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FINAL REPORT

Extinguishing Class B Fires with PNS, an Environmentally-friendly Compound

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ACRONYMS AND ABBREVIATIONS

AFFF	Aqueous film forming foam
C_n	alcohol with n carbon atoms
DETA	Diethylenetriamine
EDA	ethylenediamine
EO	ethylene oxide
E10	gasoline containing 10% ethanol
FF	Fluorine free
FFF	Fluorine Free Foam
MILSPEC	United States military standard, also known as MIL-SPEC
NRL	Navel Research Labs
PEHA	pentaetylenehexamine
PFAS	Per- and Polyfluoroalkyl substances
PFOA	Perfluorooctanoic acid, also known as C8
PIP	piperazine
PNS	Diethylenetriamine Polyphosphate, known as PNS syrup.
PNS Foam	A foam made with PNS syrup as one of the main functional ingredients
PNS-F	Molecular variant of PNS. Both PNS and PNS-F have fire extinguishing properties, PNS-F also has foaming properties.
PPA	polyphosphoric acid
SDS	sodium dodecyl sulfate also known as sodium lauryl sulfate. Lauryl and dodecyl are used interchangeably in the literature
SLES	sodium lauryl ether sulfate also known as sodium laureth sulfate
SLEP	sodium lauryl ether phosphate
SLS	sodium lauryl sulfate
TETA	triethyleneaminetetraamine
TGA	thermogravimetric analysis

KEYWORDS
Anionic surfactant
Backburn
Flame retardant
Flame retardant foam
Fluorine free
Fluorine free foam
Foaming agent
Halogen free flame retardant
Nonionic surfactant
Surfactant

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ABSTRACT

INTRODUCTION AND OBJECTIVES

Our objective is to refine PNS formulation and application to have an alternative to aqueous film forming foam (AFFF) for fuel fires that is ready for MILSPEC testing. PNS Syrup (PNS) is an environmentally friendly, proprietary fire extinguishing agent made by our company, PN Solutions. PNS is found to react with the ions and radicals in the flames and stop the chain reaction, suppressing the smoke and the fire. PNS is an effective fire extinguishing agent for large gasoline fires. We can extinguish large gasoline fires ($28ft^2$ and $50ft^2$) in less than 30 seconds by applying PNS in a mist. Despite excellent fire extinguishing characteristics, PNS is a non-foaming liquid and as such, does not have adequate burnback capability. The main objective of this project has been to develop approaches for dealing with this limitation. In this report we will discuss our efforts and outcomes with three approaches for adapting PNS to achieve good burnback. We believe the resultant formulations may also be of use to other groups working to replace AFFF.

TECHNICAL APPROACH AND RESULTS

We used three different technical approaches to add burn back capability to PNS.

1) *Combine PNS with widely used surfactants to enable foaming.* It has been discovered that sodium lauryl ether sulfate (SLES) reacts with the flame retardant PNS to form a viscous solution as the two compounds sequester each other without decomposition. This modified PNS/SLES can be made into a liquid foam concentrate by addition of glycol ether. We found that this new formulation has good fire extinguishing ability and burnback when applied as a mist compared to a commercially available FFF.

2) *Combine PNS with commercially available FFF.* PNS syrup (PNS) was added to the best performing FF foams. PNS is a fire extinguishing agent that is self-intumescent and forms a light-weight foamy char which stops the chain reaction of free radicals and ions in a flame and associated heat release. This is expected to decrease fire extinguishing time and improve foam bubble stability in FF foams. As PNS is not a foaming agent, extra surfactant may have to be added. Initial results are promising, however, PNS lowers the expansion ratio of FFF such that additional surfactants may need to be added.

3) *Chemically alter PNS to enable foaming while maintaining similar overall chemical structure and fire extinguishing properties.* A family of modified PNS compounds have been discovered and produced that have foaming properties as well as being flame retardants. When foams made with PNS-F are exposed to high heat, the modified PNS appear to convert to intumescent char that conducts heat poorly and does not become fuel. Initial experiments have demonstrated some very interesting and encouraging properties of this family of compounds. On testing, fire extinguishing ability appears similar to the original PNS. Most notably, PNS-F compounds create excellent foams with expansion ratios of between 6.5 and 10 and bubbles that are extremely long lasting. Burnback testing at Naval Research Labs (NRL) exceeded 10 minutes.

BENEFITS

While we did not reach our initial objective of a drop-in replacement for AFFF, we feel that this project represents a large body of research and development and the contribution of a family of new fire extinguishing compounds. This work has resulted in the award of two additional grants (WP22-3287 and WP23-3875) and two patent applications (PCT US 20 52061 and PCT US 22 38529). Current commercialized FF foams have improved dramatically over the past decade. Though they are still not as effective as AFFF, they will continue to improve. We believe our fire extinguishing agents could be an important "piece of the puzzle" in the arsenal of agents which will eventually bring FF foams up to the effectiveness of AFFF.

1.0 OBJECTIVE

The objective of this project was to refine PNS formulation and application to have an alternative to aqueous film forming foam (AFFF) for fuel fires that is ready for MILSPEC testing. While we are not able to deliver a replacement for AFFF at this time, PNS and the related novel compounds that were discovered as a result of this work, are effective fire extinguishing agents. Fluorine free (FF) foam technology has advanced significantly over the past decade but more work needs to be done as FF foams cannot yet match the effectiveness of AFFF. PNS and PNS-F compounds have unique and valuable properties which may be an important ingredient in new and more effective foam compositions.

2.0 BACKGROUND

PNS is a novel fire extinguishing agent developed by PN Solutions Company. PN Solutions Company was founded in 2001 by Robert V. Kasowski, PhD. A long-time environmentalist, Dr Kasowski founded PN Solutions company after retiring from a 35-year career as a research scientist at DuPont so that he could focus on developing environmentally friendly fire retarding agents.

Of all eco-friendly, fire extinguishing agents, PNS has the highest phosphorus nitrogen content (P=27%, N=14%), and converts to insulating char when exposed to intense heat or direct flame (which is called intumescent). PNS is stable to over 340^0C as measured by thermogravimetric analysis (TGA). The previous work of our company focused on using PNS to flame retard plastics. We tested PNS only recently on fuel fires in 2018 and found that PNS had impressive extinction times.

We propose that PNS has a different mechanism of action than Aqueous Film-Forming Foam (AFFF). AFFF consists of small chain, Teflon like perfluoro compounds, water and air, which form an inert barrier between flammable liquids and the flames. The environmental health problems with these foams are well documented and the reason for the SON WPSON-20-A1.

PNS works differently, as it directly reacts with the ions and free radicals which perpetuate a fire. All flames, regardless of the type of fire, consist of a chain reaction of free radicals and ions that react with air to release heat. A mist of our phosphorus nitrogen compound reacts directly with the free radicals and ions, interrupting the chain reaction, suppressing the smoke and putting out the fire.

At the time of the initial application of this proposal, we had successfully used PNS to extinguish large fuel fires in less than 30 seconds. Testing at our facilities established the excellent fire performance of PNS. We extinguished a 28ft^2 gasoline fire in less than 10 seconds and extinguished a 50ft^2 gasoline fire in our only two tests in less than 20 seconds each. The 28 ft^2 test was performed with 4 gallons of gasoline and the 50 ft^2 test was performed with 5 gallons of gasoline for safety given that the tests were performed at our facility. We were also able to meet the application rate guidelines. MILSPEC calls for an application rate of less than 2GPM; our application rate was 1.6GPM. We have tested PNS on gasoline and diesel fuel. We found diesel significantly easier to extinguish such that we did not feel that we needed to perform the larger burn tests on diesel if we obtained good fire performance with gasoline. Our test results are summarized in Table 1 and the videos of our testing can be accessed on our website, https://pnsoluctionsco.com/video-demos-1.

To achieve these rapid extinguishment times, we had been applying PNS as a mist. The mist has a very high surface area as the droplets are 1000 microns or less. The droplets react with the free radicals and ions in the flames to interrupt the chain reaction that perpetuates a fire. The PNS reaction with class A or B fuel results in a short burst of visible light but no radiant heat. This had been quantified with cone calorimeter measurements, the gold standard in quantifying combustion. In testing, we see an immediate cessation of the black smoke of combustion and a significant decrease in the heat of the fire. Both of these characteristics are valuable to personnel fighting the fire. We created and applied the mist using an inexpensive pressure washer system operating at 3000PSI and nozzles used for spraying pesticides in the agricultural industry.

Our fire extinguishing agent has several characteristics that make it an environmentally friendly option. PNS has already been tested by a company licensed by the Environmental Protection Agency (EPA) and has been found to have low toxicity to the flathead minnow (Figure 1). PNS is similar in composition to fertilizers and PNS that is not metabolized by the fire will react with the soil and can be broken down by microbes, thus preventing bio accumulation. PNS has not been evaluated for toxicity as a misting agent and this work is part of the current proposal.

3.0 MATERIALS AND METHODS

As discussed, PNS has many potential positives with regard to its inherent ability to extinguish fuel fires and the environmental profile. However, at the time of this proposal, work with PNS was in early stages and the objective of this project was to verify PNS testing externally under the MILSPEC guidelines. As part of this testing, it was important to measure burnback which we had not previously evaluated. Lastly, we needed to evaluate the application of PNS and determine whether our product could be used with the application methods currently in use across the Department of Defense.

The technical approach of this work, as initially proposed, were fourfold:

1) *Verify fire performance on 28ft^2 and 50ft^2 fuel fires in an independent testing environment:* As we had completed development and testing in our lab, we were ready for external verification of our results by an outside testing agency, Naval Research Labs (NRL).

2) *Evaluate the burn-back capability of PNS:* At the time of the proposal, we did not have sufficient testing to evaluate PNS for burnback. We suspected that our agent had some burn-back capability, as there is no repeated re-ignition that is seen with dry chemical. However, this had yet to be quantified. Surfactants could be added to our agent to modify this characteristic, if needed.

3) *Refine delivery mechanisms for large and small fires.* For large fires, we planned to investigate adapting currently used firefighting vehicles to deliver our agent. For small fires, our objective was to be able to deliver this technology in a commercially available fire extinguisher. As part of this work, we planned to have PNS tested and certified by UL as a component ingredient for fire extinguishers.

4) *Investigate the physical properties of PNS and perform additional health and safety testing to ensure the safety of military personnel.* The testing will include viscosity, stability, compatibility with other agents, elemental analysis of the resultant char, and inhalation testing.

4.0 RESULTS AND DISCUSSION

We will discuss each of the four technical approaches proposed in this grant separately.

Technical Approach 1) Verify fire performance on 28ft^2 and 50ft^2 fuel fires in an independent testing environment.

Testing of PNS at NRL was not possible for the first half of this project due to testing facility closures due to the national Covid 19 pandemic. Table 1 presents testing results for gasoline fires. While the extinguishment times are impressive, we discovered early in this project that PNS has insufficient burnback. Because of the burnback results which would not pass MILSPEC, further testing of PNS alone, without further modification to enhance burnback, was discontinued.

Additionally, we did attempt a test as a control in which water was sprayed in the same conditions as the PNS on a 28ft^2 gasoline fire. The water could not extinguish the fire after several minutes of testing. The fire eventually went out because the fuel was exhausted and not due to any extinguishing effect of the water. We discontinued any further controls as there was significant and intense smoke and heat and the testing was dangerous to our operator.

Technical Approach 2) Evaluate the burn-back capability of PNS

We began the project by evaluating burnback of PNS at our laboratories. Unfortunately, PNS was found to have essentially no burn back resistance. We are not presenting the results for this testing as the extinguished fuel reignites almost instantly with the addition of a torch to the fire pan. Thus, the main objective of this project became adding burn back resistance to PNS.

Over the course of this project, we discovered and explored three different methods to add burnback capability to PNS and we will discuss each in turn in the paragraphs below. They are:

a) Formulating PNS with a foaming agent
b) Adding PNS to commercially available FF foams as an additive
c) Chemically modifying PNS to add foaming directly to the active ingredient

4.1 FORMULATING PNS WITH A FOAMING AGENT

Our first approach consisted of making a novel FF foam by combining PNS with commercially available foaming agents.

Our best performing foam is primarily composed of PNS syrup with the widely used surfactant sodium laureth sulfate (SLES) as a foaming agent. When PNS at 45%-67% concentration is mixed with SLES 27% concentration, a viscous solution forms as apparently the two compounds sequester each other without decomposition. Addition of 93% water, organic solvent, xanthan results in a solution that forms foam with 6-8 expansion ratio. This work, along with our misting technology, is the basis for a US patent application (PCT US20/52061) submitted this year.

After small scale testing and refining, we performed several 28ft^2 burns using this new foam formulation. 24 tests were performed with our foam and an additional 5 control tests using Solberg

ATC, a commercially available FF foam. The test burn time for 5 gallons of gasoline containing 10% ethanol (E10) in a 28 sq. ft. tank is 24-50 seconds (average 36 seconds) when using our foam sprayed as a mist. Spraying a 6% solution of Solberg FF foam as a control with the same spray equipment, has a burn time of 50-67 seconds. Please see the data from these tests in Table 2 and Table 3, respectively.

For these tests, the application rate was 2 gallons per minute. The expansion ratio is in the range of 6-8. Drain time for these compositions exceeded 30 minutes. There is a large variation in times to extinguishing. External conditions, namely even the slightest wind, affect our tests as they are done outside. Four to five gallons of gasoline was used for testing. There was some variation from test to test in the amount of xanthan and glycol ether and nozzles used.

At the time of this testing, we did not have a reliable way to test burnback in our laboratories. In two tests we applied a torch at 6, 9 and 12 minutes with no re-ignition. However, subsequent backburn testing at NRL, described below, showed insufficient back burn times.

We also experimented with converting the foam created with a pressure washer to single stream. The foam created with Amerex 250 fire extinguisher had an expansion ratio of 4-5. It was applied as single stream for $8ft^2$ gasoline fires and a foam blanket forms that extinguishes the fire. The foam had to applied to a back board and then spread throughout the 8 ft^2. Our time for extinguishing a 28 ft^2 gasoline fire when the foam was applied in a single stream via the Amerex 250 fire extinguisher was 54 seconds.

We also experimented with applying the Solberg from our approximation of a single stream. In this case we could not extinguish the fire at 90 seconds when the test was stopped. We believe this may have been due to the fuel we were using, E10, which is more difficult to extinguish than the ethanol free MILSPEC E0 gasoline. Our new contract for 2022 involves doing detailed investigation of PNS/SLES foam compositions.

4.2 ADDING PNS TO COMMERCIALLY AVAILABLE FF FOAMS

While this approach may seem obvious now, at the time that this approach was conceived, there had been little to no discussion of using a flame retardant as an additive to FF foams to improve performance. We hypothesized that the performance of FF foams could be improved by the addition of chemical additives, particularly PNS.

The majority of the experience of our company has been in using PNS to flame retard plastic polymers. We also have significant experience using various additives to improve the physical properties of plastic polymers. We see the addition of PNS and other additives (if needed) to existing PFAS-free fire suppressants as a similar problem to that we have faced with plastic polymers as the aim of this work is to essentially flame retard a liquid polymer.

FF Foams do not have any inherent fire extinguishing ability and thus do not alter the reactive properties of a flammable liquid. PNS is a fire extinguishing agent that is self-intumescent and forms a light-weight foamy char which stops the chain reaction of free radicals and ions in a flame and associated heat release.

We hypothesize that PNS has two potential benefits to foams: (1) the PNS has excellent fire extinguishing ability and when combined with foam, it may contribute to a faster extinguishing time; and (2) PNS syrup as an additive may improve bubble stability. Even after a gasoline fire is extinguished, the gasoline gives off flammable vapor, which is made of free radicals and ions, and this disrupts the foam bubbles. PNS in the foam mixture may act to stabilize the foam by neutralizing the free radical and ions thus preventing the vapor from deflating the gas bubbles.

To elaborate more specifically, PFOA is basically inert Teflon with a carboxyl side group to dissolve in water. A typical FF surfactant is SLES $CH_3(CH_2)_{11}(OCH_2CH_2)nOSO3Na$. In an intense gasoline fire, PFOA will be inert to whereas SLES will convert to sulfuric acid and radicals and add fuel to the fire and the bubbles collapse. FF foam bubbles only have water molecules to protect the organic content from being turned into radicals. However, intense heat causes the water to evaporate leaving the organic content exposed to become part of the fire. PNS syrup could react with surfactants such as SLES to form a new solution, with PNS now solvating SLES instead of water. In a fire, the PNS syrup has high molecular weight and will not evaporate. The PNS syrup may be a uniquely effective additive as it turns into char that protects. Other chemicals do not self-intumesce such as ammonia phosphate and will not give as good a result.

To evaluate foam bubble stability under high heat conditions, we propose using a new, inexpensive and easy to replicate laboratory test that we have developed. The experimental design is as follows: we take equal amounts of two foam fire extinguishing agents and reconstitute them as directed by the manufacturer. We then create foam by adding the foam solution to a blender for an equal amount of time such that the suggested expansion ratio is obtained. We then add each foam to a rectangular tray approximately 9.5" by 5.5" by 3". These trays are put in a propane grill pre-heated to a temperature of 600^oF. The trays are left in the heat for 2 minutes and then checked at 1-2 minute intervals for a total of 6 minutes. We evaluate the thickness of the foam layer and when the foam layer collapses.

Our hypothesis is that by measuring the increase in foaming at high heat, we are evaluating the bubble stability by measuring their resistance to expanding and collapsing. After the conclusion of the experiment, the trays are cooled, and the foam solution is weighed. Results for PNS as compared to Solberg ATC are presented in the Tables 4 and 5. Bubble stability is improved with the addition of PNS.

We have also done some initial testing looking at the viability of adding PNS to commercially available FF foams in large fuel fires. This approach works well for 5-gallon fires in a $28ft^2$ tank if the misting nozzles are arranged to spray a large foot print. The expansion ratio is 4 to 6. Some representative test results are given for PNS/FFF as compared to FFF in Table 6. All the runs were done spraying a mist with different spray nozzles. We see that the best FFF/PNS samples outperform the FFF, with some being decidedly worse. The two tables only represent a sample of the many trials that were done.

In Table 2, results are given from $28ft^2$ testing with commercially available FF foam at 28 ft^2 and 5 gallons gasoline. For the FF foam, the range of times to extinguishment was 50-67 seconds with an average of 61.8 seconds. These tests served as a control for the PNS/FFF and PNS/SLES experiments. The method of application and conditions were identical.

First NRL Testing: On Sept 13th, 2021 we tested three foam formulations at NRL. Unfortunately, the first two formulations failed to put out the fire and the third formulation succeeded only at nearly 90 seconds. Two samples were PNS added to FFF. The other that put out the fire was a PNS/SLES sample. One definite cause of failure was that our foam had a poor expansion ratio when used with the NRL equipment. At NRL, samples 1 and 2 had expansion ratios of 2.7 and 3.4. The third sample, which did eventually put out the fire, had an expansion ratio of 4.8. We were aware that PNS lowers the expansion ratio of the FF foams however we obtained better expansion ratios with our equipment.

Though our testing was not successful, the day was productive on several fronts. We are grateful to John Farley and Stan Karwoski who spent a lot of time with us so that we could understand how to improve for next time. Before fire testing, John Farley remarked that he could tell that our foam would likely not pass when he sprayed it on the floor as the foam quality looked poor on observation. He told us what to look for with this simple observation test and showed us the NRL equipment. We were able to find a company that manufactured the MILSPEC nozzle for our use and began testing with our own nozzle at the end of 2021.

At this point, we wrote a new proposal, WP22-3287, which was approved for funding and is currently underway. This entire proposal looks at using PNS and PNS-F (described below) as additives to commercially available FF foams. For this grant we will be performing detailed testing on 1 ft^2 and 28 ft^2 fuel fires and looking at the quality of foam using both a mist application and the MILSPEC nozzle. Using PNS as an additive is a potentially useful approach but more work needs to be done to quantify the effect of PNS.

4.3 CHEMICALLY MODIFYING PNS TO ADD FOAMING DIRECTLY TO THE CHEMICAL INGREDIENT

While we were obtaining respectable results with the above two approaches, we continued to be concerned that there was too much organic material in our formulations and, as organic material is flammable, this would continue to impede our extinction times. It would be preferrable if the extinguishing agent also had foaming properties such that some of the SLES or equivalent surfactants or foaming agents could be eliminated.

It was at this time that we conceived of the idea of chemically adding foaming capability directly to the main ingredient molecule of PNS. The result has been a completely new family of compounds which we call PNS-F. We are extremely proud of this work and have applied for global patents (PCT US22 38529). To our knowledge, there have been very few novel fire extinguishing compounds developed recently. These compounds have the potential to be an effective new component of modern FF foams. This work would not have been accomplished without the support of the ESTCP/SERDP program and we are grateful for the support.

We have disclosed in great detail the proposed molecular formula for PNS-F in our grant proposal for project WP23-C2-3875 which was recently awarded funding. The proposal has molecular renderings and production methods. However, as we are still in the process of patenting PNS-F, we cannot disclose the formulas and production methods in this public document. We anticipate more IP being developed and all public documents count as prior art. Once patenting is complete, we can make this information public. The patent application will be made public by USPTO within a year and will reveal 40 examples with detailed formulas.

Initial testing of an early version of PNS-F was done at our facility on 28 ft^2 fuel fires. Results are shown in Table 7. The first 22 tests, presented in the top of the table, were performed by applying PNS-F as a mist. The following 12 tests were performed by applying PNS-F via a single stream by foam cannon which was our best approximation of the MILSPEC nozzle. The average time to extinction for the mist application was 46.7 seconds and the average time to extinction for the single stream application was 53.8. Two controls using Solberg ATC were performed with extinction times of 65 seconds for the mist application and 86 seconds for the single stream (Table 7). There is considerable variability in the times for extinction for the PNS-F samples which is likely related to the different nozzles and formulations that were used. At the time, we did not have a good small scale screening test. In general, we found that all samples worked extremely well on an 8ft^2 or smaller test. The only test that was useful in directing our efforts was the 28 ft^2 test.

However just after the tests presented in Table 7 were performed, we became aware of a new small scale 1 ft^2 test that would enable us to screen compounds without performing 28 ft^2 tests. This test was publicized as part of a "Challenge" competition during the summer of 2020. Our methods are the same as described in the challenge materials so will not be presented again here (SERDP, 2021 "*SERDP AFFF Challenge – PFAS Free Firefighting Foam Guidance*" Challenge.gov. accessed July 28 2021. https://www.challenge.gov/challenge/2021-serdp-afff-challenge/). We were also able to obtain a MILSPEC nozzle thanks to the help of John Farley at NRL.

Over the fall and winter of 2021 and spring of 2022, we performed over 400 small scale, 1ft^2, tests of PNS-F. As mentioned previously, and discussed in detail in proposal WP23-C2-3875, PNS-F can be modified in many ways such that an entire family of compounds is possible. This large number of tests was necessary to determine the general direction of the formulation.

Major results are as follows:

- We were able to achieve rapid extinguishment of the 1ft^2 fire (15-20 seconds) with **150-167g** of the best performing 3% PNS-F with ethoxylated dodecyl alcohol. Within experimental error, the results were independent of outside temperature.
- As a control, we ran several experiments using National Foam Universal Green 3% or 4% and could not extinguish the fire at any time with less than **330g** of foam.
- Solberg RF3, was also tested as a control. **200g to 220g** of 3% solution was needed to extinguish the test fire.
- PNF-F made with ethoxylated tridecyl alcohols where n=1, 2 or 3 were inferior in terms of fire performance. PNF-F made with ethoxylated tridecyl alcohols where n=18 was also inferior.
- PNS-F made with ethoxylated is decyl alcohols where n=6, 9, or 12 were best performers.
- The best performance currently as measured with the 1ft^2 test is diethylenetriamine ethoxylated isodecyl alcohol polyphosphate ester with 6 to 12 moles of ethylene oxide (EO).
- Experiments done in January, 2022 in subfreezing weather gave similar results to earlier results for the same PNS-F formulation tested at higher temperature.

Second NRL testing: On March 30, 8 samples were tested at NRL by John Farley. Results are presented in Table 9. These were samples that performed very in the $1ft^2$ Challenge test and did not contain xanthan. The best $28ft^2$ result was 85 seconds to extinguish the flame and a burnback time of 3 minutes and a few seconds. While these results do not match the best commercial FF foams, these are initial results for completely new family of fire extinguishing compounds. We were also pleased that the foam quality that we can make with our MILSPEC nozzle were similar to the foam made at NRL.

As the foam was applied, the bite was good at first but then deteriorated so that that area needed to be sprayed again. After a minute or so there were small flames throughout the test pan as well as the edges. At the Minneapolis meeting in August, John Farley stated that a short coming of fluorine free foam for large spill fires is burn through. The fire would burn through the initial foam layer and need reapplication. AFFF does not have a problem with burn through. We believe such burn through was occurring for our PNS-F formulations for the $28ft^2$ fire and likely a result of the absence of a thickener xanthan.

Upon observing the eight tests, the results became understandable. There are many PNS-F formulations that can pass the $1ft^2$ test as this test is very quick and the foam blanket need only last 10-20 seconds. The $1ft^2$ test is good at predicting fire extinguishment but does not give enough information on as to the resistance of the foam to burn through. Thus, in addition to the quick $1ft^2$ test, there is a need for a second test that picks compositions can pass a 6-minute burnback test. Based on the results of our testing at NRL, we felt that burn through was a significant problem and we endeavored to develop a small scale burnback test that we could perform at our facility.

Given the need to better understand burnback and burn through, the following test was developed at our facility to screen for burnback: To a $3ft^2$ metal tub, 2-gallon water and 1100g of gasoline is added followed by 600g of foam made with MILSPEC nozzle. A metal pan with 400 g E10 gasoline is placed in the center of the foam and ignited. The time for the fire to spread to half of the foam is recorded and compared to a control made with Solberg RF3. Solberg RF3 is chosen as control as Solberg RF3 is a top performer with very good burnback resistance. With this test, we believe we can pick better performers for the next $28ft^2$ test. We performed over 300 tests with this set up and made significant improvements to our PNS-F formulations. In Photo 1, a picture of the test in progress is shown. The flame will rise dramatically as gasoline vapor begins to escape through the foam. The tub test suggests that xanthan is necessary in order to have good burnback and burn through.

Third NRL Testing: Now we report two tests for the $28ft^2$ fuel tank fires with 10 gallons E0 gasoline and 1 inch of water conducted at the NRL fire test center at Chesapeake, Md. by John Farley's group (see Table 10). The test followed the MILSPEC test protocols with 10 gallons of E0 gas. However, the foam is made and applied with a pressure washer to which was connected the TORQ foam cannon and boom of 12 nozzles TX-26 as previously described. The foam mist is sprayed directly into the tank at 90-degree angle. The expansion ratio was measured to be approximately 8 and our flow rate was approximately 2.5 GPM as the pressure washer controls the rate. For the best test, the time to extinction was 31 seconds, very close to the AFFF MILSPEC requirement of 30 seconds. The backburn time was found to be greater than 10 minutes where the test requirement is only 6 minutes.

A second test had a different PNS-F surfactant. The time to extinction was 34 seconds, very close to the AFFF MILSPEC requirement of 30 seconds. The expansion ratio was approximately 8. The backburn time was found to be greater than 10 minutes. The burn back test was stopped because the gasoline fuel in the pan was used up. A different test done on the same day had a measured burn back of 18 minutes. John Farley at NRL indicated the burn back behavior was the AFFF. Farley also indicated that the bite or how quick the flame is knocked down is excellent. In fact, observing from a distance of about 35 feet, the hrat is intense for only the first 10 seconds. The heat radiated by the fire dramatically dies down as the mist is sprayed.

best ever measured in their test lab and exceeded the backburn behavior obtained for

The excellent backburn behavior is attributed to the use of PNS-F having inherent flame-retardant properties resulting in better thermal stability. These tests also included the thickener xanthan in the foam formulation as indicated by the 3 sqft tub test. The flame-retardant property should correlate with better thermal stability as measured in the gas grill testing. The better thermal stability should result in foam that does not collapse readily and helps lower extinction time. These results confirm that spraying mist derived from PNS-F with a large footprint overcomes inherent poor spreading coefficient of FFF. The mist appeared to cool the fire rapidly as the heat felt at a distance of 30 feet subsided very rapidly after about the initial 15 seconds. These compositions serve as a guideline.

Five tests were conducted. The first three tests in Table 10 had burn times of 52, 67 and 53 seconds. The results improved due to improved technique. The foam mist wand has to be moved around the tank rapidly as the operator is painting layer upon layer of foam mist onto the tank. It is possible that spraying at a 45-degree angle might be better. We are confident that the time can be reduced by 10 seconds or so on the next trial.

Now, we compare foams made by a MILSPEC nozzle, a foam cannon, and a foam cannon to which is attached spray nozzles that create a fine mist. Three tests will be performed to establish how expansion ratio is sensitive to how the foam is created. The tests are done sequentially with the same batch of foam. In Photo 2, a picture of the foam being ejected out of the MILSPEC nozzle is shown. The expansion ratio is shown to be 17.9. Such a high expansion ratio with a MILSPEC nozzle surprised us. The MILSPEC foam has a wide range of bubble sizes. In Photo 3, a picture of foam being ejected from a foam cannon to which is connected a simple array of 9 misting nozzles. Despite being a mist, the range is at least 10 feet and forms a wide spray pattern or footprint. The range is clearly larger than that of a MILSPEC nozzle. The expansion ratio is 6.4 and the foam has the consistency of shaving cream. A lessor amount of xanthan results in expansion ratio of 8-9. The foam cannon is powered by a pressure washer whereas the MILSPEC nozzle is pressured by compressed air. In Photo 4 is shown what the foam looks the foam cannon is used without the nine nozzles. The foam projects about 35 feet depending on the angle. The foam also spreads out nicely as it hits the air. For a large scale test at 400 sqft or more, the foam cannon foam would be ripping through the flame and reacting. We believe that very fine particle shaving cream foam always found with a foam cannon is more likely to react with the flame radicals.

In photo 5, we show a screen shot at 20 seconds at which time there is very light flaming. It takes another 11 seconds to completely stop the fire. In photo 6, a screen shot at 6 seconds at which point the spraying is kicking in.

We believe that FFF made with PNS-F have higher expansion ratios than those made with standard foaming agents such as SLES and SLS. The next line of experiments is for commercial FFF suppliers to substitute PNS-F for SLES and SLS in their compositions.

We recently received funding for project WP23-C2-3875 the objective of which is the continued development of PNS-F compounds and further measurement and characterization of the properties of these chemicals.

Technical Approach 3) Refine delivery mechanisms for large and small fires.

Our first objective under this technical approach was to have PNS tested by Underwriters Laboratory (UL) to be given approval to be used as a component in fire extinguishers and fire extinguishing formulations. This testing was accomplished by UL in 2020 and they approved PNS syrup as a component for use in fire extinguishers. Of note, we were given a non-toxic rating based on the environmental test data that we could provide. The Certificate of Completion from UL has been downloaded to SEMS.

Our second objective was to investigate the feasibility of applying a foam as a mist and to improve our misting technology. We believe that one of the reasons that FF foams have not been able to match the extinctions times of AFFF is the relatively poor spreading coefficients of FF foams. Firefighting foams need to spread rapidly over a burning fuel surface so that the foam can form a barrier before the bubbles are consumed by the heat of the fire. AFFF foams, which are composed of Teflon-like carbon fluorine bonds, will spread easily or even glide over the surface in a fire driven by the energy of the heat because the carbon fluorine bonds have little reaction with neighboring chains. FF foams, which are composed of more adhesive surfactant bonds, are harder to energize to spread out and thus have a poor spreading coefficient as compared to fluorine-based foams. The spreading coefficient for AFFF is 6.6 mN/m and the MILSPEC requirement is greater than 3. The spreading coefficient for Solberg RF3 one of the best performers for the MILSPEC test is -3.3, a very poor result (ref: Katie Hinnant).

We hypothesize that applying an FF foam as a mist over a large area helps overcome the inherent problem of spreading. Experiments presented in this project have consistently demonstrated lower extinguishing times for FF foams applied as a mist as compared to a single stream.

We have also found the misting is an important investigative tool of the fundamental foam science. Using an inexpensive, readily available and easily mobile pressure washer, we have been able to perform many large-scale fuel fire tests. We have performed experiments which show that extinguishing times are improved when applying a commercially available fluorine free foam via a coarse mist. Expansion ratios of the foam are also preserved (*Table 10*).

Our company has gained significant expertise with different nozzle and spray technology. Nozzles break the liquid into droplets, form the spray pattern, and propel the drops in the proper direction. There are dozens of nozzles and hundreds of sizes and materials of construction. Most common nozzles are flat, flood, air induction, raindrop, hollow-cone, full-cone, and others.

Flat fan nozzles are widely used for broadcast spraying of herbicides and are used in this specification. We have tested many types of nozzles for spraying fire extinguishing agent and foam and have found the flat fan type to give the best results.

Venturi educators as used by MILSPEC or by foam trucks can be converted to operate like a foam cannon by changing the diversion cone that mixes solution and air to form foam. John Farley has expressed interest in trying such a modification and we will work with Farley on such a modification. The Rosenbauer company, which supplies fire equipment world-wide, already sells misting nozzles for fire trucks. They also supply very long robotic arms to get close to the fire rapidly. Thus, it is a small step to extend from water misting to FFF containing foam mists with commercially available equipment.

Technical approach 4) Investigate the physical properties of PNS and perform additional health and safety testing to ensure the safety of military personnel.

We have made our formulations available for testing. This will likely be done with one of our next approved proposals.

5.0 CONCLUSIONS AND IMPLICATIONS FOR FUTURE RESEARCH AND BENEFITS

The goal of this project was to investigate whether a novel, fluorine free fire extinguishing compound, PNS, could be used as a replacement for AFFF in fighting fuel fires. PNS demonstrated impressive extinction times for large fuel fires but did not have any burn back capability. Thus began our efforts to add burnback capability to PNS. We addressed this problem in three innovative ways.

First, we formulated a new PNS based foam using commercially available foaming agents, particularly SLES. We achieved good results, comparable to commercial FF foams, when our foam was applied as a mist. Though applying foam as a mist is not desirable as it is not a drop-in replacement to AFFF, we believe that it has merit in improving the spreading co-efficient of our foam and other FF foams. We gained considerable knowledge on the technique of applying foams as mists which could be lent to other applications.

Second, we conceived of the idea of using PNS as an additive to improve the properties of existing FF foams. We have experience as a company in flame retarding polymers and we see this as a similar venture. PNS has excellent thermal stability, and we believe that we may be able to improve the thermal characteristics of FF foams as described in the results section of this report. Initial testing supports the validity of this approach and this work is the basis for the award of proposal WP22-3287 which is currently underway.

Third, we developed an entire family of new firefighting compounds which we call PNS-F. These compounds are structurally similar to PNS but we were able to chemically add a foaming side chain to the active ingredient molecule. This allows the active ingredient to have both foaming and fire extinguishing properties.

After months of testing and refinement, we had a successful test at NRL with PNS-F compounds. However, the foam was applied using our misting system and not prepared using the MILSPEC nozzle. The best extinction times were impressive and the burn back of the foam blanket was especially interesting. In one test our foam blanket lasted over 18 minutes which is better than results obtained for AFFF. This work is the basis of project WP23- 3875 which has been granted funding and will start in 2023. This work is also the basis of US patent application US22/38529.

This project also contributes significantly toward the ability of smaller laboratories or private companies to test new FF formulations. At the onset of this project, one of the great difficulties of working on FF foams was the lack of small-scale tests. While there is still no test that perfectly predicts the outcomes of a 28ft^2 fuel fire test, we have extensive experience with the 1ft^2 fuel fire test and a new small scale burn back test that we devised. After performing hundreds of these tests, we understand the benefits and limitations of these small tests and can share this knowledge with other labs. Additionally, while the portable sprayer technology that we use for 28ft^2 tests is not of current use to the military, it has been invaluable to us in allowing us to perform large fire tests with relative ease and low expense.

While we did not reach our objective of a drop-in replacement for AFFF, we feel that this project represents a huge amount of research and development and the contribution of a new family of fire extinguishing compounds. This work has resulted in the award of two additional grants (WP22-3287 and WP23-3875) and two patent applications (PCT US 20 52061 and PCT US 22 38529).

Current commercialized FF foams have improved dramatically over the past decade. Though they are still not as effective as AFFF, FF foams will continue to improve. We believe our fire extinguishing agents could be an important "piece of the puzzle" in the arsenal of agents which will eventually bring FF foams up to the effectiveness of AFFF.

6.0 LITERATURE CITED

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APPENDIX A

- **Toxicological information.**
- PNS has low toxicity.
- OPPTS 850.1010 Daphnid Acute Toxicity Test 48 Hr. LC_{50} = 66.8 mg/L
- OPPTS 850.1075 Fish Acute Toxicity Test (Fathead Minnow) 96 Hr. LC_{50} = 534 mg/L
- OPPTS 850.5400 Algal Toxicity Test 96 Hr. LC_{50} = 22.9 mg/L
- **Ecological information.**
- OPPTS 835.3110 Ready Biodegradability Not Readily Biodegradable (Very high phosphate content)
- DETA component degrades in soil leaving behind phosphate.

Figure 1. Environmental Testing on PNS Syrup for Groundwater Toxicity

These results were obtained by an outside company certified by the EPA to do this type of toxicology testing.

Table 1. Test Results on Fuel Fires with PNS mist

Size (ft^2)	Fuel Type	PNS Used (Gallons)	Fuel Used (Gallons)	Spray Rate (GPM)	Time to Extinguish
1	Gasoline	0.12	.5	1.6	5 seconds
8	Gasoline	0.20	2	1.6	8 seconds
8	Diesel	0.12	2	1.6	5 seconds
28	Gasoline	0.25	4	1.6	10 seconds
50	Gasoline	0.50	5	1.6	19 seconds

Results of fuel fire tests done with PNS applied as a mist. 3HP pressure washer used to apply the foam.

Table 2. PNS Foam Made with SLES Fuel Fire Tests

Table 3. Solberg ATC (control) Fuel Fire Tests

Date	Test Type	Gasoling Amt	Time (sec)	Nozzle	
10/05/2020	28ft2	4G	40	4tfvs10	7% PNS Foam
10/27/2020	28ft2	4G	50	4 tfvs10	7% PNS Foam
11/04/2020	28ft2	5G	40	4 11015	7% PNS Foam
11/05/2020	28ft2	4G	33	4 11015	7% PNS Foam
11/05/2020	28ft2	4G	30	4 11015	7% PNS Foam
11/06/2020	28ft2	4G	36	4 11010 twin	7% PNS Foam
11/07/2020	28ft2	5G	24	4 11010	7% PNS Foam
11/09/2020	28ft2	5G	54	foam cannon	7% PNS Foam
11/11/2020	28ft2	4G	30	4 11020	7% PNS Foam
11/20/2020	28ft2	5.75G	35	course 5 4tfvs10	7% PNS Foam
11/22/2020	28ft2	5G	33	11015	7% PNS Foam
12/15/2020	28ft2	5G	38	11020 Diamond	7% PNS Foam
12/16/2020	28ft2	5G	38	11020 Diamond	7% PNS Foam
12/23/2020	28f2	5G	48	11020 Diamond	7% PNS Foam
01/08/2021	28ft2	5G	36	4tfvs10	7% PNS Foam
01/20/2021	28ft2	5G	33		7% PNS Foam
01/21/2021	28ft2	5G	37	4x11020	7% PNS Foam
01/22/2021	28ft2	5G	30	4x11020	7% PNS Foam
01/27/2021	28ft2	5G	37	twin jet 11011	7% PNS Foam
01/20/2021	28ft2	5G	33		7% PNS Foam
01/21/2021	28ft2	5G	37	4x11020	7% PNS Foam
01/22/2021	28ft2	5G	30	4x11020	7% PNS Foam
01/27/2021	28ft2	5G	37	twin jet 11011	7% PNS Foam
02/10/2021	28ft2	5G	33	5 tfvs10	7% PNS Foam
	Average of 24 PNS tests		36.3333333		
9/30/2020	28ft2	4G	60		6% Solberg ATC
11/27/2020	28ft2	4.75G	50	11015	6% Solberg ATC
01/03/2021	28ft2	5G	67	11020 Diamond	6% Solberg ATC
01/03/2021	28ft2	5G	67	11020 Rectangle	6% Solberg ATC
05/11/2021	28ft2	5G	65	6 8003	6% Solberg ATC
	Average of 5 control tests		61.8		

For these tests a variety of nozzles were used which effects the extinguishing time. Additionally, modifications were made to the formulation of the PNS foam. All of the control tests were with the same formulation of Solberg ATC.

Table 4. Tray Test Results

Type of Foam	Foam Depth (cm) Start	Foam Depth (cm) at 1minutes	2 min	3 min	4 min	5 min	6 min	%Weight at end
100 g Solberg ATC	1.5	3	4.5	7	8	4	1	27
100g PNS foam	1	1.5	2.5	3	7	4	1	55
50g Solberg/50g PNS foam	1.5	2	3	4	8	5	1	42

Table 5. Tray Test Results

Type of Foam	Foam Depth (cm) Start	Foam Depth (cm) at 1minutes	2 min	3 min	4 min	5 min	6 min	% Weight at end
75 g Solberg ATC	1.5		4	8	3	collapse	n/a	40
75g PNS foam	1.5		2	5	6	3	collapse	64

Table 6. Results of 28ft^2 Testing PNS/FFF Formulations

Sample	Amount of gasoline (Gallons)	Extinction Time (seconds)	Expansion Ratio
1	*5*	*55*	*7.7*
2	*5*	*73*	*6.1*
3	*5*	*43*	*11.9*
4	*5*	*50*	*7.3*
5	*5*	*125*	*6.4*
6	*5*	*120*	*4.1*

Table 7. Initial Testing with PNS-F (formerly referred to as DETA-LP)

Date	Test Type	Gasoling Amount	Time (seconds)	Nozzle	Expansion Ratio	Extinguishing Agent
03/16/2021	28ft2	5G	57	4 tfvs10	5.5	DETA-LP
03/17/2021	28ft2	5G	67	4 11015		DETA-LP
03/24/2021	28ft2	5G	48	4 11008	2.5	DETA-LP
03/27/2021	28ft2	5G	48	2QCTF40	8	DETA-LP
3/28/22021	28ft2	5G	42	4 11908	5.2	DETA-LP
03/28/2021	28ft2	5G	50	4 8006	4.3	75% DETA-LP/25%PNS
03/31/2021	28ft2	5G	55	4 11020		DETA-LP
04/10/2021	28ft2	5G	32	4 8003	3.2	50% DETA-LP/50%PNS
04/10/2021	28ft2	5G	38	4 8003	3.2	50% DETA-LP/50%PNS
04/11/2021	28ft2	5G	60	4 8003		DETA-LP
04/13/2021	28ft2	5G	54	4 tfvs10	6.6	DETA-LP
04/14/2021	28ft2	5G	60	4 tfvs10		DETA-LP
05/09/2021	28ft2	5G	42	6 8003	4.1	DETA-LP plus some SLES
05/11/2021	28ft2	5G	15	6 8003		DETA-LP plus some SLES
05/12/2021	28ft2	5G	36	6 8003		DETA-LP
05/12/2021	28ft2	5G	31	6 8003		DETA-LP
5/13/2021	28ft2	5G	38	6 8003	4.9	DETA-LP plus some SLES
5/14/2021	28ft2	5G	55	6 8003	4	DETA-LP plus some SLES
5/21/2021	28ft2	5G	50	4tk12.5 2	8.1	DETA-LP plus FS
5/22/2021	28ft2	5G	55	25 tk	8.1	DETA-LP plus Siloxane
5/28/2021	28ft2	5G	55	6 tvfs10		5% DETA-LP plus 4% National Foam Gre
5/30/2021	28ft2	5G	40	4 tvfs10		5% DETA-LP plus 4% National Foam Gre
Average of 22 PNS-F Tests			46.727273		5.21	
04/01/2021	28ft2	5G	60	dual stream	5.5	DETA-LP
04/02/2021	28ft2	5G	55	1/2 pipes	6.5	DETA-LP
04/03/2021	28ft2	5G	44	4 1/4 inch		DETA-LP
04/05/2021	28ft2	5G	57	foam dripped in		DETA-LP
04/07/2021	28ft2	5G	60	foam dripped in	6	DETA-LP
04/12/2021	28ft2	5G	63	single stream but pitiful flow		DETA-LP
5/19/2021	28ft2	5G	34	single stream		DETA-LP plus FS
5/20/2021	28ft2	5G	60	single stream		DETA-LP plus FS
5/23/2021	28ft2	5G	48	single stream		DETA-LP plus Silwet L77
5/24/2021	28ft2	5G	50	single stream		DETA-LP plus Silwet L77
5/24/2021	28ft2	5G	45	single stream	8.1	5% DETA-LP plus 4% National Foam Gre
5/28/2021	28ft2	5G	70	single stream		5% DETA-LP plus 4% National Foam Gre
Average of 12 PNS-F Tests			53.833333		6.26	
05/09/2021	28ft2		86	single stream	5.3	Solberg ATC 3.5%
05/11/2021	28ft2		65	6 8003		Solberg ATC 3.5%
Average of 2 Control tests			75.5			

The first set of results is with the PNS-F foam applied as a mist. The second set of data is with the PNS-F applied as a single stream. The last set of two experiments were performed with Solberg ATC as a control. Loading for all of the PNS-F samples is 3-4%

Table 8. Small Scale, 1ft^2 Testing Results with PNS-F Compounds.

1ft2 TESTING MARCH (Each date represents multiple tests of the same formulation to determine lowest amount to extinguish)

date	ppa	pH soln	Exp R	drain time	%load		Pass (grams)	Fail (grams)	wt/1200 ml
mar 15 .0393	187 ud5	p 7.37??	er 10.4	v long	0.0394	best ever	145, 191 quick		119, 91, 133
mar 15 .0393	187 ud5	p 6.67	er 11.11	v long	0.0383	best ever	161, 176 easily, 183		119, 91, 133
mar 16 .0393	187 td3	p 6.9, 1.73	er 4.7	okay white s	0.0385	v good flow	216,	204, 236	
mar 16 .0393	187 da6	p 7.0 1.43	er 11.11	vg clear soln	0.0388	v g flow	160 196	141	135 77 101
mar 17 .039	187? DA9	p 1.47 6.84	er 10.0	vg clear soln	0.0391	poor flow	223	101, 117, 141	
mar 17 .03	187 da6	p 1.5 8.0	er 10.8	vg clear soln	0.0308	good flow	162 177 183		
mar 17 .03	187 ud5	p 1.53 7.11	er 8.6	vg clear soln	0.0299		153 190	130 one corner	166 138 113
mar 18 .03	187 ud5	p 1.53 7.11	er 11.3	vg clear soln	0.0295		135, 175, 177		86 123 109
mar 18 .03	187 td3	p 1.6 7.1	er 6.6	not clear	0.0291	good flow	233	184	181
mar 27 .03	150 ud6	1.6, 6.95	er 6.3	priblems mechanical		poor edge seal		f 160 f 190	
mar 27 .03	175 da6	1.59 7.0	er 9.5				p170 198	f 145 at edge	101 125 152
mar 27 .03	150 ud5	1.52 6.82	er 11.4		0.033		p 154	f 146 one edge	111 114 107 89
mar 28 .03	187 da9	1.58, 6.81	er 13.6		0.0308		p 233 easy	f 139 131	102 111 88 52
mar 28 .03	187 ud5		er 12.3		0.0297		p 174 180 v easy	f 138 almost rt edge	116 98 76

This is a small, representative sample of data collected from over 400 tests that were performed. The tests above were performed on 6 days. Multiple tests were performed per day as each "pass" or "fail" amount is one test. For example, on March 15th five tests were performed, two with one formulation (187 UD5 pH 7.37) and three tests with the second formulation (187 UD5 pH 6.67)

Table 9. Second Test Date at NRL Testing PNS-F Compounds

NRL TESTING 30 MARCH

Formulation	pH soln	% load	pH	burn time	burnback	drain time	expansion ratic
#5 ud5	1.76 7.14 #5	0.0293	glu 40to 68	01:45	02:04	19:10	9.9
#6 ud5	1.45 7.0	0.0383	2.16	01:47	03:45	26:29:00	10.5
#8 da6	1.71, 6.8	0.0299	1.75	fail		24:52:00	9.3
#7 ud5 silwet	1.61 6.94	0.0262	2.16	fail		18:29	8.1
#3 ud5	1.54 6.93	0.0307	2.16	85 sec	02:17	12:56	8.3
#1 da9	#1	0.0305	133, 6.91	fail			
#2da6	#2	0.0336	1.32, 7.0	fail		10:07	7.3
#4 da6	1.74, 7.01	0.0289	2.67	very bad			11.9

Table 10. Third Test Date at NRL Testing PNS-F Compounds

Test	Extinction Time (s)	Burnback Time (s)	Spray Rate (GPM)	Fuel Type
1	53	18:50	2.5	10 Gallons E10
2	52	10:57	2.5	10 Gallons E10
3	67	4:09	2.5	10 Gallons E10
4	31	10:30*	2.5	10 Gallons E10
5	35	10:39	2.5	10 Gallons E10

*test pan ran out of gas before the end of the test, actual burnback would have been longer

Load was 3.1% for all tests

Table 11. Expansion Ratio for Different Nozzles

Nozzle Type	Type of Foam	Expansion Ratio
8005	Solberg ATC 6%	6.25
11008	Solberg ATC 6%	7.21
11005	Solberg ATC 6%	8.25
None, foam cannon	Solberg ATC 6%	8.56
11008	PNS/SLES Foam 7%	6.67
8005	PNS/SLES Foam 7%	5.10

Photo 1. Tub Test

Photo 2. Milspec Nozzle

Photo 3. Pressure Washer with Foam Cannon (9 mist nozzles)

Photo 4. Pressure Washer with Foam Cannon (no misting nozzles)

Photo 5. NRL test at 20 Seconds (Test Time 31 Seconds)

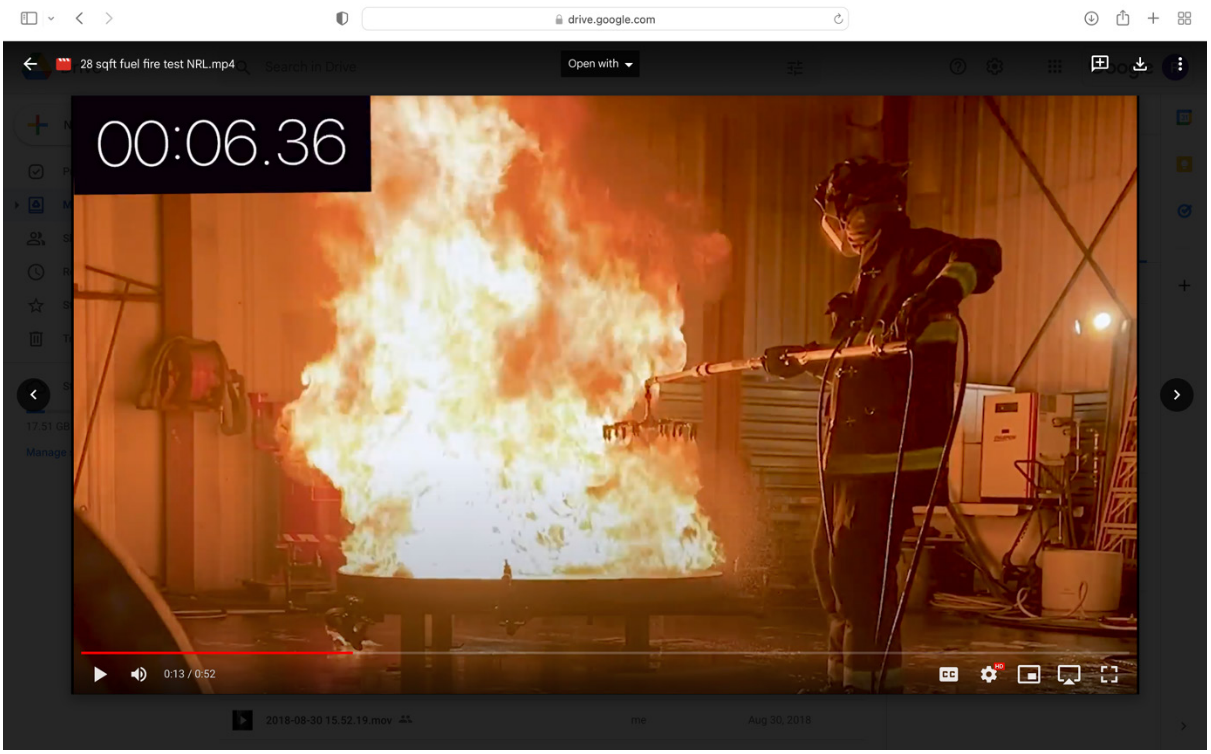

Photo 6. NRL Test at 6 Seconds (Test Time 31 Seconds)