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Atlantic City International Airport
New Jersey 08405

Evaluation of Surrogate Liquid for Fluorine-Free Foam Concentrate in Output-Based Aircraft Rescue and Firefighting Vehicle Tests

August 2026

Final Report

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EVALUATION OF SURROGATE LIQUID FOR FLUORINE-FREE FOAM CONCENTRATE IN OUTPUT-BASED AIRCRAFT RESCUE AND FIREFIGHTING VEHICLE TESTS

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16. Abstract

Under Title 14 Code of Federal Regulations Part 139, *Certification of Airports*, certificated airports are required to conduct output-based proportioning tests when using fluorine-free foams (F3s) to ensure their aircraft rescue and firefighting (ARFF) vehicle is in an operationally capable state. Output-based testing with F3 can be restricted by environmental regulations and can incur significant clean-up costs. This research identified the currently approved MIL-PRF-32725 F3 concentrates and evaluated whether a surrogate liquid could be used in place of F3 concentrates during ARFF vehicle foam proportioner verification testing. Two MIL-PRF-32725 F3 concentrates and matched surrogate liquids were evaluated. Bench-scale testing with a custom-built, vacuum-based fixture and full-scale output-based testing with an ARFF vehicle were used to evaluate surrogate performance under controlled and operational conditions.

Results indicated that the surrogate replicated F3 flow behavior when its viscosity was closely matched to the target concentrate. Vacuum-based testing with surrogate liquid well matched to its F3 concentrate showed an average difference in flow rate across all discharges of 0.71%. When the surrogate liquid was less well matched, an average difference in flow rate across all discharges of 4.61% was observed. During output-based testing, the average difference between F3 and surrogate proportioning rates was 0.38% proportioning rate, with differences ranging from 0.01% to 0.93% proportioning rate. Differences in proportioning rates during output-based tests can be attributed to a lack of temperature control during testing. These data are expressed in proportioning rate percentage (i.e., a portion of a nominal 3% proportioning rate). Conductivity-based proportioning rate measurements produced results comparable to tank drop-based proportioning rate measurements. Discharges of F3s had an average difference of 0.32% (standard deviation (SD) = 0.41) proportioning rate and discharges of surrogate had an average difference of 0.33% (SD = 0.29) proportioning rate, between the two proportioning rate measurement methods. The results indicate that a properly mixed and viscosity-matched surrogate liquid can serve as an effective substitute for F3 concentrates during output-based ARFF vehicle foam proportioner verification testing.

17. Key Words

Aircraft Rescue and Firefighting, Foam, Fluorine-free foams, Output-based test, Surrogate liquid

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LIST OF ACRONYMS

AFFF	Aqueous film forming foam
ARFF	Aircraft Rescue and Firefighting
ATR	Airport Technology Research & Development
cDAQ	Compact Data Acquisition System
CFR	Code of Federal Regulations
DOD	Department of Defense
FAA	Federal Aviation Administration
F3	Fluorine-free foam
gpm	Gallons per minute
HRET	High-reach extendable turret
IBC	Intermediate bulk container
NI	National Instruments
ml	milliliter
NFPA	National Fire Protection Association
QPL	Qualified Products List
SD	Standard deviation
USB	Universal serial bus

EXECUTIVE SUMMARY

Output-based testing is currently the primary method used to verify Aircraft Rescue and Firefighting (ARFF) vehicle foam-proportioning systems. Following the transition from aqueous film forming foam (AFFF) to fluorine-free foams (F3s), or the initial implementation of F3, airport operators are required to conduct output-based testing using actual F3 concentrate to verify proper proportioning performance of the ARFF vehicle to ensure it is in an operationally capable state. This process requires discharge of foam solution and can create operational, environmental, and cost burdens associated with discharge containment, wastewater management, and compliance with local environmental regulations. As a result, there is interest in determining whether a surrogate liquid can be used in place of F3 concentrates during proportioning-system verification testing.

This research had three objectives: (1) identify all currently approved MIL-PRF-32725 F3 concentrates, (2) evaluate whether a surrogate liquid can replicate the results of output-based ARFF foam proportioner testing conducted with F3 concentrates, and (3) determine whether surrogate liquids represent a viable option for Part 139 airport operators, including identifying any operational limitations or required modifications for implementation. Five F3 concentrates were identified on the Department of Defense Qualified Products List at the time of this research. Two of those concentrates were selected for testing because they represented the extremes of the currently available MIL-PRF-32725 F3 viscosity range.

Two complementary evaluation methods were used. Bench-scale testing with a custom-built vacuum-based fixture was used to compare the flow characteristics of F3 concentrates and their matched surrogate liquids under controlled conditions while minimizing external variables. Full-scale output-based testing was then performed using the Federal Aviation Administration (FAA) ARFF research vehicle, Crash 9, to compare proportioning-system performance when using F3 concentrates and surrogate liquids. Proportioning rates were determined using both conductivity-based measurements and tank drop calculations to evaluate the reliability of the measurement methods.

The results demonstrated that the surrogate liquid closely replicated the flow behavior of the corresponding F3 concentrates when the surrogate was mixed to closely match the viscosity of the target concentrate. In vacuum-based testing, SOLBERG® F3, compared to its surrogate, produced average flow-rate differences of 0.71% across the representative discharge conditions; while BIOEX® F3, compared to its surrogate, exhibited a larger average difference of 4.61%, which corresponded to a greater mismatch in viscosity than occurred during surrogate mixing. These findings indicate that surrogate performance is highly dependent on the accuracy of viscosity matching during mixture preparation.

Output-based testing produced similar conclusions. Across all tested discharge configurations, differences between F3 and surrogate proportioning rates were significant in some tests due to errors that could be attributed to temperature changes that were not accounted for during testing. Despite those errors, the tests demonstrated that the surrogate provided a reasonable representation of F3 proportioning performance. During output-based testing, the average difference between F3 and surrogate proportioning rates was 0.38% proportioning rate, with differences ranging from 0.01% to 0.93% proportioning rate. These data are expressed in

proportioning rate percentage (i.e., a portion of a nominal 3% proportioning rate). The analysis also showed that conductivity-based measurements produced results consistent with tank drop measurements. F3 discharges had an average difference of 0.32% proportioning rate, and surrogate discharges had an average difference of 0.33% proportioning rate between the two proportioning rate measurement methods, indicating that the use of the surrogate did not introduce additional measurement uncertainty. These findings support the use of conductivity measurements as a practical means of determining proportioning rates during surrogate-based testing.

An important finding of the research was the effect of viscosity and temperature on surrogate performance. Testing showed that increasing or decreasing fluid temperature significantly altered the viscosity of both F3 concentrates and surrogate mixtures. Because proportioning-system performance is directly affected by the concentrate's viscosity, departments using surrogate liquids must ensure that the surrogate is mixed to closely match the target F3 and should verify viscosity if temperature conditions change significantly between mixing and testing. This research suggests that accurate viscosity matching and maintenance of viscosity through temperature changes is necessary for successful surrogate use.

Based on the data collected during this study, the surrogate liquid evaluated can serve as a viable substitute for F3 concentrates during output-based ARFF vehicle foam-proportioner verification testing. No modifications to existing ARFF vehicles or output-based testing procedures were identified as necessary for implementation. For airport operators, the use of an appropriately mixed and viscosity-matched surrogate liquid offers the potential to reduce the environmental and operational burden associated with proportioning-system verification while maintaining confidence that ARFF vehicles are performing as intended.

1. INTRODUCTION

Under Title 14 Code of Federal Regulations (CFR), Part 139, (Certification of Airports, XXXX), the Federal Aviation Administration (FAA) currently requires Part 139 airport operators to ensure their Aircraft Rescue and Firefighting (ARFF) vehicles are maintained in an operationally capable state. Part of this requirement is meant to ensure that the firefighting foam system is working properly and producing a finished foam product with the correct ratio of water to foam concentrate.

Currently, the only acceptable means of compliance to initially test foam proportioning rates after transition to, or initial implementation of fluorine-free foams (F3s) is by performing an output-based test using actual foam concentrate according to FAA CertAlert 24-11 (FAA, 2024). Prior to the approval of F3s, foam concentrates were very similar to water in viscosity. Input-based test systems were an acceptable means of compliance for verifying ARFF vehicle proportioning systems using water, but the new F3s vary in viscosity and might not be accurately represented by water during input-based testing. This requires airport operators to discharge foam solution to ensure that proper proportioning is achieved with the new F3s. To do this, airport operators may have to work with an environmental department in their jurisdiction and must follow any additional local laws and regulations concerning containment of discharges to find a suitable location and process to adhere to these requirements. This can be operationally burdensome and costly.

The FAA Airport Technology Research & Development (ATR) branch ARFF Research program conducted testing and evaluation of the effectiveness of a surrogate liquid used to test ARFF vehicles' foam -proportioning systems instead of F3 during output-based tests. Surrogate liquids are materials used to simulate the properties and behavior of liquids so that systems can be validated in a safer manner.

2. PURPOSE

The purpose of this study was to test and evaluate the effectiveness of a surrogate liquid used to test ARFF vehicle's proportioning system instead of an output-based test with F3.

3. OBJECTIVES

This research had three objectives:

1. Identify all types of F3 currently approved by the Naval Sea Systems Command (Ship Systems) Military Specification MIL-PRF-32725 (DOD, 2023).

2. Compare the results of surrogate-liquid output-based testing with traditional F3 output-based foam-proportioner testing to determine whether a surrogate can accurately represent F3 performance during ARFF vehicle proportioning verification.

3. Determine whether surrogate liquids are a viable means for Part 139 airports to verify ARFF foam proportioning systems, including identification of any operational limitations or required modifications.

For surrogate liquids to be considered suitable for use by Part 139 airports in meeting the requirement for testing the foam-proportioner system in their ARFF vehicles, it must first be determined if the surrogate solution can replace F3 concentrates as a viscosity-matched substitute. Then, it must be determined if currently used methods of measuring proportioning rates of discharge samples can reliably verify proportioning rates during output-based ARFF vehicle foam-proportioner verification tests using the surrogate.

4. METHODS

4.1 IDENTIFICATION OF CURRENTLY APPROVED MIL-PRF-32725 F3S

All types of F3 currently approved by the Naval Sea Systems Command (Ship Systems) Military Specification MIL-PRF-32725 (DOD, 2023) are listed on the Department of Defense's (DOD) Qualified Products List (QPL). The QPL can be accessed via the DoD's website at https://qpldocs.dla.mil. This research effort uses the list of approved F3s, as shown on the QPL (DOD, n.d.).

4.2 SURROGATE IDENTIFICATION

A market survey was conducted to determine if any products were marketed as surrogates for MIL-PRF-32725-certified foams. The surrogate liquid solution must be compatible with ARFF vehicle foam systems, representative of the viscosity of its F3 counterpart, and its proportioning concentration measurable using established means to be viable for use in the output-based testing of ARFF vehicles. NoFoam Systems Surrogate Solution was identified for use in ARFF vehicles to conduct output-based foam-proportioner testing in place of MIL-PRF-32725-certified foams.

4.3 SURROGATE EVALUATION

The following sections detail the two methods used to test and evaluate the use of the surrogate for foam-proportioner verification.

4.3.1 Selection of F3 Concentrates

As it was cost- and time-prohibitive to test all five concentrates and their matching surrogates, testing was conducted with the F3 concentrates that represented the extremes of the currently available MIL-PRF-32725 F3 viscosity range. Previously, all the available QPL F3s were tested using bench-scale testing with a custom-built vacuum-based fixture, against aqueous film forming foam (AFFF) concentrate to analyze their viscosity differences. At the time of this test, there were five QPL-approved F3 concentrates available. The surrogate is intended to be a viscosity-matched replacement for F3 foams for output-based foam-proportioner verification, thus by testing the F3 concentrates most similar and least similar in viscosity to AFFF concentrate, the range of available F3 concentrate viscosities is covered, and the results of the surrogate testing will be representative of the whole viscosity range of currently available QPL F3 concentrates. All the vacuum-tested F3 concentrates were more viscous than the AFFF concentrate. SOLBERG® 3% MIL-SPEC SFFF was selected because it was most similar in viscosity to the AFFF concentrate, while BIOEX ECOPOL A3+ was chosen because it was least similar in viscosity to the AFFF concentrate, as determined during previous vacuum-based testing. SOLBERG® 3% MIL-SPEC SFFF and BIOEX ECOPOL A3+ were used in both testing methods below.

4.3.2 Vacuum-Based Testing

This vacuum-based testing method has been used to test QPL F3 concentrates against AFFF concentrate using a custom-made, bench-scale vacuum-based testing fixture (Figure 1). The data generated from previous testing provided data points for comparison to the surrogate liquid. Vacuum-based testing eliminates almost all variables not directly related to a fluid's ability to flow through an orifice under vacuum. Errors are limited to the accuracy of the flow meter equipped with the vacuum-based testing fixture. Errors from temperature, weather, ARFF vehicle variance, and human error are eliminated.

Figure 1. Custom-Built, Vacuum-Based Testing Fixture

The custom-built, vacuum-based testing fixture draws a liquid through an orifice at an adjustable, vacuum-driven pressure differential. The flow of the liquid under test is measured using a magnetic type of flow meter, which allows flow characteristics of different liquids to be compared with as few variables as possible. This technique produced repeatable results while isolating any variables introduced by full-scale vehicle testing.

4.3.2.1 Vacuum-Based Testing Equipment

The primary piece of equipment for vacuum-based testing was the custom-built, vacuum-based testing fixture, which was designed and constructed in-house by the ARFF research team at the FAA William J. Hughes Technical Center for Advanced Aerospace, referred to as the FAA Technical Center. The vacuum-based testing fixture is intended to mimic the conditions inside of a plate proportioner in an ARFF vehicle, while reducing the variables present when testing using that ARFF vehicle. Using a vacuum generator (Figure 2) to generate a pressure differential, foam concentrates are drawn out of their container through a magnetic-type flow meter (Figure 3), then through an orifice plate designed to mimic the orifice in Crash 9's plate proportioner (Figure 4). Crash 9, the FAA ARFF research vehicle (Figure 5), is a 1992 E-ONE® Titan™ 4x4 equipped with a Snozzle 501 high-reach extendable turret (HRET). Using a vacuum to move the foam concentrate through the orifice plate mimics the conditions inside of the foam educting system in an ARFF vehicle.

Figure 2. Vacuum Generator

Figure 3. IFM Efector, Inc. SM2604 Magnetic-Type Flow Meter Used on Vacuum-Based Testing Fixture

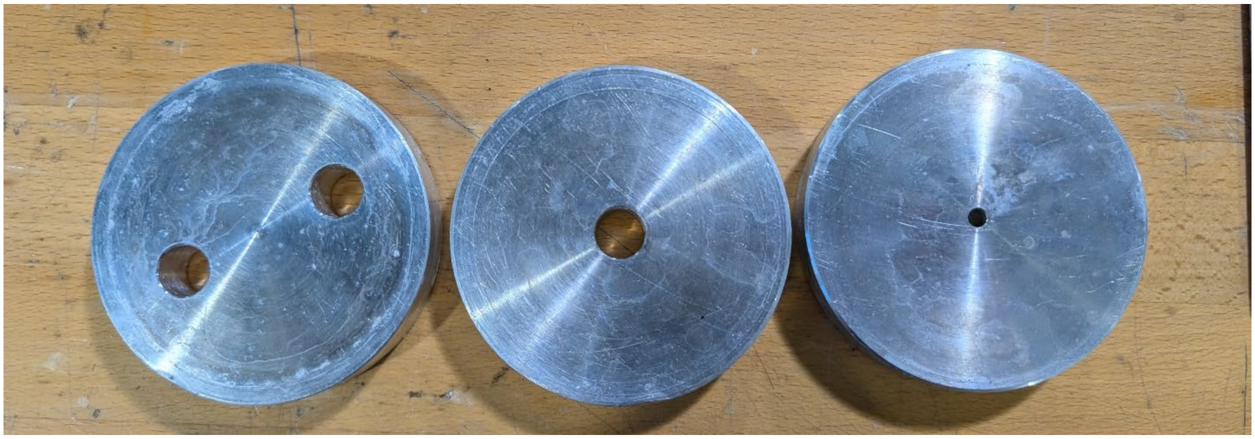

Figure 4. Orifice Plates for Vacuum-Based Testing
(Left to right: 2x 0.451″, 1x 0.451″, 1x 0.200″)

Figure 5. Crash 9 FAA ARFF Research Vehicle, 1992 E-ONE Titan 4x4

4.3.2.2 Vacuum-Based Testing Baseline Values

A set of test conditions was established using measured concentrate flows and orifice plate sizes from Crash 9.

Table 1 presents measured water, foam concentrate, and proportioning rate data obtained via input-based testing, following procedures described in National Fire Protection Association (NFPA) 460 (NFPA, 2024). Orifice sizes were measured from the orifice plate installed in the foam proportioning system of Crash 9. These data were used solely for the establishment of baseline values for vacuum-based testing. Crash 9 uses two orifices for high-flow discharges and a single orifice for low-flow and handline discharges. The data in the Vacuum Required column represent the vacuum required in the vacuum-based testing fixture (measured in inches Mercury [inHg]) to achieve the same flow rates (measured in gallons per minute [gpm]) with water through the same size and number of orifices.

Table 1. Crash 9 Proportioning Data for Vacuum Testing Baseline

Discharge	Measured Flow Rate (gpm)	Measured Proportioning Rate (gpm)	Proportioning Percentage (%)	Orifice Size	Vacuum Required (in Hg)
Bumper Low	383.83	11.23	2.93	1x 0.451″	9.13
HRET Low	409.52	11.62	2.84	1x 0.451″	10.99
Bumper High	731.18	21.22	2.90	2x 0.451″	9.48
HRET High	702.73	23.42	3.33	2x 0.451″	11.53
Handline	52.41	1.62	3.09	1x 0.200″	11.71

It is assumed that in an ARFF vehicle, the foam educting system generates the same amount of vacuum for each discharge configuration regardless of the viscosity of the concentrate in the foam proportioning system. By using these baselines and assumptions, other concentrates and liquids can be tested in the vacuum-based testing fixture, and their flow rates can be tested under the same starting conditions as AFFF, the foam concentrate that Crash 9's foam educting system was originally designed to proportion. Results from flow testing of different concentrates can be compared, analyzing their flow rates in situ. For this research, flow rates of F3s can be directly compared to flow rates of their matching surrogates with variables introduced by other types of testing removed.

Previously, tests of the two chosen F3s, SOLBERG® 3% MIL-SPEC SFFF and BIOEX ECOPOL A3+ MIL-SPEC SFFF, were conducted using the vacuum-based testing fixture. Using the same starting test conditions, tests were conducted using surrogate mixtures for each F3.

Data for the vacuum-based testing fixture are collected using a vacuum sensor and the flow meter, produced by IFM Efector, Inc. (Figure 3) connected to a National Instruments (NI) Compact Data Acquisition System 9174 (cDAQ-9174) (Figure 6).

Figure 6. National Instruments cDAQ-9174

The NI cDAQ is connected via universal serial bus (USB) to a computer running National Instruments LabVIEW with a data collection program. The data collection program records chamber vacuum and fluid flow rate throughout the tests and records the data in a spreadsheet for later analysis.

This fixture allows for fast and repeatable data collection for analyzing flow characteristics of different fluids through an orifice. This fixture also does not modify the fluid under test in any way. After testing, the fluid can be returned to its original container, and very little waste is created.

4.3.3 Output-Based Testing

Output-based testing primarily followed Method A from NFPA 460, Section 29.2.2 (NFPA, 2024) with additional data collection steps. The tests consisted of discharges using F3 concentrates and surrogate material. For each F3 and its matching surrogate, 15 discharges were completed using Crash 9 (Figure 5). Crash 9 has five discharge modes for foam proportioning: Bumper High, Bumper Low, HRET High, HRET Low, and Handline. Each discharge was tested three times. The firefighting appliances installed on the Bumper and HRET positions can be operated in high- and low-flow mode. Each flow mode uses a different combination of valves, piping, and foam proportioning devices to achieve the desired flow rate.

For each discharge, a sample of the discharged solution was taken. This sample was then analyzed using conductivity meters. Refractometry was not used because, according to the manufacturer, the surrogate discharge mixtures could not be analyzed using refractometry. The amount of water and F3/surrogate concentrate used during each discharge test was also recorded via tank drop measurements. Tank drop measurements consisted of filling the water and foam tanks on the vehicle to a repeatable point, and measuring the fluid added after each test to determine the amount of fluid used during the test. Tank drop measurements were performed to validate the results obtained from conductivity measurements, confirming their reliability for determining proportioning rates when using NoFoam Systems surrogate.

4.3.3.1 Output-Based Testing Equipment

Output-based testing used FAA ARFF research vehicle Crash 9 with its Feecon® around-the-pump proportioning system. This vehicle was selected because the Feecon® system is fully mechanical, relying on a plate proportioner and eductor to mix foam concentrate. ARFF vehicles with this type of proportioning system are the primary focus of this research, as these systems lack any ability to self-correct foam proportioning rates.

During testing, discharge from Crash 9 flowed into a manway on a 21,000-gallon, flat-top, corrugated wall tank (Figure 7). This tank was used to contain the bulk of the foam generated during testing. Containing the foam blanket in this manner while it drained back into liquid reduced the amount of labor required for foam containment and minimized wastewater generation, as less water was needed to assist in breaking down the foam blanket.

Figure 7. The 21,000-Gallon, Flat-Top, Corrugated Wall Tank

A sample collection board and tubing (Figure 8) were affixed to the manway of the tank. This allowed the discharge stream of the vehicle to be directed onto the sample collection board when appropriate, based on Method A outlined in NFPA 460, 29.2.2 (NFPA, 2024). The discharge sample was collected from the end of the tube into a graduated cylinder and transported indoors for testing (Figure 9).

Figure 8. Sample Collection Board and Tubing Affixed to the Wall Tank Manway

Figure 9. Sample Collection

During each test, the amount of water and F3/surrogate concentrate used was recorded to compare to the data collected by the conductivity meters using tank drop measurements. The water tank on Crash 9 was filled using an on-site water hydrant flowing through an E-ONE ECOLOGIC® Mobile Cart system (Figure 10). This system has a magnetic-type flow meter with a totalizer. Readings from this flow meter were used to determine water use for each discharge.

Figure 10. E-ONE ECOLOGIC® Mobile Cart System

A battery-operated IFM Efector, Inc. SM8621 flow meter (Figure 11) was installed on the discharge of an intermediate bulk container (IBC) to assist in filling the foam tank. The IBC was suspended above Crash 9 on a forklift so that the foam tank could be filled by the flow meter via gravity. The totalizer on the flow meter was used to determine the amount of concentrate used for each discharge.

Figure 11. IFM Efector, Inc. SM8621 Flow Meter Affixed to IBC

A Mettler Toledo FiveEasy F30 Benchtop Conductivity Meter was used for conductivity measurements (Figure 12). The conductivity meter was temperature-compensated and calibrated daily following the manufacturer instructions.

Figure 12. Conductivity Meter Used in Testing, Mettler Toledo FiveEasy F30

5. PROCEDURES

5.1 SURROGATE PREPARATION

The surrogate was prepared according to instructions and using the equipment provided by NoFoam Systems. The surrogate is provided in a powdered form, packaged to produce approximately 50 gallons of surrogate concentrate solution per bag. (Figure 13)

Figure 13. NoFoam Systems Surrogate Test Liquid Packaging and Mesh Bag

The powder comes in two separate bags: one bag of primary powder and one small packet of finishing powder. The bags come packaged in a mesh bag, which is used during mixing to reduce clumping (Figure 14).

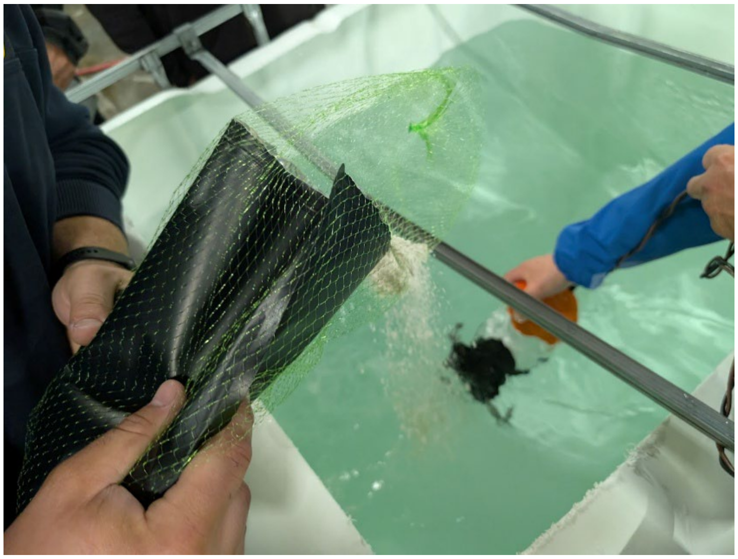

Figure 14. Bag of Primary Powder Being Shaken Into IBC Through Mesh Bag Into Flow of Mixing Pump

For mixing, an IBC was used with the top removed, allowing easy access to the inside of the container (Figure 15).

Figure 15. Intermediate Bulk Container with Top Removed

Fabricated falling ball viscometers (Figure 16) were used to compare the viscosity of the surrogate mixture to the viscosity of the matching F3. One viscometer was filled with F3, and the other filled with surrogate solution intended to match the F3. These were used to adjust the surrogate mixture to get it as close as possible in viscosity to the matching F3. Per the mixing instructions provided by NoFoam Systems, the difference in F3 and surrogate viscosity was considered acceptable if, during the falling ball viscometer test the falling balls were separated by a distance less than the length of the clip-on cover, located at the bottom of the falling ball viscometers, after falling the full length of the viscometer tube. Whenever possible, a significant effort was made to get the falling ball speeds as closely aligned as possible.

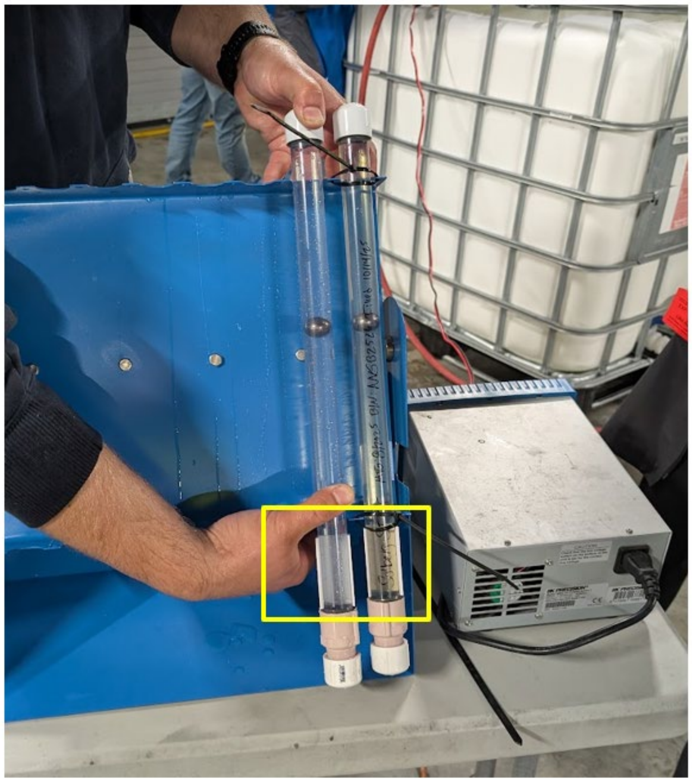

Figure 16. Falling Ball Viscometers with 1.5-in.-Long "Allowable Error" Clip on Cover Outlined in Yellow

The following procedure outlines the preparation of the surrogate solution and the steps used to compare and adjust its viscosity to match the F3 concentrate:

1. One falling ball viscometer was filled with F3 concentrate, and care was taken to ensure that no air remained in the falling ball viscometer tube.

2. The IBC was cleaned.

3. Using a flow meter, the IBC was filled with 200 gallons of water.

4. Using the mixing pump provided by NoFoam Systems, five bags of primary powder were slowly shaken into the water in the IBC through the mesh bags provided, taking care to avoid causing clumps of material, as they would be difficult to break up later.

5. Five packets of finishing powder were slowly shaken into the IBC in the same manner.

6. The mixing pump was left in the IBC for at least 30 minutes to allow sufficient mixing.

7. A second falling ball viscometer was filled with surrogate solution, taking care to ensure that there was no air remaining in the falling ball viscometer tube.

8. Using a purpose-built stand, the falling ball viscometers were allowed to settle and then the stand was flipped. The speed of the falling ball in each viscometer tube was compared. The difference in speed was used to assess the viscosity of surrogate mixture.

    a. If the ball in the surrogate tube fell slower than the ball in the F3 tube, the surrogate was more viscous than the F3 and more water needed to be added to the solution.

        i. If necessary, more water was added to the solution to achieve the desired viscosity. Adjustments were made in small steps.

    b. If the ball in the surrogate tube fell faster than the ball in the F3 tube, the surrogate was less viscous than the F3, and more powder needed to be added to the solution.

        i. If necessary, more powder was added to the solution to achieve the desired viscosity. As the finishing powder has already been added to the solution, adding additional primary powder directly to the solution is not possible. Instead, additional primary powder is blended into a small quantity of water in a separate container and incorporated into the solution. No additional finishing powder is added.

    c. The falling ball viscometer speeds were measured using a camera and a timer.

        i. The falling ball viscometers were recorded with a handheld camera at 120 frames per second. The recording was later played back at 30 frames per second and falling ball times were recorded with a timer.

        ii. The percent difference in falling ball time was then calculated, as it is more useful than the raw falling ball times when comparing data across different F3s and surrogates.

9. Adjustments were made to the mixture until the falling ball viscometers fell at approximately the same speed. Efforts were made to get the falling ball speeds as close as possible.

    a. Care was taken to ensure the viscometers remained at the same temperature. When the viscometers were not being used, they were suspended in the liquid in the IBC.

10. Once mixed, the solution could be stored for several days. Beyond that, the vendor recommended adding a biocide to prevent biological growth in the solution. The mixed

solutions were mixed and used over two days, so biocides were not used during these tests.

5.1.1 Surrogate Mixing Instructions Provided by NoFoam Systems

The above mixing procedure was a more rigorous version of the procedure provided by NoFoam Systems. The mixing procedure, as provided by NoFoam Systems' instruction video, is listed below. (NoFoam Systems, 2024) This procedure was used to mix surrogate for the vacuum-based testing rounds.

1. The provided mixing pump was placed in the bottom of an open top 55-gallon drum.

2. A hose was used to begin filling the drum with water

3. Once enough water was added to submerge the mixing pump 2 in. below the water's surface, the mixing pump was turned on.

4. The surrogate powder was added into the flow of the mixing pump through the provided mesh bag as the drum filled with water

5. The drum was filled to approximately 50 gallons, about 10% below the top of the barrel.

6. The finishing powder was added.

7. The liquid was allowed to mix for 10–15 minutes until the mixture became clear.

8. One viscometer was filled with F3 and placed in a bucket of water.

9. Once the liquid finished mixing, a second viscometer was filled with surrogate solution and placed it in the same bucket of water to equalize the temperature of the ball viscometers.

10. Once the ball viscometers were at the same temperature, they were removed from the bucket of water.

11. The viscometers were held in-hand and turned over to compare the speed of the balls as they moved through the fluids. The viscosities of the two fluids are considered the same when the falling balls arrive at the bottom of the tube together, with an allowable difference of the length of the clip-on white plastic sleeve. (Figure 16)

    a. If the ball in the surrogate viscometer was slower than the F3, more water was added to the surrogate mixture.

    b. If the ball in the surrogate viscometer was faster than the F3, more powder was added to the surrogate mixture.

5.2 VACUUM-BASED TESTING PROCEDURE

The following procedure to test fluids using the bench-scale, vacuum-based testing fixture was developed for an ongoing research effort using that fixture. This study used the same procedure, thus results from testing could be used for both efforts.

1. The vacuum chamber was cleaned and dried.

2. The vacuum-based testing fixture was connected to compressed air and power.

3. The USB cable on the vacuum-based testing fixture was connected to the computer and started the LabView data collection program.

4. The required orifice plate was installed into the orifice plate holder (Table 1, Figure 4, and Figure 17).

Figure 17. Orifice Plate Holder and Clear Intake Tubing

5. The intake tubing was placed into the container of fluid being tested, as shown in Figure 1.

6. The compressed air valve was opened (Figure 18).

Figure 18. Compressed Air Valve (circled in yellow) and Compressed Air Regulator (adjustment circled in red)

7. The intake valve was opened to prime the intake piping.

8. Once all air was clear, the intake valve was closed. Using the clear intake piping, it was verified that intake was clear of all air (Figure 17).

9. The compressed air regulator was adjusted to achieve the prescribed vacuum in the chamber (Figure 18).

10. The intake valve was opened.

11. The “Start” in the LabView data collection program was pressed.

    a. The program collected data for 60 seconds and produced an output file containing test data.

12. Once the 60-second data collection period was completed, as displayed by the LabView program, the intake valve was closed.

13. The compressed air valve was closed.

14. Using a forklift, the vacuum chamber was raised, and the contents of the vacuum chamber were drained back into the original container.

15. When the testing of a particular fluid was completed, the vacuum chamber was cleaned with water and allowed to dry to prepare for the next test.

5.3 OUTPUT-BASED TESTING PROCEDURE

The following output-based testing procedure was developed by combining Method A, outlined in NFPA 460, 29.2.2 (NFPA, 2024), with a procedure to measure the volume water and concentrate used during each discharge. NFPA 460 allows for the use of refractometry or conductivity measurements of discharge samples. Conductivity was chosen for this research, as NoFoam Systems Surrogate is not compatible with refractometry measurements according to the manufacturer.

5.3.1 Equipment Positioning

Figure 19 shows the positioning of all the components required for output-based testing in the following procedure.

Figure 19. Positioning of Equipment for Output-Based Testing

1. The 21,000-gallon, flat-top corrugated wall tank (Figure 7) was positioned on the waste collection area at the 311 Fire Testing Complex at the FAA Technical Center so that the manway on the front of the tank was accessible. The door on the front manway was removed.

2. The sample collection board was installed on the manway, and the sample tubing was secured with zip ties where appropriate (Figure 8).

3. Using heavy-duty tape, stop marks were added inside of Crash 9's water tank, allowing operators to have a reliable mark of where to stop filling the tank for each discharge. A structural gusset was used in the foam tank as a reliable "full" mark.

4. Crash 9 was positioned so that the appropriate discharge could be flown into the open manway on the front of the tank.

5. The water hydrant on site was connected to a gated wye via two lengths of 2½-inch fire hose.

    a. One output of the gated wye was connected to two lengths of 1¾-inch hose, terminating in a combination firefighting nozzle. This nozzle was used for foam management and cleanup.

    b. The other output of the gated wye was connected to the E-ONE ECOLOGIC cart (Figure 10) using the appropriate adapters.

6. The E-ONE ECOLOGIC cart (Figure 10) was connected to the tank fill piping on Crash 9 using the appropriate adapters. The cart was also connected to power on site.

7. The IFM Efector, Inc. flow meter and tubing were connected to the IBC (Figure 11). The forklift was used to raise the IBC above Crash 9, and the hose was placed in the foam tank.

5.3.2 Test Procedure

The test procedure followed these steps:

1. The water tank was filled to the pre-marked stop line (bottom of red tape line circled in yellow in Figure 20), and the totalizer value from the E-ONE ECOLOGIC flow meter (Figure 10) was recorded.

Figure 20. Water Tank Pre-Marked Stop Line

2. The foam tank was filled to the pre-marked stop line (top of the red gusset circled in yellow in Figure 21), and the totalizer value from the ifm flow meter was recorded.

Figure 21. Foam Tank Pre-Marked Stop Line

3. The vehicle operator started the engine on Crash 9.

4. On countdown from the vehicle operator, the discharge under test was opened, the pump was engaged, and a stopwatch was started.

5. The position of the discharge was adjusted so that enough of the discharge was being deflected into the tubing by the sample board.

6. At 30 seconds on the stopwatch, a sample was collected in a graduated cylinder from the sample tubing (Figure 9).

    - For handline discharges, the sample was collected at 90 seconds.

7. Once the sample was collected, on countdown from the vehicle operator, the pump was disengaged, the discharge closed, and the stopwatch was paused.

    - For handline discharges, the discharge was flowed for 180 seconds. This gives a more granular measurement for tank drop readings to help reduce error.

8. The time on the stopwatch was recorded.

9. At the start of the next test, the tanks were filled, and the flow meter totalizer values were recorded again. These totalizer values were later analyzed to calculate the amount of water and concentrate consumed during each discharge.

10. The sample was moved to the conductivity measurement area for data collection.

5.3.2.1 Conductivity Measurement Procedure

5.3.2.1.1 Calibration

For each day of testing, all four meters were calibrated using the same calibration solution, according to the following procedure.

1. Three beakers were prepared and labeled "Calibration," "Rinse Water," and "Deionized Water."

2. A packet of 1,413 micro-Siemens (µS) conductivity calibration solution was opened and placed in the Calibration beaker to prevent it from spilling. The calibration solution was used by inserting the conductivity probes directly into the packet, rather than emptying the packet into the beaker, to avoid any possible contamination during the calibration procedure.

3. The Rinse Water beaker was filled with tap water.

4. The Deionized Water beaker was filled with deionized water.

5. Each conductivity probe/meter was placed in the conductivity solution, and the meter was calibrated using the manufacturer's instructions.

6. Each probe/meter was rinsed in the Rinse Water beaker and dried.

7. Each probe/meter was rinsed in the Deionized Water beaker and dried.

8. The contents of the Rinse Water and Deionized Water beakers were discarded. Each beaker was cleaned and dried.

9. The contents of the Calibration beaker were discarded. The beaker was cleaned and dried.

5.3.2.1.2 Baseline Establishment

A Mettler Toledo FiveEasy F30 conductivity meter was used for baseline and test data measurements. For each day of testing, a baseline was established. The procedure was as follows:

1. Seven clean and dry beakers were prepared. The beakers were labeled as follows:

    - Tank water
    - Concentrate
    - 2%
    - 3%
    - 4%
    - Rinse water
    - Deionized water

2. A sample of tank water exceeding 700 milliliters (ml) was taken from Crash 9's water tank.
3. A sample of F3 concentrate or surrogate exceeding 200 ml was taken from Crash 9's foam tank.
4. The tank water beaker was filled with approximately 100 ml of tank water sample.
5. The concentrate beaker was filled with approximately 100 ml of foam tank sample.
6. Using pipettes, 98 ml of tank water and 2 ml of foam tank sample was added to the 2% beaker and mixed thoroughly.
7. Using pipettes, 97 ml of tank water and 3 ml of foam tank sample was added to the 3% beaker and mixed thoroughly.
8. Using pipettes, 96 ml of tank water and 4 ml of foam tank sample was added to the 4% beaker and mixed thoroughly.
9. The rinse water beaker was filled with tap water.
10. The deionized water beaker was filled with deionized water.
11. The conductivity of the liquid in the following beakers was measured. Each measurement was repeated three times. Each measurement was recorded. Between each measurement, the sample in the beaker was stirred with the conductivity probe.
    - Tank water
    - Concentrate
    - 2%
    - 3%
    - 4%
12. Between each sample measurement, the conductivity probe was dried with a clean paper towel, thoroughly rinsed in the rinse water beaker, dried again with a clean paper towel, thoroughly rinsed in the deionized water beaker, and dried with a clean paper towel.
    - During testing, the conductivity of the rinse water and deionized water was measured. Based on these measurements, the rinse water and deionized water were occasionally refreshed.
13. The conductivity measurements from the 2%, 3%, and 4% beakers were then plotted, and a linear regression line was fit to the plot.
14. The point slope formula of the linear regression line was the baseline. Using the baseline and conductivity readings from samples taken in later testing, the proportioning rate was calculated.

15. The conductivity measurements of the tank water and concentrate were used to ensure consistency across tests. An unexpected change in the conductivity of these items would indicate an issue with the test starting conditions.

16. Once the baseline was established, the contents of all the beakers and sample containers were discarded. The containers were cleaned and dried.

5.3.2.1.3 Test Data Measurement

Test data were measured as follows:

1. Once collected and moved to the conductivity measuring area (see 5.3.1), the sample was allowed to drain down in the sample container, if necessary, until there was more than 100 ml of liquid in the sample container.

2. The sample was transferred to a smaller, clean, dry beaker. The beaker was labeled to identify what discharge the sample was collected from.

3. Before measurements were taken, all air was allowed to settle out of the sample, as air in the liquid sample can interfere with the conductivity measurement.

4. The sample was measured. Each measurement was taken three times. Between each measurement, the sample in the beaker was stirred with the conductivity probe.

5. Between each individual sample, the conductivity probe was dried with a clean paper towel, thoroughly rinsed in the rinse water beaker, dried again with a clean, thoroughly rinsed in the deionized water beaker, and dried with a clean paper towel.

    - During testing, the conductivity of the rinse water and deionized water was measured. Based on these measurements, the rinse water and deionized water were occasionally refreshed.

6. The conductivity measurement was then used to calculate the proportioning rate of the sample.

6. TESTING RESULTS

6.1 IDENTIFICATION OF CURRENTLY APPROVED MIL-PRF-32725 F3S

The following is a list of the F3s currently listed on the QPL at the time of this report. The listed order is the same order they appear on the QPL. (DOD, n.d.)

1. AVIOF3 GREEN MIL 3%
2. ECOPOL A3+ MILSPEC
3. FOMTEC ENVIRO MIL
4. SOLBERG 3% MIL-SPEC SFFF
    - This F3 is listed on the QPL two times, as it is manufactured in two different locations.

5. SOLBERG EVOLUTION 3% SFFF

6.2 VACUUM-BASED TESTING RESULTS

For each round of vacuum-based testing, three orifice plates were used to represent the orifice plate installed in Crash 9's foam proportioning system (Figure 4). Two plates were tested at two vacuum levels to replicate different discharges and are detailed in Table 1.
Twenty-five tests were conducted for each concentrate being evaluated. Five tests were conducted for each configuration representing a discharge (Table 1). Tests that had a vacuum within 0.20 inHg of the target vacuum for the duration of the test were considered acceptable. All five tests for each discharge were averaged to achieve the most accurate result possible.

6.2.1 SOLBERG® 3% MIL-SPEC SFFF

Testing for SOLBERG® 3% MIL-SPEC SFFF was conducted on June 23, 2025. The chemical was from batch ANGB2513, which was manufactured in May 2025. The results are shown in Table 2. The maximum deviations in the table represent the maximum deviation from the average during the five tests for that discharge.

Table 2. SOLBERG® 3% MIL-SPEC SFFF Vacuum-Based Testing Results

Discharge Represented	Liquid Tested	Target Vacuum	Actual Vacuum (Avg.)	Max. Vacuum Deviation	Flow Rate (Avg.)	Max. Flow Rate Deviation
Handline	SOLBERG® 3% MIL-SPEC SFFF	11.18 inHg	11.18 inHg	0.03 inHg	1.30 gpm	0.01 gpm
Bumper Low	SOLBERG® 3% MIL-SPEC SFFF	9.13 inHg	9.14 inHg	0.07 inHg	8.97 gpm	0.09 gpm
HRET Low	SOLBERG® 3% MIL-SPEC SFFF	10.99 inHg	11.00 inHg	0.10 inHg	10.37 gpm	0.14 gpm
Bumper High	SOLBERG® 3% MIL-SPEC SFFF	9.48 inHg	9.49 inHg	0.07 inHg	16.96 gpm	0.14 gpm
HRET High	SOLBERG® 3% MIL-SPEC SFFF	11.53 inHg	11.56 inHg	0.20 inHg	19.92 gpm	0.24 gpm

6.2.2 BIOEX ECOPOL A3+ MIL-SPEC SFFF

Testing for BIOEX ECOPOL A3+ MIL-SPEC SFFF was conducted May 18, 2025. The chemical was from batch 23J24M0, which was manufactured in December 2023. The results are shown in Table 3. The maximum deviations in the table represent the maximum deviation from the average during the five tests for that discharge.

Table 3. BIOEX ECOPOL A3+ MIL-SPEC SFFF Vacuum-Based Testing Results

Discharge Represented	Liquid Tested	Target Vacuum	Actual Vacuum (Avg.)	Max. Vacuum Deviation	Flow Rate (Avg.)	Max. Flow Rate Deviation
Handline	BIOEX ECOPOL A3+ MIL-SPEC SFFF	11.18 inHg	11.16 inHg	0.02 inHg	1.14 gpm	0.09 gpm
Bumper Low	BIOEX ECOPOL A3+ MIL-SPEC SFFF	9.13 inHg	9.14 inHg	0.06 inHg	7.91 gpm	0.15 gpm
HRET Low	BIOEX ECOPOL A3+ MIL-SPEC SFFF	10.99 inHg	10.99 inHg	0.04 inHg	9.20 gpm	0.15 gpm
Bumper High	BIOEX ECOPOL A3+ MIL-SPEC SFFF	9.48 inHg	9.50 inHg	0.07 inHg	14.04 gpm	0.21 gpm
HRET High	BIOEX ECOPOL A3+ MIL-SPEC SFFF	11.53 inHg	11.56 inHg	0.09 inHg	16.49 gpm	0.58 gpm

6.2.3 SOLBERG® 3% MIL-SPEC SFFF NoFoam Systems Surrogate

Testing for SOLBERG® 3% MIL-SPEC SFFF NoFoam Systems Surrogate was conducted on June 30, 2025. The surrogate mixture was prepared and tested on the same day, containing one package of NoFoam Systems surrogate powder and 53.54 gallons of water. Using a timer, the falling time of the ball in each viscometer was recorded following the procedure discussed in Section 5.1. Times differed by about 2%, with the surrogate ball falling faster. The concentrate used in the SOLBERG® 3% MIL-SPEC SFFF viscometer was from batch ANGB2513, which was manufactured in May 2025. The results of this test are shown in Table 4. The maximum deviations in the table represent the maximum deviation from the average during the five tests for that discharge.

Table 4. SOLBERG® 3% MIL-SPEC SFFF NoFoam Systems Surrogate Vacuum-Based Testing Results

Discharge Represented	Liquid Tested	Target Vacuum	Actual Vacuum (Avg.)	Max. Vacuum Deviation	Flow Rate (Avg.)	Max. Flow Rate Deviation
Handline	SOLBERG® 3% MIL-SPEC SFFF NoFoam Systems Surrogate	11.18 inHg	11.19 inHg	0.03 inHg	1.30 gpm	0.01 gpm
Bumper Low	SOLBERG® 3% MIL-SPEC SFFF NoFoam Systems Surrogate	9.13 inHg	9.14 inHg	0.03 inHg	9.15 gpm	0.10 gpm
HRET Low	SOLBERG® 3% MIL-SPEC SFFF NoFoam Systems Surrogate	10.99 inHg	11.00 inHg	0.03 inHg	10.49 gpm	0.07 gpm
Bumper High	SOLBERG® 3% MIL-SPEC SFFF NoFoam Systems Surrogate	9.48 inHg	9.46 inHg	0.05 inHg	16.95 gpm	0.09 gpm
HRET High	SOLBERG® 3% MIL-SPEC SFFF NoFoam Systems Surrogate	11.53 inHg	11.53 inHg	0.08 inHg	19.88 gpm	0.17 gpm

6.2.4 BIOEX ECOPOL A3+ MIL-SPEC SFFF NoFoam Systems Surrogate

The testing for BIOEX ECOPOL A3+ MIL-SPEC SFFF NoFoam Systems Surrogate was conducted on July 2, 2025. The surrogate mixture was prepared and tested on the same day, containing one package of NoFoam Systems surrogate powder mixed with 50.04 gallons of water. Using a timer, the falling time of the ball in each viscometer was recorded following the procedure discussed in Section 5.1. The times differed by about 11%, with the surrogate ball falling faster. The concentrate used in the BIOEX ECOPOL A3+ MIL-SPEC SFFF viscometer was from batch 23J24M0, which was manufactured in December 2023. Table 5 shows the results from this test. The maximum deviations in the table represent the maximum deviation from the average during the five tests for that discharge.

Table 5. BIOEX ECOPOL A3+ MIL-SPEC SFFF NoFoam Systems Surrogate Vacuum-Based Testing Results

Discharge Represented	Liquid Tested	Target Vacuum	Actual Vacuum (Avg.)	Max. Vacuum Deviation	Flow rate (Avg.)	Max. Flow Rate Deviation
Handline	BIOEX ECOPOL A3+ MIL-SPEC SFFF NoFoam Systems Surrogate	11.18 inHg	11.19 inHg	0.01 inHg	1.20 gpm	0.01 gpm
Bumper Low	BIOEX ECOPOL A3+ MIL-SPEC SFFF NoFoam Systems Surrogate	9.13 inHg	9.14 inHg	0.13 inHg	7.52 gpm	0.20 gpm
HRET Low	BIOEX ECOPOL A3+ MIL-SPEC SFFF NoFoam Systems Surrogate	10.99 inHg	11.01 inHg	0.08 inHg	9.69 gpm	0.09 gpm
Bumper High	BIOEX ECOPOL A3+ MIL-SPEC SFFF NoFoam Systems Surrogate	9.48 inHg	9.45 inHg	0.18 inHg	14.71 gpm	0.40 gpm
HRET High	BIOEX ECOPOL A3+ MIL-SPEC SFFF NoFoam Systems Surrogate	11.53 inHg	11.50 inHg	0.06 inHg	18.07 gpm	0.08 gpm

6.3 OUTPUT-BASED TESTING RESULTS

6.3.1 SOLBERG® 3% MIL-SPEC SFFF

Output-based testing on SOLBERG® 3% MIL-SPEC SFFF was conducted between October 1, 2025, and October 7, 2025. Each discharge was tested three times. The product used for this testing was from batch ANGB2528, manufactured in August 2025. The results are shown in Table 6 and Table 7.

Table 6. SOLBERG® 3% MIL-SPEC SFFF Tank Drop Data

Discharge Tested	Date Tested	Water Flow Meter Totalizer Difference from Start to End (gal)	Foam Flow Meter Totalizer Difference from Start to End (gal)	Discharge Time (s)	Water Flow Rate (gpm)	Foam Flow Rate (gpm)	Calculated Proportioning Rate (Tank Drop) (%)
Bumper High 1	10/1/2025	468.3	16.7	37.99	739.62	26.38	3.70
Bumper High 2	10/6/2025	534.7	19.3	44.86	715.16	25.81	3.74
Bumper High 3	10/6/2025	506.53	17.8	42.86	709.09	24.92	3.64
Bumper Low 1	10/1/2025	250.23	9.8	38.84	386.56	15.14	4.08
Bumper Low 2	10/1/2025	246.62	9.4	40.75	363.12	13.84	3.96
Bumper Low 3	10/1/2025	261.62	9.9	38.49	407.83	15.43	3.93
HRET High 1	10/2/2025	437.39	19.3	38.04	689.89	30.44	4.62
HRET High 2	10/2/2025	486.97	20.8	43.1	677.92	28.96	4.46
HRET High 3	10/2/2025	445.38	18.8	38.19	699.73	29.54	4.41
HRET Low 1	10/2/2025	208.94	7.7	31.62	396.47	14.61	3.83
HRET Low 2	10/6/2025	285.12	11.8	43.51	393.18	16.27	4.32
HRET Low 3	10/7/2025	237.63	9.7	36.09	395.06	16.13	4.26
Handline 1	10/1/2025	151.9	2.9	180	50.63	0.97	1.95
Handline 2	10/6/2025	125.4	2.8	150	50.16	1.12	2.28
Handline 3	10/6/2025	142.43	4.5	180	47.48	1.5	3.26

Data in the Standard Deviation column in Table 7 represent the standard deviation of the preceding average. Standard deviation is a statistical measurement that analyzes how far discrete points in a dataset are dispersed from the average of that set, calculated as the square root of the variance. Lower standard deviations indicate that the data points used to calculate the preceding average are close to that average, while a higher standard deviation indicates that the data points used to calculate the preceding average are far from that average.

Table 7. SOLBERG® 3% MIL-SPEC SFFF Conductivity Data

Discharge	Date Tested	Avg. Conductivity (µS)	Standard Deviation	Calculated Proportioning Rate (%)
Bumper High 1	10/1/2025	643.60	0.30	3.72
Bumper High 2	10/6/2025	649.93	0.12	3.83
Bumper High 3	10/6/2025	652.70	0.10	3.86
Bumper Low 1	10/1/2025	645.07	0.67	3.73
Bumper Low 2	10/1/2025	639.87	0.25	3.69
Bumper Low 3	10/1/2025	654.43	0.60	3.81
HRET High 1	10/2/2025	709.20	0.20	4.32
HRET High 2	10/2/2025	715.57	0.55	4.38
HRET High 3	10/2/2025	722.93	1.19	4.44
HRET Low 1	10/2/2025	683.33	0.25	4.10
HRET Low 2	10/6/2025	647.67	2.31	3.81
HRET Low 3	10/7/2025	710.27	1.07	4.18
Handline 1	10/1/2025	633.50	2.31	3.64
Handline 2	10/6/2025	659.83	1.45	3.92
Handline 3	10/6/2025	645.33	1.12	3.79

6.3.2 BIOEX ECOPOL A3+ MIL-SPEC SFFF

Output-based testing on BIOEX ECOPOL A3+ MIL-SPEC SFFF was conducted between October 20, 2025, and October 27, 2025. Each discharge was tested three times. The product used for this testing was from batch 25C18C0. Table 8 and Table 9 show the results of these tests.

Table 8. BIOEX ECOPOL A3+ MIL-SPEC SFFF Tank Drop Data

Discharge Tested	Date Tested	Water Flow Meter Totalizer Difference from Start to End (gal)	Foam Flow Meter Totalizer Difference from Start to End (gal)	Discharge Time (s)	Water Flow Rate (gpm)	Foam Flow Rate (gpm)	Calculated Proportioning Rate (Tank Drop) (%)
Bumper High 1	10/21/2025	458.34	16.1	41.64	660.43	23.2	3.64
Bumper High 2	10/21/2025	436.03	14.8	38.13	686.12	23.29	3.51
Bumper High 3	10/22/2025	439.62	15.9	38.17	691.05	24.99	3.75
Bumper Low 1	10/20/2025	224.8	7.4	35.18	383.4	12.62	3.40
Bumper Low 2	10/21/2025	215.23	7	35.54	363.36	11.82	3.36
Bumper Low 3	10/22/2025	233.6	7.2	38.68	362.36	11.17	3.18
HRET High 1	10/22/2025	436.42	16.6	38.03	688.54	26.19	3.95
HRET High 2	10/23/2025	373.13	13.2	32.51	688.64	24.36	3.67
HRET High 3	10/23/2025	405.18	15.1	35.3	688.69	25.67	3.87
HRET Low 1	10/23/2025	224.73	7.1	34.04	396.12	12.51	3.26
HRET Low 2	10/27/2025	245.73	8.8	36.81	400.54	14.34	3.71
HRET Low 3	10/27/2025	232.29	8	36.72	379.56	13.07	3.57
Handline 1	10/20/2025	146.08	5.6	180	48.69	1.87	3.99
Handline 2	10/20/2025	148.05	5.1	180	49.35	1.7	3.57
Handline 3	10/20/2025	149.11	4.7	180	49.7	1.57	3.25

Table 9. BIOEX ECOPOL A3+ MIL-SPEC SFFF Conductivity Data

Discharge	Date Tested	Avg. Conductivity (µS)	Standard Deviation	Calculated Proportioning Rate (%)
Bumper High 1	10/21/2025	1,469.33	8.96	3.50
Bumper High 2	10/21/2025	1,501.33	1.15	3.58
Bumper High 3	10/22/2025	1,433.67	3.51	3.20
Bumper Low 1	10/20/2025	1,329.33	0.58	3.40
Bumper Low 2	10/21/2025	1,398.67	1.53	3.31
Bumper Low 3	10/22/2025	1,422.67	6.81	3.17
HRET High 1	10/22/2025	1,703.67	2.52	3.94
HRET High 2	10/23/2025	1,648.67	1.53	3.83
HRET High 3	10/23/2025	1,678.00	3.00	3.91
HRET Low 1	10/23/2025	1,407.33	0.58	3.15
HRET Low 2	10/27/2025	1,445.33	6.43	3.21
HRET Low 3	10/27/2025	1,461.00	8.89	3.25
Handline 1	10/20/2025	1,331.67	1.53	3.41
Handline 2	10/20/2025	1,504.00	0.00	3.97
Handline 3	10/20/2025	1,467.33	0.58	3.85

6.3.3 SOLBERG® 3% MIL-SPEC SFFF NoFoam Systems Surrogate

Output-based testing on SOLBERG® 3% MIL-SPEC SFFF NoFoam Systems surrogate was conducted on October 14, 2025, and October 15, 2025. Each discharge was tested three times. Table 10 and Table 11 show the test results.

Table 10. SOLBERG® 3% MIL-SPEC SFFF NoFoam Systems Surrogate Tank Drop Data

		Water Flow Meter Totalizer	Foam Flow Meter Totalizer				
Discharge Tested	Date Tested	Difference from Start to End (gal)	Difference from Start to End (gal)	Discharge Time (s)	Water Flow Rate (gpm)	Foam Flow Rate (gpm)	Calculated Proportioning Rate (Tank Drop) (%)
Bumper High 1	10/14/2025	361.28	13.7	33.84	640.57	24.29	3.94
Bumper High 2	10/15/2025	419.49	12.7	37.62	669.04	20.26	3.12
Bumper High 3	10/15/2025	400.78	16.1	34.55	696	27.96	4.19
Bumper Low 1	10/14/2025	210.58	6.6	34.42	367.08	11.5	3.24
Bumper Low 2	10/14/2025	206.25	6.8	34	363.97	12	3.41
Bumper Low 3	10/14/2025	222.36	7.2	36.9	361.56	11.71	3.35
HRET High 1	10/14/2025	443.92	17.1	38.13	698.54	26.91	4.01
HRET High 2	10/15/2025	437.26	17.4	37.17	705.83	28.09	4.14
HRET High 3	10/15/2025	433.6	17.5	36.72	708.5	28.59	4.21
HRET Low 1	10/14/2025	231.92	7.1	35.87	387.93	11.88	3.16
HRET Low 2	10/15/2025	253.02	7.7	37.19	408.21	12.42	3.14
HRET Low 3	10/15/2025	250.07	7.7	37.27	402.58	12.4	3.18
Handline 1	10/14/2025	160.85	6	180	53.62	2	3.87
Handline 2	10/14/2025	154.64	4.9	180	51.55	1.63	3.27
Handline 3	10/14/2025	161.43	5.3	180	53.81	1.77	3.39

Table 11. SOLBERG® 3% MIL-SPEC SFFF NoFoam Systems Surrogate Conductivity Data

Discharge	Date Tested	Avg. Conductivity (µS)	Standard Deviation	Calculated Proportioning Rate (%)
Bumper High 1	10/14/2025	356.47	0.25	3.68
Bumper High 2	10/15/2025	348.23	0.40	3.78
Bumper High 3	10/15/2025	344.90	0.00	3.70
Bumper Low 1	10/14/2025	332.00	0.52	3.17
Bumper Low 2	10/14/2025	331.90	0.20	3.17
Bumper Low 3	10/14/2025	331.50	0.10	3.16
HRET High 1	10/14/2025	365.97	0.15	3.88
HRET High 2	10/15/2025	368.67	0.15	4.26
HRET High 3	10/15/2025	365.97	0.68	4.19
HRET Low 1	10/14/2025	332.17	0.35	3.17
HRET Low 2	10/15/2025	329.07	0.15	3.34
HRET Low 3	10/15/2025	328.67	0.40	3.33
Handline 1	10/14/2025	334.83	0.60	3.23
Handline 2	10/14/2025	339.63	0.51	3.33
Handline 3	10/14/2025	332.97	0.15	3.19

6.3.4 BIOEX ECOPOL A3+ MIL-SPEC SFFF NoFoam Systems Surrogate

Output-based testing on BIOEX ECOPOL A3+ MIL-SPEC SFFF NoFoam Systems Surrogate was conducted on November 4, 2025, and November 5, 2025. Each discharge was tested three times. During BIOEX ECOPOL A3+ MIL-SPEC SFFF NoFoam Systems Surrogate testing, the surrogate concentrate material was exhausted before all tests were completed, so discharge Bumper Low 3, was not attempted. As repeated tests were averaged for data analysis, the uncompleted test had no signifigant impact on the data collected or the data analysis completed. The volume of surrogate available would not have been sufficent to fill the foam concentrate tank posttest to record the tank drop measurement, as discussed in 5.3.1, Step 9. Table 12 and Table 13 show the results of these tests.

Table 12. BIOEX ECOPOL A3+ MIL-SPEC SFFF NoFoam Systems Surrogate Tank Drop Data

		Water Flow Meter Totalizer	Foam Flow Meter Totalizer				
Discharge Tested	Date Tested	Difference from Start to End (gal)	Difference from Start to End (gal)	Discharge Time (s)	Water Flow Rate (gpm)	Foam Flow Rate (gpm)	Proportioning Rate (Tank Drop) (%)
Bumper High 1	11/4/2025	459.89	16.7	37.02	745.36	27.07	3.77
Bumper High 2	11/4/2025	443.8	15.7	35.43	751.57	26.59	3.67
Bumper High 3	11/4/2025	433.48	15	34.34	757.39	26.21	3.58
Bumper Low 1	11/5/2025	269.93	7.3	36.89	439.03	11.87	2.78
Bumper Low 2	11/5/2025	247.02	8.4	37.34	396.93	13.5	3.52
Bumper Low 3	Insufficient surrogate concentrate. Test not attempted.						
HRET High 1	11/4/2025	447.41	17.4	37.76	710.93	27.65	4.01
HRET High 2	11/5/2025	462.01	15.6	36.56	758.22	25.6	4.14
HRET High 3	11/5/2025	458.67	18.3	37.66	730.75	29.16	4.21
HRET Low 1	11/5/2025	270.33	7.8	36.6	443.16	12.79	3.16
HRET Low 2	11/5/2025	268.28	10.3	37.07	434.23	16.67	3.14
HRET Low 3	11/5/2025	269.13	11.2	38.08	424.05	17.65	3.18
Handline 1	11/4/2025	170.61	6.7	180	56.87	2.23	3.87
Handline 2	11/5/2025	154.79	3.4	180	51.6	1.13	3.27
Handline 3	11/5/2025	154.59	5.8	180	51.53	1.93	3.39

Table 13. BIOEX ECOPOL A3+ MIL-SPEC SFFF NoFoam Systems Surrogate Conductivity Data

Discharge	Date Tested	Avg. Conductivity (µS)	Standard Deviation	Calculated Proportioning Rate (%)
Bumper High 1	11/4/2025	371.87	0.45	3.43
Bumper High 2	11/4/2025	369.47	1.27	3.39
Bumper High 3	11/4/2025	369.17	0.84	3.39
Bumper Low 1	11/5/2025	359.47	0.47	3.47
Bumper Low 2	11/5/2025	365.17	0.21	3.60
Bumper Low 3	Insufficient surrogate concentrate. Test not attempted/completed.			
HRET High 1	11/4/2025	393.67	0.90	3.74
HRET High 2	11/5/2025	387.43	0.29	4.11
HRET High 3	11/5/2025	386.70	0.17	4.09
HRET Low 1	11/5/2025	377.13	0.65	3.87
HRET Low 2	11/5/2025	377.30	0.95	3.88
HRET Low 3	11/5/2025	379.27	0.35	3.92
Handline 1	11/4/2025	369.67	0.47	3.40
Handline 2	11/5/2025	355.90	0.20	3.39
Handline 3	11/5/2025	360.70	0.44	3.50

7. ANALYSIS

7.1 VACUUM-BASED TESTING

During vacuum-based testing, the NoFoam Systems surrogate mixtures exhibited similar flow rates when compared to their F3 counterparts.

The surrogate mixing instructions provided by NoFoam Systems (Section 5.1.1) allow for the falling ball viscometer speed to be within the length of the NoFoam Systems-provided plastic cover, which can be seen on the bottom of the ball viscometers in Figure 16. This plastic cover is 1/8 the length of the falling ball viscometer. This is an allowable deviation of 12.5% falling ball speed between the two viscometers. Researchers attempted to match falling ball viscometer speeds as closely as possible during mixing, requiring several rounds of adding of small amounts of water and re-checking falling ball viscometer speed.

Following the instructions provided (Section 5.1.1), the SOLBERG® 3% MIL-SPEC SFFF surrogate equivalent was mixed so that the falling ball viscometer rate was within approximately 2% falling ball speed. The difference in flow rates shown in Table 14 is very small relative to the total flow rate of each represented discharge. The error is small enough that it can be attributed to instrumentation accuracy and the 2% difference in falling ball viscometer speed.

The Percent Difference in Flow Rate column in Table 14 represents the percentage difference between the flow rates in the Solberg SFFF Avg. Flow Rate and Solberg SFFF Surrogate Avg. Flow Rate columns. The percent difference is calculated using Equation 1, where p is the data in the Percent Difference in Flow Rate column, a is the data in the Solberg SFFF Surrogate Avg. Flow Rate column, and b is the data in the Solberg SFFF Avg. Flow Rate column.

$$p = \frac{a-b}{(a+b)/_2} * 100 \quad (1)$$

Table 14. SOLBERG® 3% MIL-SPEC SFFF vs. SOLBERG® 3% MIL-SPEC SFFF NoFoam Systems Surrogate Analysis: Vacuum-Based

Represented Discharge	Solberg SFFF Avg. Flow Rate (gpm)	Standard Deviation	Solberg SFFF Surrogate Avg. Flow Rate (gpm)	Standard Deviation	Difference in Flow Rate (Surrogate) (gpm)	Percent Difference in Flow Rate (Surrogate) (%)
Handline	1.30	0.01	1.30	0.00	+0.00	+0.26
Bumper Low	8.97	0.04	9.15	0.07	+0.18	+1.96
HRET Low	10.37	0.13	10.49	0.05	+0.11	+1.09
Bumper High	16.96	1.21	16.95	1.18	-0.01	-0.05
HRET High	19.92	0.17	19.88	0.11	-0.04	-0.21
		Average Percent Difference in Flow Rate, All Discharges:				0.71

Following the instructions provided by NoFoam Systems (Section 5.1.1), BIOEX ECOPOL A3+ MIL-SPEC SFFF surrogate equivalent was mixed so that the falling ball viscometer rate was within approximately 11% falling ball speed. This larger difference was due to the mixing instructions, which stated to mix the powder with 50 gallons of water, then to check the falling ball viscometer speed. Fifty gallons of water was too much, thus the viscosity of the surrogate mixture was slightly lower than the viscosity of the F3, and additional powder was not available to increase the viscosity as desired. Since an 11% error in falling speed is within the allowable error based on the NoFoam Systems instructions, vacuum-based testing was conducted.

The difference in flow rates shown in Table 15 is small and was expected. Errors can be attributed to the difference in falling ball viscometer speed observed in the mixing process. The Percent Difference in Flow Rate column represents the difference between the flow rates in the Bioex Ecopol A3+ Avg. Flow Rate and Bioex Ecopol A3+ Surrogate Avg. Flow Rate columns. The percent difference is calculated using Equation 1, where p is the data in the Percent Difference in Flow Rate column, a is the data in the Bioex Ecopol A3+ Avg. Flow Rate column, and b is the data in the Bioex Ecopol A3+ Surrogate Avg. Flow Rate column.

Table 15. BIOEX ECOPOL A3+ MIL-SPEC SFFF vs. BIOEX ECOPOL A3+ MIL-SPEC SFFF NoFoam Systems Surrogate Analysis: Vacuum-Based

Represented Discharge	Bioex Ecopol A3+ Avg. Flow Rate (gpm)	Standard Deviation	Bioex Ecopol A3+ Surrogate Avg. Flow Rate (gpm)	Standard Deviation	Difference in Flow Rate (Surrogate) (gpm)	Percent Difference in Flow Rate (Surrogate) (%)
Handline	1.14	0.05	1.20	0.01	+0.06	+0.58
Bumper Low	7.91	0.07	7.52	0.12	-0.39	-1.98
HRET Low	9.20	0.10	9.69	0.05	+0.49	+4.98
Bumper High	14.04	0.89	14.71	1.44	-0.66	-3.59
HRET High	16.49	0.42	18.07	0.06	+1.58	+11.90
		Average Percent Difference in Flow Rate, All Discharges:				4.61%

The contrast in flow rate differences shown in Table 14 and Table 15 expose the need for rigor in ensuring the mixture of the surrogate is as accurate as possible. NoFoam Systems provides falling ball viscometers with their surrogate mixing supplies, and ARFF departments will need to take great care to ensure the falling ball viscometer speeds are as close as possible. Extra surrogate powder should also be kept on hand to increase the viscosity of the surrogate mixture if too much water is inadvertently added.

7.2 OUTPUT-BASED TESTING

Table 16 through Table 19 compare the proportioning rates collected during output-based testing. Tank drop-based proportioning rates were calculated using the amount of water and concentrate consumed during a test, measured using the tank drop measurement discussed in Section 5.3.1. Conductivity-based proportioning rates were calculated based on conductivity readings and established baselines discussed in Section 5.3.1.1. Additionally, in Table 16 through Table 19, the column labeled Difference in Calculated Proportioning Rates displays the difference in the two types of proportioning rate measurement used in this research. The data in this column are calculated using Equation 2, where Δ is the data in the column labeled Difference in Calculated Proportioning Rates, a is the data in the column labeled Tank Drop-Based Proportioning Rate, and b is the data in the column labeled Conductivity-Based Proportioning Rate.

$$\Delta = |a - b| \tag{2}$$

Table 16. SOLBERG® 3% MIL-SPEC SFFF Output-Based Testing Data Analysis

Discharge Tested	Tank Drop-Based Proportioning Rate (%)	Conductivity-Based Proportioning Rate (%)	Difference in Calculated Proportioning Rates (%)
Bumper High 1	3.70	3.72	0.02
Bumper High 2	3.74	3.83	0.09
Bumper High 3	3.64	3.86	0.21
Bumper Low 1	4.08	3.73	0.34
Bumper Low 2	3.96	3.69	0.27
Bumper Low 3	3.93	3.81	0.12
HRET High 1	4.62	4.32	0.29
HRET High 2	4.46	4.38	0.08
HRET High 3	4.41	4.44	0.04
HRET Low 1	3.83	4.10	0.27
HRET Low 2	4.32	3.81	0.51
HRET Low 3	4.26	4.18	0.08
Handline 1	1.95	3.64	1.69
Handline 2	2.28	3.92	1.64
Handline 3	3.26	3.79	0.53

Table 17. BIOEX ECOPOL A3+ MIL-SPEC SFFF Output-Based Testing Data Analysis

Discharge Tested	Tank Drop-Based Proportioning Rate (%)	Conductivity-Based Proportioning Rate (%)	Difference in Calculated Proportioning Rates (%)
Bumper High 1	3.64	3.50	0.14
Bumper High 2	3.51	3.58	0.07
Bumper High 3	3.75	3.20	0.55
Bumper Low 1	3.40	3.40	0.00
Bumper Low 2	3.36	3.31	0.05
Bumper Low 3	3.18	3.17	0.01
HRET High 1	3.95	3.94	0.01
HRET High 2	3.67	3.83	0.16
HRET High 3	3.87	3.91	0.04
HRET Low 1	3.26	3.15	0.11
HRET Low 2	3.71	3.21	0.50
HRET Low 3	3.57	3.25	0.32
Handline 1	3.99	3.41	0.58
Handline 2	3.57	3.97	0.40
Handline 3	3.25	3.85	0.59

Table 18. SOLBERG® 3% MIL-SPEC SFFF NoFoam Systems Surrogate Output-Based Testing Data Analysis

Discharge Tested	Tank Drop-Based Proportioning Rate (%)	Conductivity-Based Proportioning Rate (%)	Difference in Calculated Proportioning Rates (%)
Bumper High 1	3.94	3.68	0.26
Bumper High 2	3.12	3.78	0.66
Bumper High 3	4.19	3.70	0.48
Bumper Low 1	3.24	3.17	0.07
Bumper Low 2	3.41	3.17	0.24
Bumper Low 3	3.35	3.16	0.19
HRET High 1	4.01	3.88	0.12
HRET High 2	4.14	4.26	0.11
HRET High 3	4.21	4.19	0.01
HRET Low 1	3.16	3.17	0.01
HRET Low 2	3.14	3.34	0.20
HRET Low 3	3.18	3.33	0.15
Handline 1	3.87	3.23	0.65
Handline 2	3.27	3.33	0.06
Handline 3	3.39	3.19	0.21

Table 19. BIOEX ECOPOL A3+ MIL-SPEC SFFF NoFoam Systems Surrogate Output-Based Testing Data Analysis

Discharge Tested	Tank Drop-Based Proportioning Rate (%)	Conductivity-Based Proportioning Rate (%)	Difference in Calculated Proportioning Rates (%)
Bumper High 1	3.77	3.43	0.34
Bumper High 2	3.67	3.39	0.28
Bumper High 3	3.58	3.39	0.19
Bumper Low 1	2.78	3.47	0.69
Bumper Low 2	3.52	3.60	0.08
Bumper Low 3	Insufficient surrogate concentrate. Test not attempted		
HRET High 1	4.05	3.74	0.31
HRET High 2	3.49	4.11	0.62
HRET High 3	4.16	4.09	0.07
HRET Low 1	2.97	3.87	0.90
HRET Low 2	3.99	3.88	0.11
HRET Low 3	4.34	3.92	0.42
Handline 1	4.09	3.40	0.69
Handline 2	2.25	3.39	1.14
Handline 3	3.90	3.50	0.40

Across all four concentrates tested, there appears to be a difference between the proportioning rate calculated based on tank drop measurements and conductivity measurements. This may be caused by several sources including human error. Tank drop measurements require manual interaction, estimation, and determination as to when to stop filling a tank at its stop mark, which are subject to error. During high-flow discharge tests, this error was averaged and likely insignificant; however, lower-flow discharges, such as handline tests, were more heavily affected. The larger proportioning rate differences observed in handline discharges can be attributed to this factor. Therefore, conductivity-based proportioning rate calculations are likely more reliable.

Vehicle operation may be another source of error. Two operators controlled Crash 9 for all the output-based discharges. Each time a discharge started and ended, the action necessitated two switches to be flipped in the cab of the vehicle. The speed and consistency with which the vehicle responded to these controls—engaging pumps, actuating valves, governing engine RPM and water pressure, and displacing air in the system—and the consistency in how these controls were operated are unknown and were not recorded.

The difference in proportioning rates between F3 tests and surrogate tests for each type of measurement are shown in Table 20 and Table 21. These data are expressed in proportioning rate percentage (i.e., a portion of a nominal 3% proportioning rate).

Table 20. SOLBERG® 3% MIL-SPEC SFFF vs. SOLBERG® 3% MIL-SPEC SFFF NoFoam Systems Surrogate Analysis: Output-Based

Discharge Tested	Tank Drop	Conductivity
	Δ% Proportioning Rate F3 vs. Surrogate	Δ% Proportioning Rate F3 vs. Surrogate
Bumper High 1	0.24	0.04
Bumper High 2	0.62	0.05
Bumper High 3	0.54	0.15
Bumper Low 1	0.84	0.57
Bumper Low 2	0.55	0.52
Bumper Low 3	0.59	0.65
HRET High 1	0.61	0.44
HRET High 2	0.32	0.12
HRET High 3	0.20	0.25
HRET Low 1	0.67	0.93
HRET Low 2	1.18	0.47
HRET Low 3	1.08	0.85
Handline 1	1.93	0.41
Handline 2	0.99	0.59
Handline 3	0.13	0.60

Table 21. BIOEX ECOPOL A3+ MIL-SPEC SFFF vs. BIOEX ECOPOL A3+ MIL-SPEC SFFF NoFoam Systems Surrogate Analysis: Output-Based

Discharge Tested	Tank Drop	Conductivity
	Δ% Proportioning Rate F3 vs Surrogate	Δ% Proportioning Rate F3 vs Surrogate
Bumper High 1	0.13	0.07
Bumper High 2	0.15	0.19
Bumper High 3	0.17	0.19
Bumper Low 1	0.62	0.07
Bumper Low 2	0.16	0.29
Bumper Low 3	Insufficient surrogate concentrate. Test not attempted.	
HRET High 1	0.09	0.20
HRET High 2	0.17	0.28
HRET High 3	0.28	0.18
HRET Low 1	0.29	0.72
HRET Low 2	0.28	0.67
HRET Low 3	0.78	0.67
Handline 1	0.10	0.01
Handline 2	1.32	0.58
Handline 3	0.64	0.35

The primary source of this difference in proportioning rates in Table 20 and Table 21 is likely temperature. Throughout testing, no effort was made to control temperature. Weather varied throughout the testing period from October 1, 2025, to November 5, 2025, ranging from a high of 79 °F to a low of 36 °F. Testing was conducted throughout the day, with most test days spanning the high and low temperatures of the day. Crash 9 and materials required testing, including concentrates, were stored in a building without climate control. Temperatures of water and concentrates were not recorded during this testing effort. Section 7.2.1 evaluates the effect of temperature on the viscosity of an F3 and its matching surrogate. The effect of temperature on the viscosity of the fluids used during this testing was exacerbated by the time span of the testing done during this research. A fire department mixing and using this product over the span of a day would see smaller variations due to smaller overall temperature changes.

The goal of recording tank drop-derived and conductivity measurement-derived proportioning rates was to verify the reliability of the conductivity-based calculations when using the NoFoam Systems Surrogate. The average difference in the type of proportioning rate measurement during F3 tests was 0.32% (standard deviation [SD] = 0.41) proportioning rate. The average difference in the type of proportioning rate measurement during surrogate tests was 0.33% (SD = 0.29) proportioning rate. Given the differences observed between both types of proportioning rates, it can be concluded that the differences were caused by measurement error and not the NoFoam Systems Surrogate solution. The spread and error of the measurements was observed in both types of proportioning rates. Surrogate tests were observed to have a smaller standard deviation with almost the same average as F3 tests. Conductivity measurements of baseline samples for both surrogate and F3 were consistent, and as expected. The measurements from these samples produced linear and predictable baselines with which to calculate discharge test measurements. Although some measurements had a significant degree of error between both types of proportioning rates, conductivity measurements of F3 discharge samples performed identically to conductivity measurements of surrogate samples. Based on the data available, conductivity readings performed with NoFoam Systems Surrogate discharges can be deemed reliable.

7.3 TEMPERATURE EFFECT EVALUATION OF F3 AND SURROGATE CONCENTRATES

Due to the suspected error caused by temperature changes throughout output-based testing, a small test was conducted to help quantify the effect of temperature on the concentrates. Six falling ball viscometers were used: three filled with BIOEX ECOPOL A3+ MIL-SPEC SFFF and three filled with BIOEX ECOPOL A3+ MIL-SPEC SFFF NoFoam Systems Surrogate.

One pair of falling ball viscometers was placed in a refrigerator, another pair in a climate-controlled room, and another in an incubator overnight to provide cold, normal, and hot weather data points for the F3 and the surrogate. At the time of testing, the cold pair measured at 46.6 °F, the warm pair at 69.7 °F, and the hot pair at 90.0 °F. Figure 22 and Figure 23 show the falling ball viscometers with the falling balls in motion.

Figure 22. Temperature Effect Evaluation for F3 Using Falling Ball Viscometers

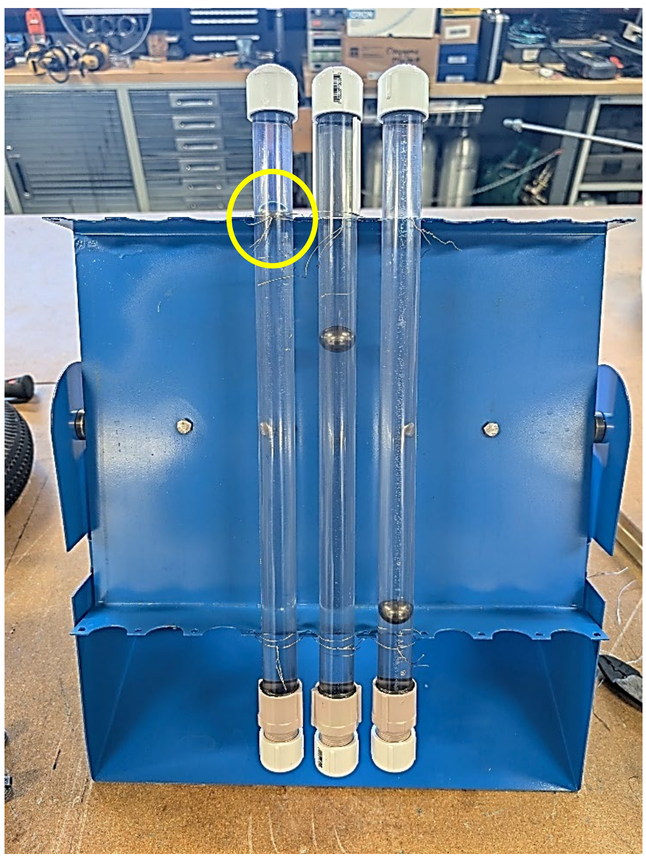

Figure 23. Temperature Effect Evaluation for Surrogates Using Falling Ball Viscometers
(Note the ball in the left viscometer is circled in yellow to show its position.)

In both figures, the falling ball viscometers, from left to right, are ordered by cold, room temperature, and hot. The falling ball viscometers were affixed to a stand with a pivot. The stand holds all three falling ball viscometers at the same angle for consistent measurements. The balls in the viscometers are allowed to settle to the bottom of the viscometer tubes. The viscometer stand was then flipped, allowing all balls in the viscometers to start at the same time. Figure 22 and Figure 23 show a significant difference in falling ball rate, which indicates a difference in viscosity. For the F3 trial, the hot falling ball viscometer fell 48% faster than the room temperature viscometer, while the cold viscometer fell 50% slower than the room temperature viscometer. For the surrogate trial, the hot viscometer fell 80% faster than the room temperature, and the cold viscometer fell 40% slower.

Compared to vacuum-based testing, the increase in the difference of the falling ball speed from 2% to 11% changed the average flow difference between an F3 and its surrogate from 0.71% to 4.61% of overall concentrate flow (see Table 14 and Table 15). A speed difference of 80% or more would cause a substantial variation in flow rate during both vacuum-based and output-based testing.

The conclusion drawn from this evaluation is that temperature changes have a significant effect on the viscosity of these concentrates, but, due to the limited data, additional conclusions cannot be drawn about the effects of temperature on these concentrates.

The difference in temperature observed during this research may contribute to measurement errors. A fire department mixing and using the NoFoam Surrogate Solution on the same day would likely not observe the temperature differences discussed in Section 7.2. Temperature swings should be less of a concern for departments using this product as intended, but departments should be made aware of the effect temperature has on the viscosity of the surrogate solution in the manufacturer's instructions. It may be necessary to adjust the viscosity of the surrogate mixture throughout its use if temperature conditions change.

8. CONCLUSIONS

The surrogate works as the manufacturer intends and can act as a direct viscosity replacement for MIL-PRF-32725 F3 concentrates. All currently certified MIL-PRF-32725 F3s were identified, two of which were selected for this research effort. The two selected represented the most and least viscous of the F3s to represent spectrum of allowable viscosities. To serve as a direct replacement, however, care must be taken when mixing the surrogate and matching the viscosity with consideration given to temperature, conductivity, etc. In vacuum-based testing, SOLBERG® F3 compared to its surrogate produced average flow-rate differences of 0.71% across the representative discharge conditions, while BIOEX and its surrogate exhibited a larger average difference of 4.61%, that corresponded to a greater mismatch in viscosity that occurred during surrogate mixing. When the surrogate mixture and F3 were close in viscosity, there was little difference in flow rate through an orifice. When the mixture had a larger difference in viscosity from the F3, its flow rate through an orifice changed in predictable ways.

Though differences were observed in proportioning rates obtained via tank drop measurements and proportioning rates obtained via conductivity measurements, these differences were consistent across all F3 and surrogate trials. Discharges of F3s had an average difference of

0.32% proportioning rate and discharges of surrogate had an average difference of 0.33% proportioning rate between the two proportioning rate measurement methods. Because these differences were consistent across all trials, the surrogate was not the source of the difference, so it can be concluded that conductivity measurement is a reliable means of measuring proportioning rate with the surrogate solution.

Based on the available data, the surrogate liquid evaluated in this research can serve as a viable substitute for F3 concentrates during output-based ARFF vehicle foam proportioner verification testing. No modifications to ARFF vehicles or existing output-based testing procedures were identified as necessary for implementation. Successful use of the surrogate requires careful viscosity matching during mixing and consideration of temperature effects, which can significantly affect fluid viscosity and testing results. Because only one surrogate product was evaluated, these conclusions apply solely to the surrogate liquid tested and should not be generalized to all surrogate products.

9. REFERENCES

Certification of Airports, 14 C.F.R. §139 (2024). https://www.ecfr.gov/current/title-14/chapter-I/subchapter-G/part-139

Department of Defense (DOD). (n.d.). *Qualified products database*. https://qpldocs.dla.mil/

DOD. (2023). *Fire extinguishing agent, fluorine-free foam (F3) liquid concentrate, for land-based, fresh water applications* (Military Performance Specification MIL-PRF-32725). https://media.defense.gov/2023/Jan/12/2003144157/-1/-1/1/MILITARY-SPECIFICATION-FOR-FIRE-EXTINGUISHING-AGENT-FLUORINE-FREE-FOAM-F3-LIQUID-CONCENTRATE-FOR-LAND-BASED-FRESH-WATER-APPLICATIONS.PDF

Federal Aviation Administration (FAA). (2024). *Required output based testing after completion of fluorine free foam (F3) transition* (FAA National Part 139 CertAlert 24-11). https://www.faa.gov/airports/airport_safety/certalerts/part_139_certalert_24_11

National Fire Protection Association (NFPA). (2024). *Standard for aircraft rescue and firefighting services at airports, recurring proficiency of airport fire fighters, and evaluating aircraft rescue and firefighting foam equipment* (NFPA 460). https://www.nfpa.org/codes-and-standards/nfpa-460-standard-development/460

NoFoam Systems. (2024, December 16). *NoFoam surrogate liquid mixing—Instructional video* [Video]. YouTube. https://youtu.be/t2VtzRDYRrQ