor discharge. Any future monitoring would be prudent to adjust the sampling plan to better protect the monitoring badges from liquid contact.

The results from the monitoring badges are reported in Table 7. For each of the five foam concentrates tested, the results for the support personnel (1 sample each) and collection personnel (2 samples each) are listed. These exposure results have been adjusted, based on the time each badge was exposed, to the exposure that would have occurred for 8 hours exposure. This time weighted average (TWA) can be compared to the allowed American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit value (TLV) of 10 parts per million 8 hour TWA for butyl carbitol that is listed in the far right column of Table 7. The results for the support personnel were < 0.5 ppm TWA exposure for all tests indicating safe levels of butyl carbitol in the facility during testing.

As stated above, it is believed that the collection personnel results were contaminated by liquid contact with the badges. Two of the ten collection personnel results were the same as the support personnel and the other eight were higher. The conclusion is that these two badges were kept from liquid contact. For the other eight results, no conclusion can be made about if the collection personnel were exposed to higher concentrations in air of butyl carbitol since the potential for liquid contact may have affected those readings. A similar trial could include additional monitoring with static sensors or collection badges protected from liquid contact. The protected monitors will provide clearer assessment of volatile butyl carbitol during discharge.

Table 7. Butyl Carbitol Breathing Zone Monitoring Results

Foam Concentrate Type	Support Personnel Results (8 hr. TWA)	Collection Personnel Results (8 hr. TWA)	ACGIH TLV (8 hr. TWA)
Ansulite 3% AFFF	<0.5 ppm	<0.5 ppm 0.5 ppm	10 ppm
Solberg Re-Healing Foam RF 3%	<0.1 ppm	4.5 ppm 8.8 ppm	10 ppm
BioEx Ecopol-A	<0.1 ppm	<0.1 ppm 2.3 ppm	10 ppm
Fomtec Enviro USP	0.1 ppm	1.4 ppm 5.1 ppm	10 ppm
National Foam Avio Green KHC 3%	0.1 ppm	33.5 ppm 22.5 ppm	10 ppm

5. CONCLUSIONS

No detectable quantities of PFHxS or PFOS were detected in any discharge test. The first water discharge and AFFF discharge samples showed detectable quantities of PFHxA and PFOA. After triple rinsing the foam concentrate tank then flushing the system with two, one-minute, water-only system discharges low levels of PFHxA were detected. No other representative PFAS were detected. The samples analyzed from PFF trials did not reveal any of the analytes. The present results suggest triple rinsing the bladder tank and flushing water through piped system reduced the representative PFAS below detectable levels in subsequent uses of the system. The present test was not exhaustive, longer residence time and liquid contact with the fire suppression system components may dissolve residue in interstitial spaces and release PFAS into liquid. This is higher potential in the bladder tank where long term storage of foam concentrate in a potentially contaminated bladder may release PFAS into the foam concentrate.

A series of quantitative assessments of the discharge and mixing operations showed generally good compatibility of the PFF with the existing system. Agent application rates were 0.11-0.12 gpm/ft² for all AFFF and all PFF tests with the exception of tests with the PC-50 nozzle. The lower k-factor of the PC-50 nozzle decreased application rate to 0.09 gpm/ft² in the four tests that it was used.

The floor monitor proportioning delivered concentrate and mixed with water acceptably. All tests showed mixed agents were 3.0-3.9%, matching targeted values and recommended concentrations. The results using the original facility proportioner and nozzle were comparable to the alternative proportioners and nozzles specified by the manufacturer for three of the four PFF tested. The Solberg non-Newtonian foam was actually closer to the target 3% with the original facility proportioner and nozzle than with the manufacturer-specified components.

The simulated closed-head sprinkler proportioning evaluations had less consistent results even though the same discharge nozzles and orientations were used for each test. Only two of the eight proportioning samples were within the acceptable concentration range (3.0-3.9%), one from a low flow test and one from a high flow test. None of the wide range proportioners accurately metered and mixed PFF at both extremes of low and high flow sprinkler discharge rates.

The foam quality (i.e., expansion ratio and 25% drain times) were determined following floor monitor discharge and compared. Direct comparisons of the AFFF and PFF using the existing system (drop-in) showed 3 of 4 PFF had higher expansion ratios. The drain times for Newtonian foams were comparable and the thick, non-Newtonian foams drain times were much longer. The foam quality characteristics for PFF tested using a manufacturer specified non-air aspirated nozzle were comparable to the drop-in test except the expansion and drain time for the non-Newtonian Solberg foam was higher. The air-aspirated nozzle tests differed, three of the four PFF had statistically lower expansion ratios than with the non-air aspirated nozzles and drop-in tests; the drain times were comparable to the drop-in test for 3 of 4 foams. Again, the drain time for the Solberg PFF increased markedly compared to the drop-in test hardware.

The foam quality results for sprinkler heads were largely irrelevant because the nozzles was too close to the floor and the proportion of foam concentrates were not within proper working range. For example the proportioning system mixed the non-Newtonian Fomtec agent to 12.2%; the 25% drain time of the resulting foam was 19,800 seconds, more than 8-fold longer than the test with drop-in floor monitors.

From the perspective of foam proportioning, foam quality, and application rates, all Newtonian and non-Newtonian PFF concentrates evaluated were suitable as drop in agents in floor monitor discharge. Fire suppression performance was not evaluated in this study. Conversely, none of the PFF proportioned within acceptable limits in both low flow and high flow sprinkler discharges.

Butyl carbitol is commonly used in AFFF and PFF and excess exposure has negative health consequences. Personnel exposure was monitored during tests and operation activities using commercial sampling badges. The badge material effectively compiles volatile butyl carbitol, but are fouled if exposed to any liquid. The valid materials (those that remained dry throughout use), showed TWA exposure to butyl carbitol <0.5 ppm for all tests. That level is well below the formal risk regulation, the TLV of 10 ppm.

6. RECOMMENDATIONS

- Investigate if long term storage of fluorine foam concentrate in a contaminated bladder may release PFAS into the foam concentrate.
- In future monitoring for airborne butyl carbitol from foam agent floor monitor or other discharge tests it would be prudent to adjust the sampling plan to better protect the monitoring badges from liquid contact.
- A wide range proportioner was not found to accurately proportion PFF at both extremes of low and high flow sprinkler discharge rates. Additional investment is warranted to match a wide-range proportioner for a closed head sprinkler system to a promising PFF.

7. REFERENCES

1. **Performance Specification, Fire Extinguishing Agent, Aqueous Film-Forming Foam (AFFF) Liquid Concentrate, for Fresh and Sea Water.** s.l. : Naval Sea Systems Command, 2017. MIL-PRF-24385F.
2. **Back, Jerry. Capabilities Assessment of Commercially Available PFAS-free Foams.** *<https://www.serdp-estcp.org/Program-Areas/Weapons-Systems-and-Platforms/Noise-and-Emissions/WP19-5324>*. s.l. : ESTCP WP19-5324, 2021.
3. **National Fire Protection Association (NFPA) 11 Standard for Low-, Medium-, and High-Expansion Foam.** 2016.
4. **National Fire Protection Association (NFPA) 412 Standard for Evaluating Aircraft Rescue and Fire-Fighting Foam Equipment.** 2014.
5. **Jia, Shenglan, et al. Recent advances in mass spectrometry analytical techniques for per- and polyfluoroalkyl substances (PFAS).** *Analytical and bioanalytical chemistry*. 2022. Vols. 1-13.

Appendix A: System Test Setup Drawings

Drawings were provided by Industrial-Commercial Fire Protection, Inc.

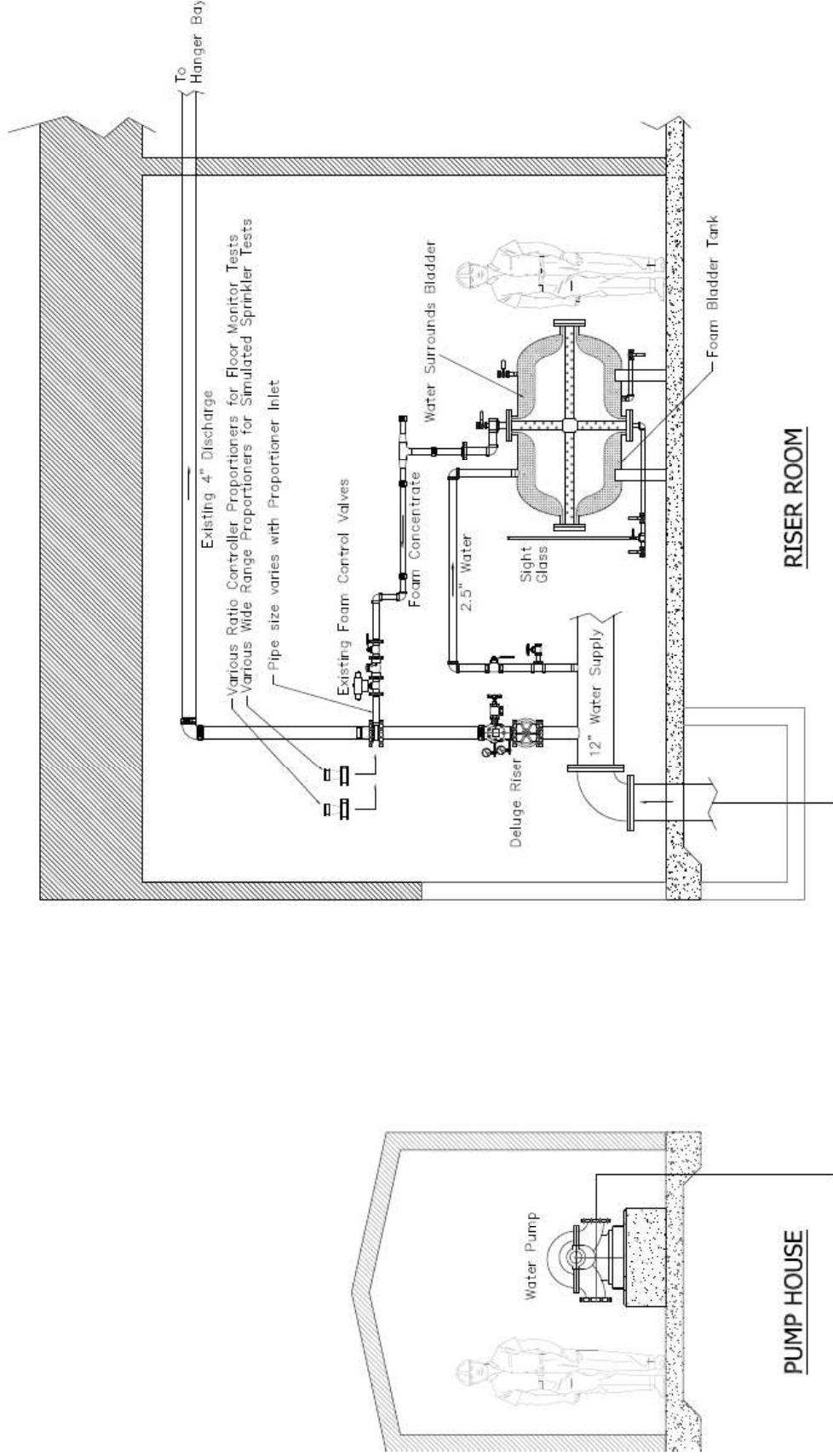


Figure A- 1. Pump House and Riser Room Details Schematic

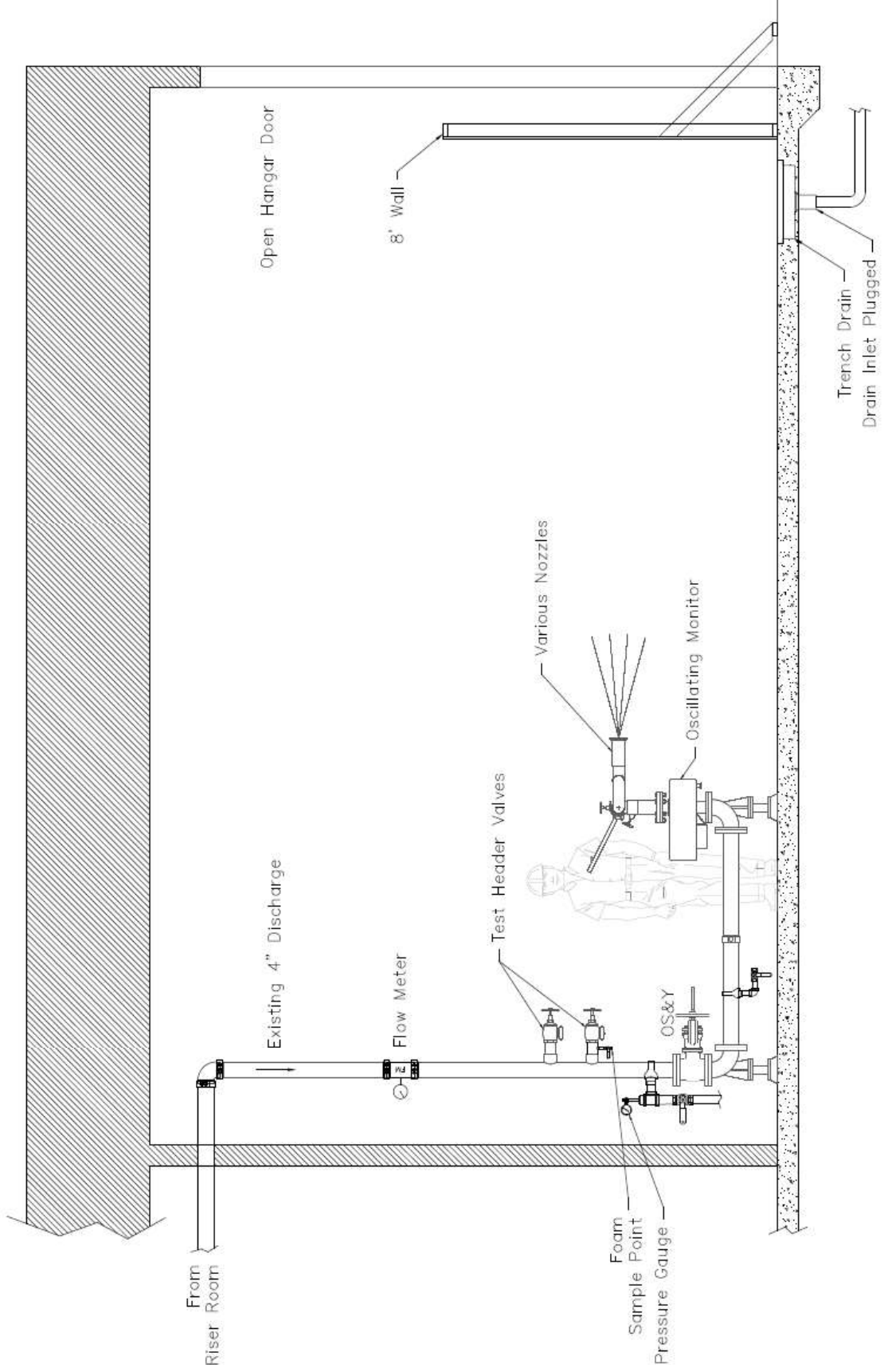


Figure A- 2. Hangar Bay Turret Discharge Details Schematic

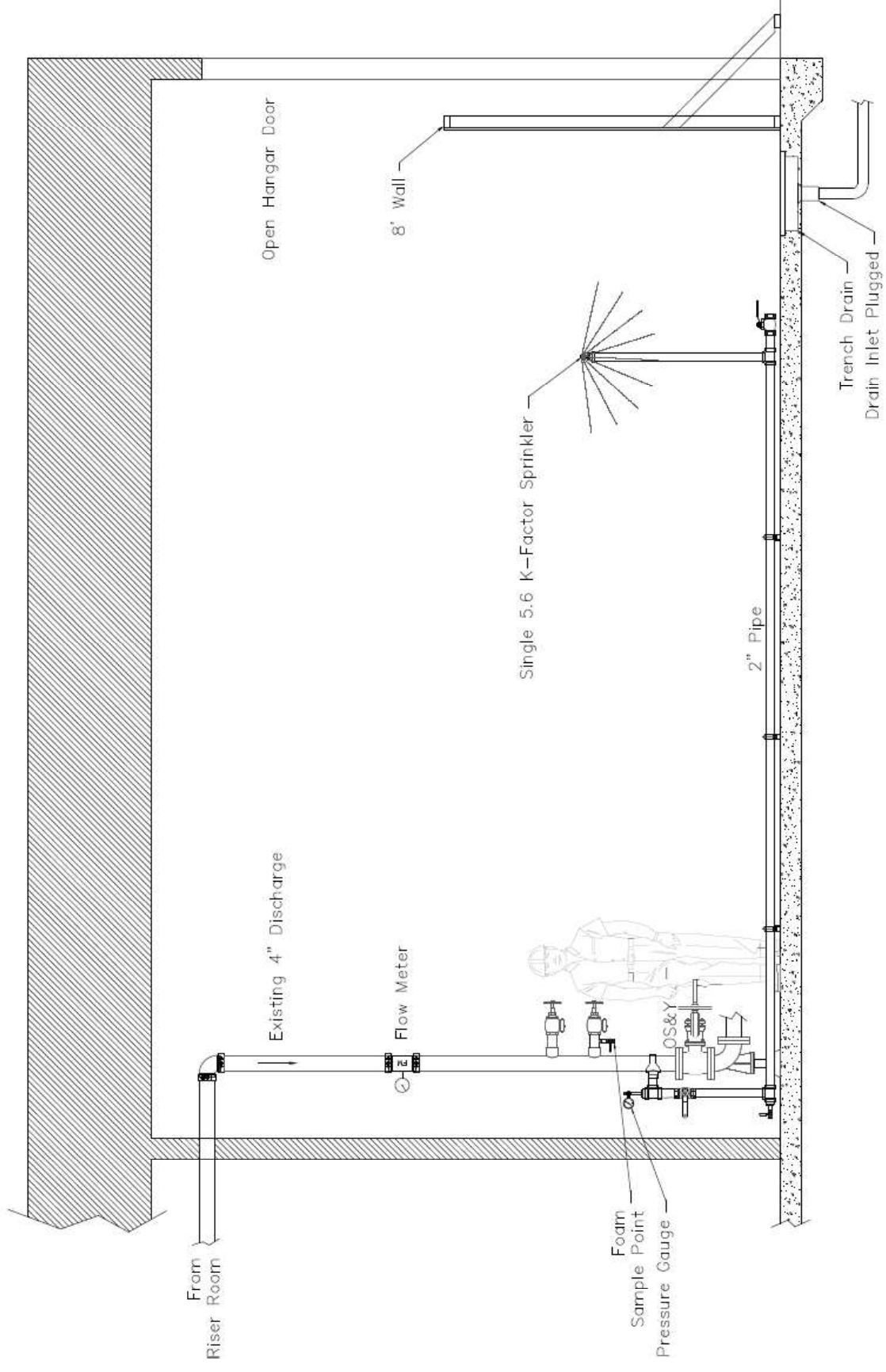


Figure A-3. Hangar Bay Low Flow Sprinkler Discharge Details Schematic

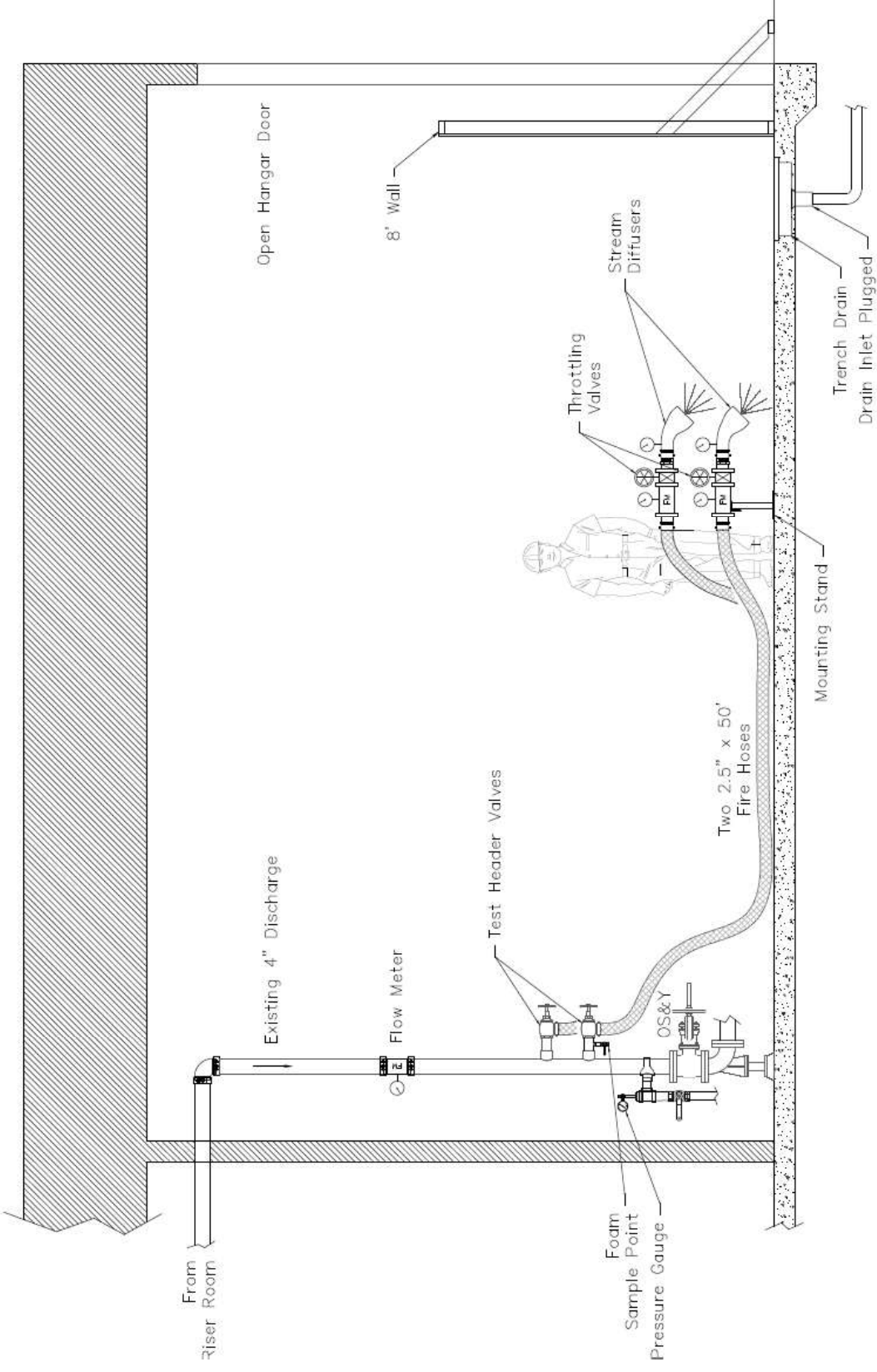


Figure A- 4. Hangar Bay High Flow Sprinkler Discharge Details Schematic

Appendix B: Test Data

Test #	Agent	Nozzle	K-factor calculated	Prop. Type	Flow Rate (gpm)	Application Rate (gpm/sq ft)	Nozzle (psi)	Exp. A (X:1)	Exp. B (X:1)	Drain A (s)	Drain B (s)	Prop. %	PFHxA (ppt)	PFOA (ppt)	PFHxS (ppt)	PFOS (ppt)
	Water	K 5.6 sprinkler		Original	-	-	-	-	-	-	-	-	783	79.8	ND	ND
1	AFFF	Williams	50	Original	550	0.11	123	25.7*	24.5*	190	188	3	5370	136	ND	ND
2	AFFF	Williams	50	Original	550	0.11	123	13.0	12.4	110	112	3.02	3050	187	ND	ND
3	AFFF	Williams	50	Original	555	0.11	121	14.3	14.3	100	100	3.02	6190	135	ND	ND
	Tank Triple Rinse	-	-	-	-	-	-	-	-	-	-	-	26.8	ND	ND	ND
4	Water	Williams	48	Original	520	0.11	115	-	-	-	-	-	28.7	ND	ND	ND
5	Water	Williams	49	Original	515	0.11	112	-	-	-	-	-	18.2	ND	ND	ND
6	Solberg	Non-Air Aspirated	51	Ratio Controller	550	0.11	118	18.6	18.3	1752	1902	*	ND	ND	ND	ND
7	Solberg	Non-Air Aspirated	50	Ratio Controller	550	0.11	119	22.2	21.4	1632	1793	5.32	ND	ND	ND	ND
8	Solberg	Air-Aspirated	52	Ratio Controller	565	0.12	117	11.5	10.2	1699	1800	3.47	ND	ND	ND	ND
9	Solberg	Air-Aspirated	52	Ratio Controller	560	0.11	115	9.7	9.3	2002	1968	5.31	ND	ND	ND	ND
10	Solberg	K 5.6 sprinkler	5.6	Wide Range	63	-	126	6.7	-	1379	-	6.34	ND	ND	ND	ND
11	Solberg	-	92	Wide Range	800	-	75	-	-	-	-	3.67	ND	ND	ND	ND
12	Solberg	Williams	52	Original	580	0.12	125	18.3	16.9	1217	1255	3.2	ND	ND	ND	ND
14	Solberg	Williams	52	Original	580	0.12	126	18.2	17.5	977	990	3.37	ND	ND	ND	ND
15	Ecopol-A	Williams	48	Original	540	0.11	124	14.4	14.4	227	199	3.82	ND	ND	ND	ND
16	Ecopol-A	Williams	48	Original	540	0.11	124	14.8	13.5	133	135	3.81	ND	ND	ND	ND
17	Ecopol-A	Air-Aspirated	37	Original	435	0.09	137	10.4	11.9	109	103	3.85	ND	ND	ND	ND
18	Ecopol-A	Air-Aspirated	37	Original	435	0.09	136	12.4	12.5	124	118	3.83	ND	ND	ND	ND
19	Ecopol-A	K 5.6 sprinkler	5.6	Flowmax CL	64	-	130	4.7	-	<90	-	3.9	ND	ND	ND	ND

20	Ecopol-A	800 gpm	103	Flowmax CL	830	-	65	-	-	-	-	-	4.46	ND	ND	ND
21	Enviro USP	Non-Air Aspirated	46	Ratio Controller	525	0.11	131	15.1	16.0	2460	2460	2460	5.46	ND	ND	ND
22	Enviro USP	Non-Air Aspirated	47	Ratio Controller	540	0.11	130	14.9	13.4	2544	2424	2424	4.12	ND	ND	ND
23	Enviro USP	Air-Aspirated	37	Ratio Controller	440	0.09	138	10.4	10.4	2502	2608	2608	3.86	ND	ND	ND
24	Enviro USP	Air-Aspirated	38	Ratio Controller	440	0.09	136	12.1	11.7	3222	3090	3090	3.81	ND	ND	ND
25	Enviro USP	K 5.6 sprinkler	5.6	Wide Range	64	-	131	13.9	-	19800	-	-	12.21	ND	ND	ND
26	Enviro USP	800 gpm	96	Wide Range	800	-	70	-	-	-	-	-	8.32	ND	ND	ND
27	Enviro USP	Williams	51	Original	570	0.12	125	16.1	16.6	2760	2768	2768	4.77	ND	ND	ND
28	Enviro USP	Williams	51	Original	570	0.12	124	14.6	14.7	1920	1949	1949	3.83	ND	ND	ND
29	AVIO Green	Williams	50	Original	545	0.11	121	12.7	12.5	120	128	128	3.67	ND	ND	ND
30	AVIO Green	Williams	50	Original	545	0.11	121	11.7	11.9	110	117	117	3.69	ND	ND	ND
31	AVIO Green	Non-Air Aspirated	49	Ratio Controller	549	0.11	127	14.1	13.8	116	99	99	3.92	ND	ND	ND
32	AVIO Green	Non-Air Aspirated	49	Ratio Controller	549	0.11	127	13.2	12.9	122	121	121	3.92	ND	ND	ND
33	AVIO Green	Air-Aspirated	49	Ratio Controller	549	0.11	127	14.4	14.6	101	98	98	3.92	ND	ND	ND
34	AVIO Green	Air-Aspirated	49	Ratio Controller	549	0.11	127	13.3	13.8	100	108	108	3.87	ND	ND	ND
35	AVIO Green	K 5.6 sprinkler	5.6	Wide Range	64	-	130	4.6	-	69	-	-	0.26	ND	ND	ND
36	AVIO Green	800 gpm	94	Wide Range	800	-	73	-	-	-	-	-	4.80	ND	ND	ND

* Collection cups filled from foam layer on the floor instead of from the backboard

** Sample not representative. Collected after system was shut down.

ND-Analyte not detected or detected below the detection limit

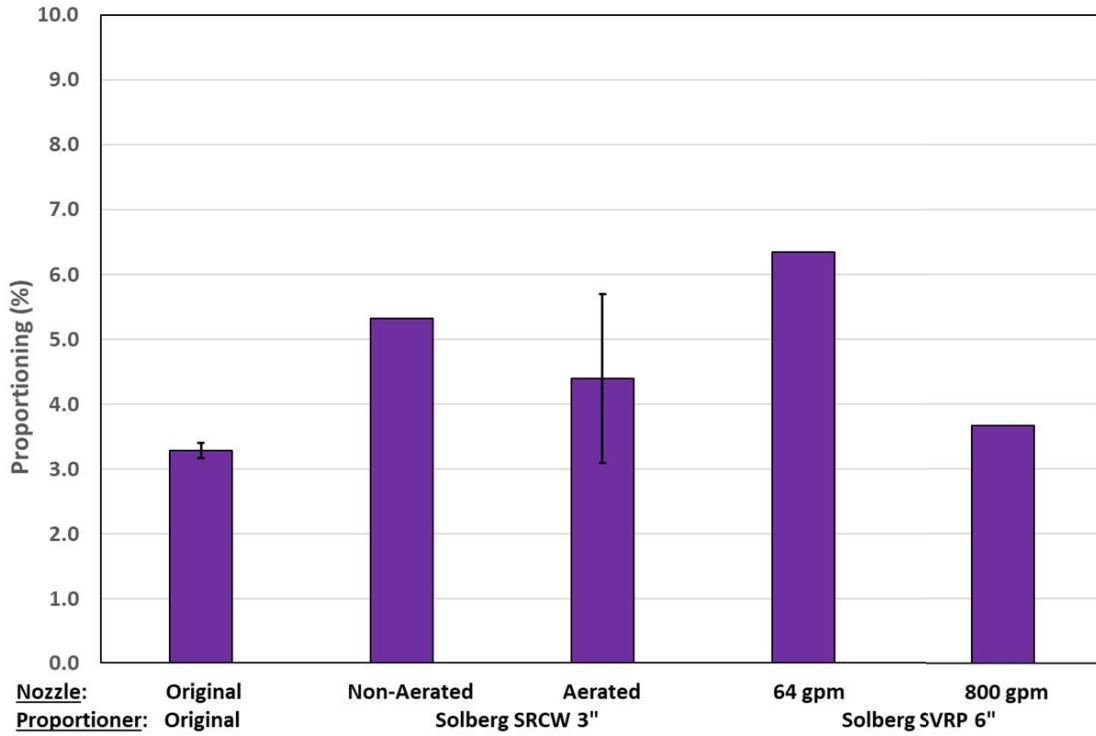


Figure B- 1. Solberg Proportioning Results

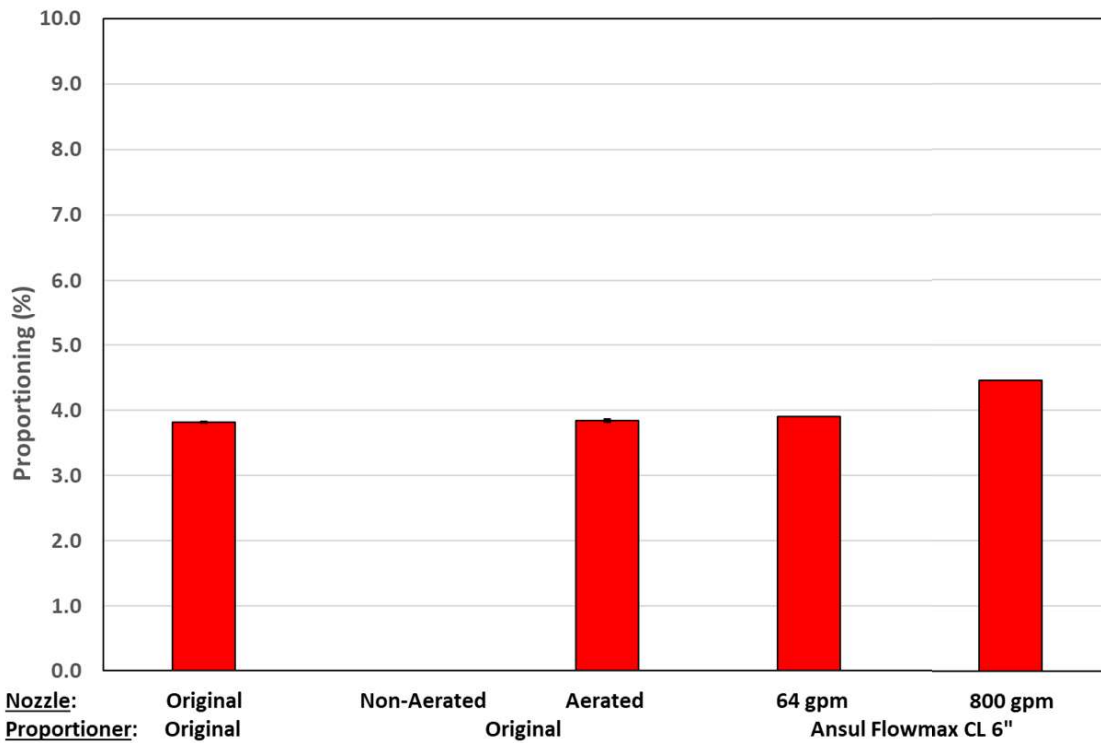


Figure B- 2. Ecopol-A Proportioning Results

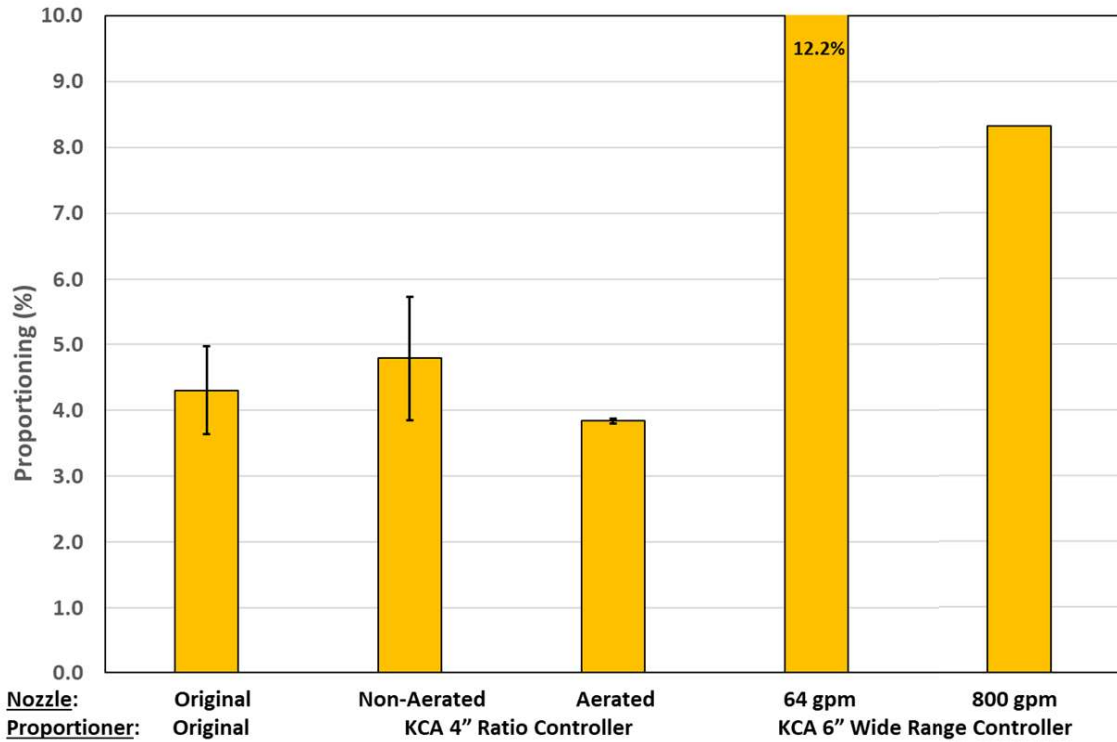


Figure B- 3. Fomtec Proportioning Results

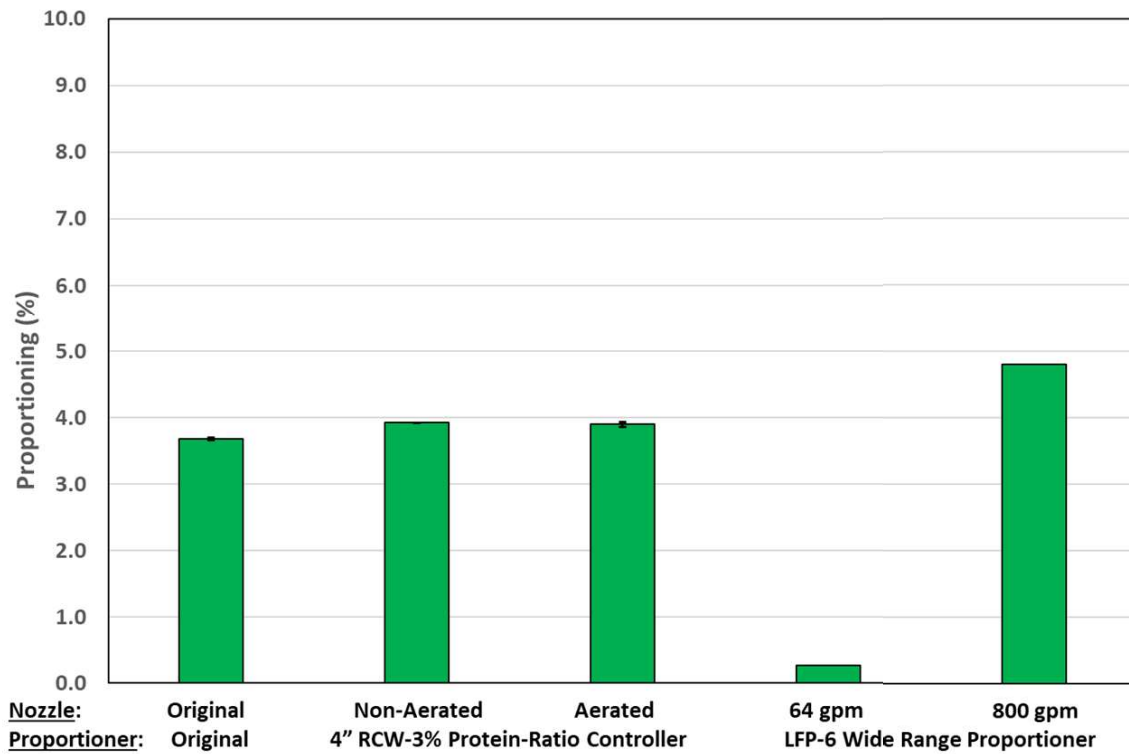


Figure B- 4. National Foam Proportioning Results

LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

ACGIH	American Conference of Governmental Industrial Hygienists
AFFF	aqueous film-forming foam
C-6	AFFF with 6-carbon chain surfactant molecules
C-8	AFFF with 8-carbon chain surfactant molecules
DoD	Department of Defense
gpm	gallons per minute
I.D.	internal diameter
NFPA	National Fire Protection Association
NPT	national pipe thread
PFAS	perfluoroalkyl substances
PFHxA	perfluoro-n-hexanoic acid
PFHxS	perfluoro-1-hexanesulfonate
PFOA	perfluoro-n-octanoic acid
PFOS	perfluoro-1-octanesulfonate
ppt	parts per trillion
psi	pounds per square inch
TFT	Task Force Tips
TLV	threshold limit value
TWA	time weighted average