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Foam property tests to evaluate the potential for longwall shield dust control

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Abstract

Tests were conducted to determine properties of four foam agents for their potential use in longwall mining dust control. Foam has been tried in underground mining in the past for dust control and is currently being reconsidered for use in underground coal longwall operations in order to help those operations comply with the Mine Safety and Health Administration's lower coal mine respirable dust standard of 1.5 mg/m^3. Foams were generated using two different methods. One method used compressed air and water pressure to generate foam, while the other method used low-pressure air generated by a blower and water pressure using a foam generator developed by the U.S. National Institute for Occupational Safety and Health. Foam property tests, consisting of a foam expansion ratio test and a water drainage test, were conducted to classify foams. Compressed-air-generated foams tended to have low expansion ratios, from 10 to 19, with high water drainage. Blower-air-generated foams had higher foam expansion ratios, from 30 to 60, with lower water drainage. Foams produced within these ranges of expansion ratios are stable and potentially suitable for dust control. The test results eliminated two foam agents for future testing because they had poor expansion ratios. The remaining two foam agents seem to have properties adequate for dust control. These material property tests can be used to classify foams for their potential use in longwall mining dust control.

Introduction

About one-half of U.S. underground coal is produced by longwall mining, which allows for mining high volumes of coal but generates significant amounts of coal mine dust. This can lead to overexposures for longwall miners and possibly occupational respiratory diseases, including black lung and silicosis, which have no cure and can be disabling or fatal. The only method to avoid these occupational illnesses is through elimination of exposure to respirable coal mine dust and crystalline silica (quartz). The current occupational exposure limit for respirable coal mine dust is 1.5 mg/m^3 during each shift that a miner is exposed in the active workings of the mine or in mine facilities (Mine Safety and Health Administration

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(MSHA), 2015a). When respirable quartz is present, the mine must maintain average concentrations at or below 0.1 mg/m^3. If the mine exceeds the 0.1 mg/m^3 respirable quartz dust concentration, then the applicable respirable dust standard is reduced, calculated as 10 divided by the percent quartz present (MSHA, 2015b).

Respirable dust samples collected by U.S. MSHA inspectors for the five-year period from 2010 to 2014 found that 5.6 percent — 53 of 943 respirable coal mine dust samples — of the longwall operators on the tailgate side exceeded the coal mine dust standard, and 4.3 percent — 76 of 1,768 samples — of the jacksetters exceeded the standard. If silica is present, the reduced standard is implemented, meaning that 11.4 percent — 36 of 316 respirable coal mine samples analyzed for dust — of the jacksetters exceeded the reduced standard (Joy, 2015). Had the 1.5 mg/m^3 standard been in effect during this period, noncompliant samples would have been much higher. For example, more than 15 percent of the samples collected for the tailgate shearer occupation would have exceeded the lower standard.

All longwall mining operations use water sprays to control dust during mining activities. Water sprays are often located on the shearer drums, at the headgate splitter arm, on manifolds on the shearer body between the head and tailgate drums, on manifolds above the lump breaker or on the shearer body directed toward the tailgate shearer, at tailgate splitter arms, and on the underside of the shields (Rider and Colinet, 2011). These water sprays operate at specific pressures and directions to confine the dust to the longwall face, preventing it from entering the longwall walkway.

However, for shield dust control, there are not as many resources to address the problem as for the shearer. The shield dust, generated due to the shield movement, can directly disperse downwind into the walkway, affecting the miners downstream. Water sprays, applied at the area between the shield tip and the longwall face, have been shown to be inadequate to prevent operator exposures to shield-generated dusts. Water is unable to remain in-place in adequate quantities for the necessary duration between application and shield advance. Prior research has suggested that applying foam to the roof/shield interface will provide a barrier between the loose roof material and the ventilating airstream. This study investigates the properties of foam that are most relevant for use in this mining application.

The Pittsburgh Mining Research Division of the U.S. National Institute for Occupational Safety and Health (NIOSH) is currently conducting research to determine the efficacy of foam use to remediate the generation of longwall shield dust. The purpose is not to develop foam agents for dust control but to evaluate existing foam agents in the marketplace that could potentially be used for longwall shield dust control. This report documents the results of testing to determine different foam properties for each foam agent.

Past foam studies

The use of foam for dust control has been investigated in the past. Monsanto Research Corp., under contract from the U.S Bureau of Mines, completed a series of studies that evaluated foam for the control of respirable coal dust. These have formed the basis for efficacy of foam application for dust control. These studies resulted in significant dust reductions, but the technology described was not readily adopted by industry because of foam generation complexity, cost and operational concerns.

Salyer et al. (1970) evaluated different surfactants, foaming agents, polymers and others to develop a foam that would work satisfactorily for respirable coal dust control in underground coal mining. This included evaluating the development of foam using pure versus hard water, and acidic versus basic water. The results showed that hard water and acidic water were beneficial for higher foam expansion factors ranging from 22 to 400. Testing was also conducted to determine the effectiveness of the foam for respirable coal dust control. It was considered that the foam must trap the coal dust particle at its source, as it forms by fracturing. Once airborne, foam is not able to easily trap the particles.

A foam generating system was constructed, and testing was completed to determine optimal parameters for foam generation. Parameters evaluated included foam solution concentration, water flow rate, pressure at the water nozzle, spray pattern, foam-generating screen geometry, and rate of air to the foam nozzle. The foam generation system was then developed for use on a continuous mining machine to apply foam on the cutter head. The foam system was found to have 19 percent better reduction in respirable dust concentration than the water spray system (Wojtowicz et al., 1974).

Additional studies on a fixed head ripper, an auger and a longwall shearer showed that the use of foam resulted in dust levels lower than those from using water sprays. The improvement ranged from 25 to 35 percent lower with some improvements as high as 60 percent (Hiltz, 1975). Another study of a longwall system showed a 49 percent improvement for foam — with dust level at 3.30 mg/m^3 — over water sprays — with dust level at 6.53 mg/m^3 (Singh and Laurite, 1984). A study on continuous miners demonstrated foam respirable dust reductions of 10.6 to 96.2 percent. However, there were conditions where the foam did not provide any reductions (Bhaskar and Gong, 1992).

Recent foam research on underground cutterheads in China shows that the use of foam reduces the amount of respirable dust by 85 percent while using 80 to 90 percent less water (Wang, Wang and Ren, 2011). Other tests were conducted using 0.5 percent foaming agent to generate a foam having control efficiencies of 69 percent (foam) versus 40 percent (water) for respirable dust (Ren et al., 2012).

Testing on a roadheader using specially designed nozzles demonstrated that the efficiency of foam for respirable dust control was approximately 84.4 percent, while the efficiency of water sprays for respirable dust control was approximately 18.5 percent. Water consumption was 1.5 to 2.5 m^3/hr (7 to 11 gpm) with 0.6 to 0.8 percent concentration of foaming agent. During testing, a foam expansion ratio of up to 30 was found to be optimal. Expansion ratios above 30 were too dry to penetrate the dust source. Expansion ratios of 20 or below were found to use too much water (Wang et al., 2013).

Foam generation methods and foam agents

To test the foam properties for dust control, there are two primary methods available to generate foam. Method one, designated as compressed-air foam, uses compressed air with

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water pressure to generate foam. This method uses an existing foam generator, the Lafferty Model 916105 HV foamer (Lafferty Equipment Manufacturing, North Little Rock, AR), that was developed for carwash applications. Water pressure and airflow parameters are important factors for foam generation. The device has inlets for water and compressed air and siphons the foam agent to develop foam that is expelled through a hose and out a nozzle (Fig. 1).

Method two, designated blower-air foam, uses a blower, the Roots Model DVJ 2504 blower (Dresser Roots Inc., Houston, TX) with a 5-hp Dayton Model 5KV79A electric motor and Dayton Model 3HX79 AC inverter variable frequency drive, to generate low-pressure airflow that is applied to a high-pressure water flow to generate foam (Fig. 2). This foam generator was designed by NIOSH, and several components of this system used precise specifications in order to prevent foam breakdown. This foam generator requires water, blower-generated air and a foaming agent to create the foam.

Since the purpose of this research was to test foam agents that would be suitable for generating foam for dust control using both compressed-air and blower-air foam generation methods, four foam agents — A, B, C and D — were identified for this testing. Their properties are listed in Table 1.

Important foam generation properties

A comprehensive review of foam studies showed that three important properties are concentration, foam expansion ratio and foam drainage time. The first two define the foam agent's ability to generate foam, and the third is an indicator of the ability of foam to retain water and the fluidity of the foam. Due to space limitations, only foam expansion ratio and drainage time are compared here. The foam concentration tests can be found in Reed et al. (2017).

Foam expansion ratio and drainage time are foam properties originally developed for firefighting foams. The U.S. Bureau of Mines used foam expansion ratio extensively to describe foams for firefighting and, subsequently, dust control in underground coal mines. Methods to calculate these properties are published by the National Fire Protection Association (NFPA, 2014).

The expansion ratio is defined as the ratio of the foam collection vessel's volume to the final foamable liquid weight collected during the foam stability tests, calculated by:

$$\mathrm{Expansion} = \mathrm{Vol}_{\mathrm{empty}} / (\mathrm{Weight}_{\mathrm{full}} - \mathrm{Weight}_{\mathrm{empty}})$$

where *Expansion* is the nondimensional expansion of the foam; Vol_{empty} is the known volume of the empty collection vessel, in milliliters; $Weight_{\mathrm{full}}$ is the weight of the full collection vessel, filled with foam, in grams; and $Weight_{\mathrm{empty}}$ is the weight of the empty collection vessel, in grams.

Generally, foams fall into three categories: (1) low expansion foams, with 0 to 20 expansion ratio, (2) medium expansion foams, with 20 to 200 expansion ratio, and (3) high expansion foams, with >200 expansion ratio (NFPA, 2011). While these are useful categories for firefighting, they may not relate to dust control. However, foam expansion ratio is useful for comparing different foam agents. It was found through previous studies and verified by these laboratory experiments that foams with higher expansion ratios were “drier” foams (Schwendeman et al., 1972; Wang et al., 2013).

Foam drainage time is an indicator of the ability of foam to retain water. It also indicates the fluidity of the foam. The standard value for comparison is the 25 percent foam drainage time (NFPA, 2014). Data from the foam stability tests are generally used to calculate this value using:

$$\text{Foam solution loss}=\text{Vol}_{\text{gradcyl}}/\mathit{25}\ \text{percent drainage time}$$

where *Foam solution loss* is the rate of solution loss from foam in milliliters per minute; Vol_{gradcyl} is the volume of solution in the graduated cylinder, in milliliters; and *25 percent drainage time* is the time for foam to drain 25 percent, in minutes. Foams with lower values of foam solution loss will be more desirable than foams with higher values.

In preliminary testing, 25 percent drainage time was not achievable in many instances for foam generation tests. Therefore, the 25 percent foam drainage time test was modified to determine the drainage from the foam at consistent 2-min time intervals up to approximately 10 min after filling the test flask. This modified drainage test is useful in comparing foam agents. With this modification, foams with lower values of foam water loss are still more desirable than foams with higher values.

To calculate these properties, foam was projected from the foam generator (Fig. 3) onto a simple wooden foam collection stand (Fig. 4). The foam created was funneled into a collection container for further timed observations (Fig. 5).

The foam collection stand used in the NIOSH tests was built to accommodate three collection containers, and be able to conduct three trials simultaneously. Preliminary testing was conducted to minimize the parameters to be tested. For the compressed-air foam, water pressure was tested at 0.41 and 0.028 MPa (60 and 40 psi). Preliminary testing demonstrated that 0.14 MPa (20 psi) water pressure was not sufficient to generate foam. The air pressure was always set to 0.07 MPa (10 psi) less than the water pressure, according to the operating directions of the Lafferty foamer (Fig. 1). The foam solution targeted a 2 to 3 percent foam agent. This was accomplished by inserting a specific metering tip in the foam agent siphon inlet. Two spray nozzle conditions were tested: one without any nozzles (end of the hose) and the other using a VeeJet SS CO H3/4U nozzle (Spraying Systems, Wheaton, IL). A smaller nozzle was tested during preliminary testing, but its diameter and corresponding cross-sectional area were found to be too small, resulting in the destruction of any foam generated.

For the blower-air generated foam, only B and D were tested, as prior test results from compressed-air generated foam eliminated A and C as viable foam agents. As the foam generation methodology is different from compressed-air generated foam, the water pressure and air supply properties were different. Water pressure was tested at 0.41 and 0.21 MPa (60 and 30 psi). Air supplied was tested at full power, obtained by operating the electric motor's variable frequency drive at 60 Hz, and half power, obtained by setting the variable frequency drive to 30 Hz. However, during testing it was found that full-power air supply was too much, resulting in deteriorated foam properties. Therefore, only two tests were conducted at full power. The internal spray nozzle was kept constant using an SS CO 50 W for all tests. No nozzle was used at the end of the foam generation hose. Foam solution concentration targeted 1.5 to 2.0 percent foam agent.

Foam property results for compressed-air generated foam

Table 2 shows the foam property results for compressed-air generated foam. Each line represents the average of three trials conducted for the properties listed. The results are shown as expansion ratio, drainage, and time. Time corresponds to the length of time that the drainage test was conducted. From the results, foam dispersion testing was limited to using no nozzle and using the VeeJet SS CO H3/4U nozzle.

Foam agent A

Foam agent A had a higher viscosity than all of the other foam agents. Handling this foam agent revealed that siphon metering may be difficult. The concentration of foam agent A ranged from 1.11 to 1.66 percent throughout testing. The highest concentration that could be obtained was 2.32 percent with the siphon metering tip removed, corresponding to maximum siphon capability with the Lafferty foam generator. The highest expansion ratio was 5.00 at the highest solution concentration of 2.32 percent with water drainage of 311 mL. An attempt was made to reduce the viscosity by mixing with water to produce a solution with a 1:1 ratio of water to foam agent A. However, the result was not improved: at 0.41 MPa (60 psi) water, 0.34 MPa (50 psi) air-generated foam with no nozzle, the expansion ratio was 4.53 with water drainage of 338 mL. Therefore, in comparing foam properties, this is not a preferred foam agent for further testing, and due to the siphon-metering difficulties with this foam agent, testing was discontinued.

Foam agent B

Foam agent B performed adequately by binding the water into the foam matrix. There was less water drainage from this foam among all the foam agents. The 0.41 MPa (60 psi) water, 0.34 MPa (50 psi) air-generated foam with no nozzle had the highest expansion ratio of 16.27 and the lowest water drainage of 2 mL. When the no-nozzle foam is compared with the foam using the VeeJet SS CO H3/4U nozzle, it is seen that using a nozzle deteriorates the foam.

Foam agent C

Foam agent C had adequate expansion ratios but higher levels of water drainage. The 0.41 MPa (60 psi) water, 0.34 MPa (50 psi) air-generated foam with no nozzle had a high expansion ratio of 9.38 and high water drainage of 154 mL. There was one test where the concentration of foam agent C in solution was 8 percent; this test operated at 0.28 MPa (40 psi) water, 0.21 MPa (30 psi) air with no nozzle and had the highest expansion ratio of 14.71 and low water drainage of 87 mL. However, the use of this much foam agent may be prohibitively expensive and only produced results similar to foam agents B and D. Again, it can be seen from the results of property testing that the use of a nozzle deteriorates the foam to the point where the expansion ratios were lower than those of foam agents B and D. Therefore, in comparing foam properties, this is not a preferred foam agent for further testing.

Foam agent D

Foam agent D generated foam with generally higher expansion ratios. Various pressure states were evaluated, with 0.28 MPa (40 psi) water, 0.21 MPa (30 psi) air and 0.41 MPa (60 psi) water, 0.34 MPa (50 psi) air having superior results. The 0.41 MPa (60 psi) water, 0.34 MPa (50 psi) air-generated foam with no nozzle had the highest expansion ratio of 18.86 and a low water drainage of 44 mL.

Foam property results for blower-air-generated foam

Foam property tests were only conducted for foam agents B and D using the blower-air foam generator. Agents A and C were not tested due to their earlier foam property results. Table 3 summarizes the testing results. As in Table 2, each line represents the average of three trials. For this testing, the three trials were repeated three times to ensure consistency among the blower-air generated foam, except for the cases using full air power, which was not repeated and is the average of three trials only. For all trials, no nozzle was used at the end of the hose distributing the foam. The results are shown as expansion ratio, drainage and time. Time corresponds to the length of time the drainage test was conducted.

Foam agent B

Throughout testing, foam agent B produced a lower expansion ratio than foam agent D, but also a much smaller amount of drainage over an approximate 10-min span. The highest expansion ratios and lowest amount of drainage were found with 0.21 MPa (30 psi) water pressure and half airflow power (30 Hz), producing an average expansion ratio of 41.77 and a total of 0 mL water drainage for all tests. When the water pressure was increased to 0.41 MPa (60 psi), the average expansion ratio lowered to 33.23 while still maintaining 0 mL drainage. The lowest average expansion ratio of 19.16 occurred with 0.21 MPa (30 psi) water pressure and full, 60-Hz airflow power. This single test was also the only one of the seven to produce any drainage, although it was minimal at 1 mL.

Foam agent D

Testing foam agent D showed that it produced a higher expansion ratio than foam agent B, but it also had a larger amount of drainage over an approximate 10-min span. Similar to agent B, the highest expansion ratios and lowest drainage totals were found with the 0.21 MPa (30 psi) water pressure and half airflow power (30 Hz), producing an average expansion ratio of 60.50 and an average water drainage of 5.17 mL. With 0.21 MPa (30 psi) water pressure and full airflow power (60 Hz), the average expansion ratio decreased to 36.73, while the average water drainage increased to 9.00 mL. The least desirable results for foam agent D occurred when the water pressure was increased to 0.41 MPa (60 psi) at half airflow power (30 Hz). Under these conditions, the average expansion ratio lowered to 36.57 while the average drainage increased to 14.33 mL.

Conclusions

In this study, foam properties of four foam agents were evaluated using expansion ratio and water drainage over time. These properties will be important to evaluate and select foaming agents for future use as a mining dust control method, especially in reducing dust generated from longwall shield movement. Reducing miner exposure to longwall shield dust will improve miners' health by reducing their exposure to black lung or silicosis.

For foam expansion ratios, a foam agent that can only produce an expansion ratio of 5 or less would be rejected. Higher expansion ratios are preferable, as is minimal water drainage. It should be noted that these properties may not be indicative of dust control effectiveness.

Reviewing the results of compressed-air generated foam, the foam agents B and D were the best performers. The foam applied with no nozzle had better properties than with a nozzle. The nozzle opening being smaller than the hose diameter tends to degrade or destroy the foam. Agent D tended to have higher expansion ratios, but agent B had significantly less water drainage. This indicates that agent B may be better at binding the water into the foam matrix. Overall, compressed-air generated foams produced foams with expansion ratios ranging from 5 to 19. Water drainage ranged from 2 to 239 mL and was dependent upon the foam agent used.

Foam agent A had the weakest performance of all the foam agents. As the highest expansion ratio is less than 5, testing with agent A will be discontinued. Foam agent C produced foam, but the foam was watery and basically looked like a water and surfactant solution. Therefore, testing with foam agent C will also be discontinued.

Use of an air blower to generate foam was shown to have advantages and disadvantages. While the overall system is bulky and made of several customized parts, compared with compressed-air-generated foams, blower-air-produced foams had higher expansion ratios ranging from 19 to 65 and lower water drainage ranging from 0 to 15 mL.

Further testing will be conducted with foam agents B and D, particularly with the inclusion of dust to test their respective dust control effectiveness. Future planned testing of the foam agents for dust control along with their properties will provide information for a more definitive selection process for mining dust control using foam properties as criteria.

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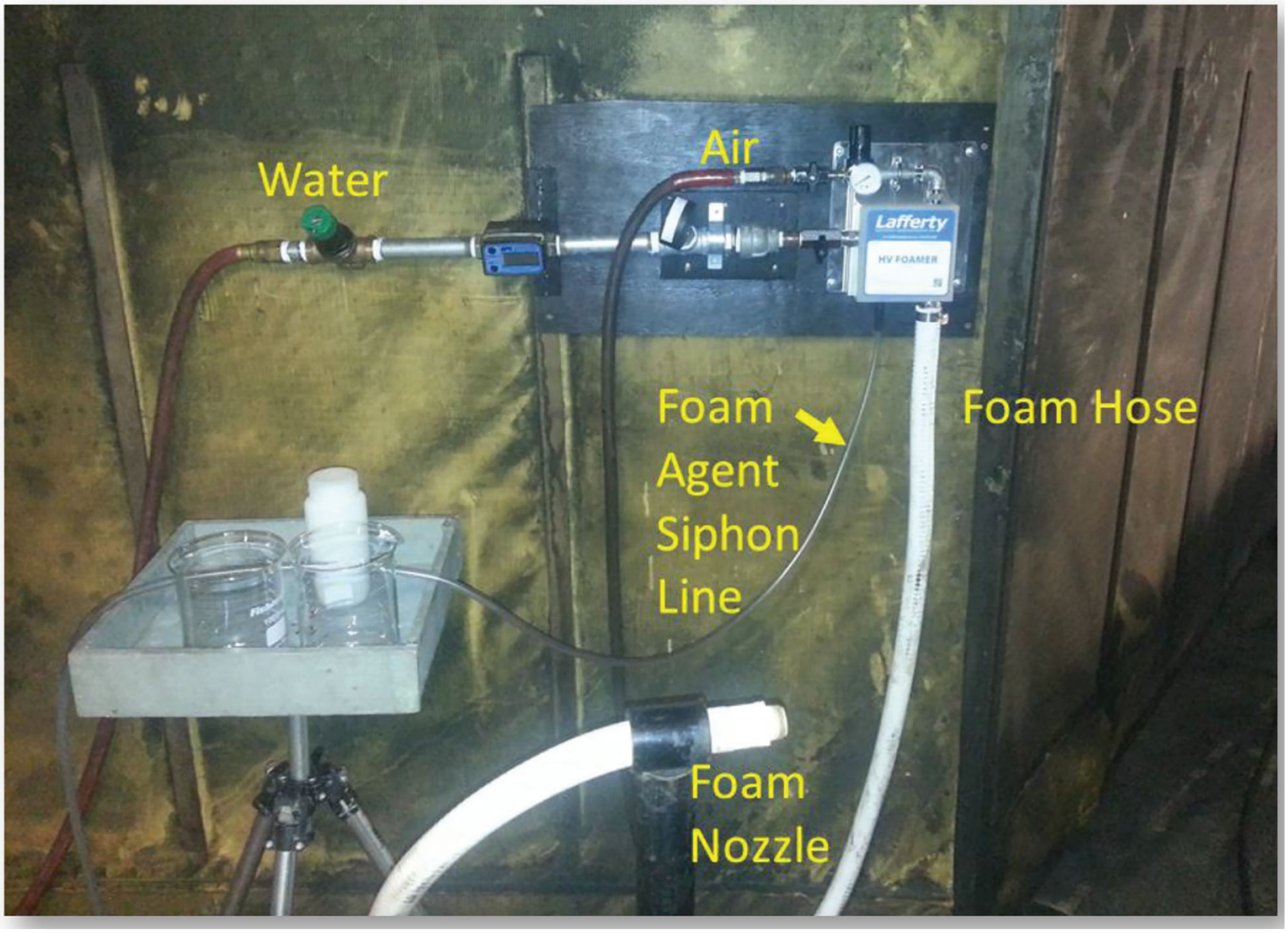

Figure 1.
Foam generator setup for compressed-air foam.

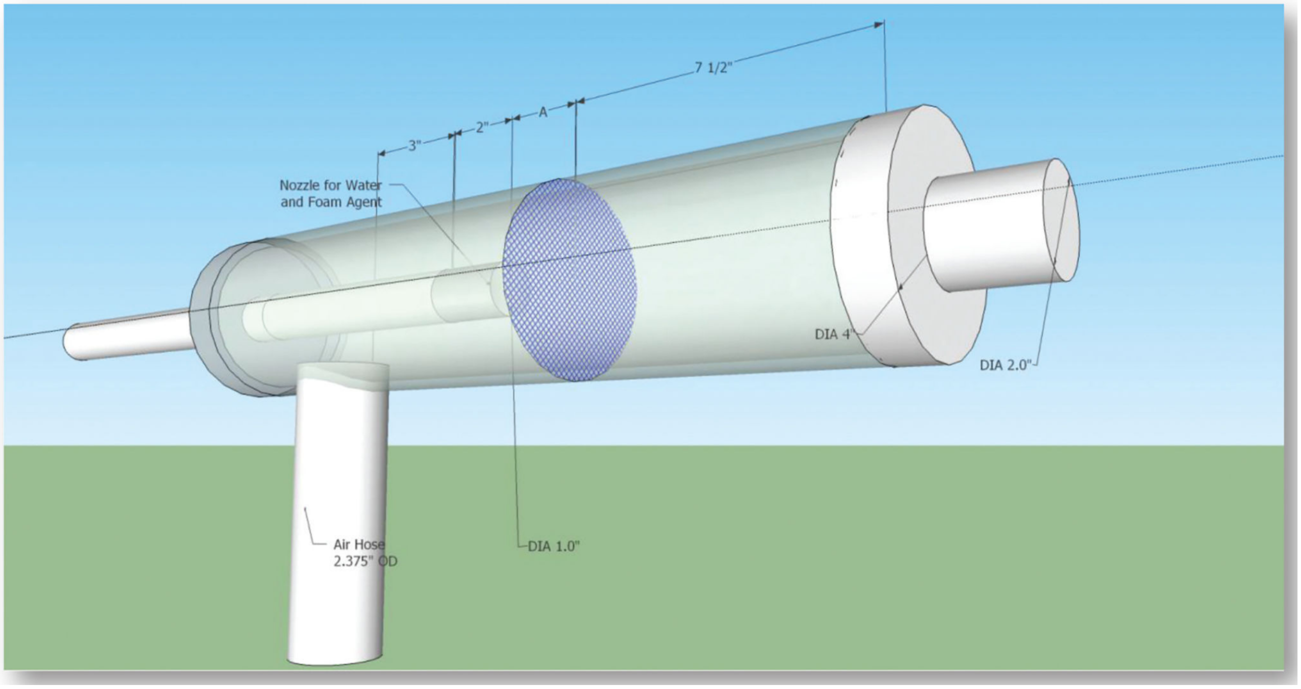

Figure 2.
Foam generator setup for blower-air foam, developed by NIOSH.

Figure 3.
Foam collection stand test using foam agent B at 0.41 MPa (60 psi) water, 0.34 MPa (50 psi) air and no nozzle.

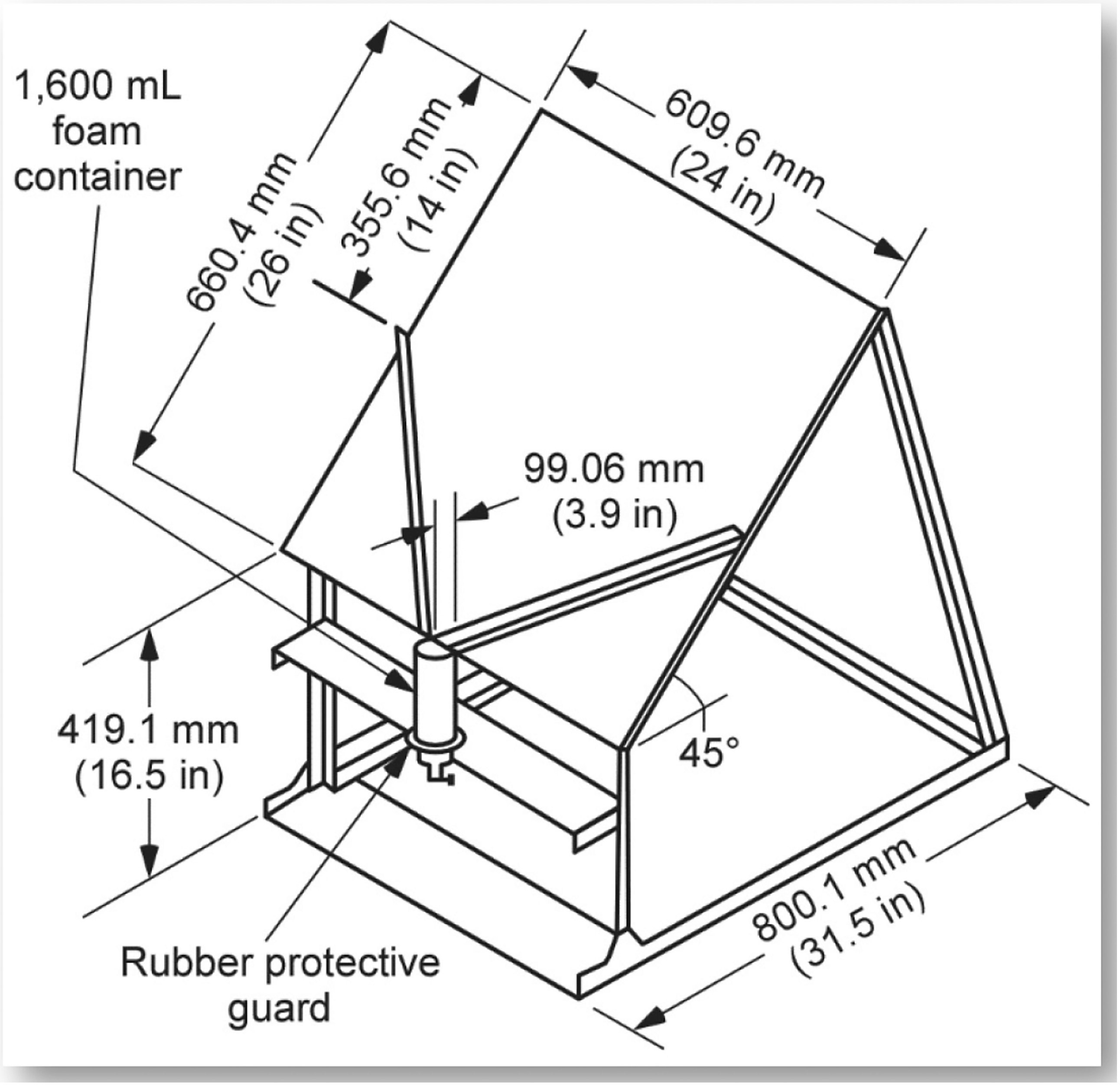

Figure 4.
Typical foam collection stand (NFPA, 2014).

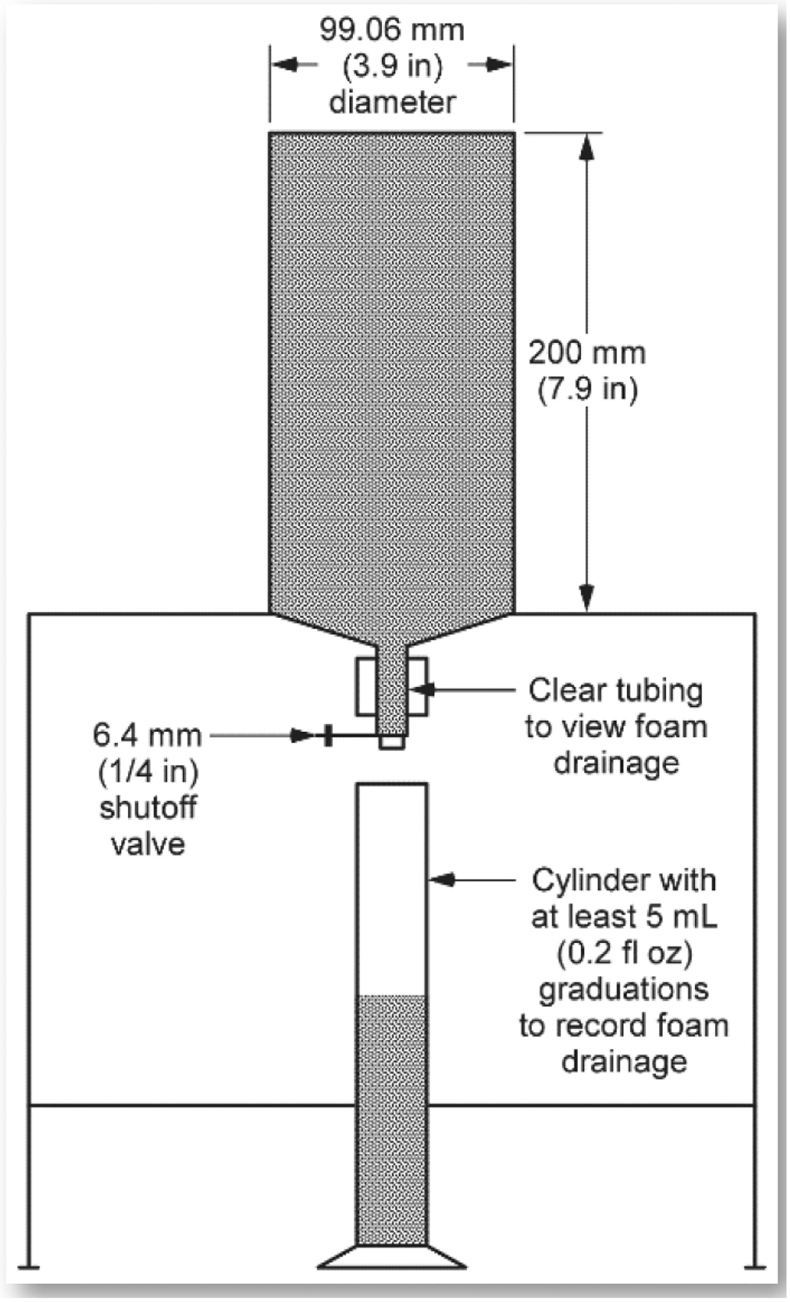

Figure 5.
Typical foam collection container and graduated cylinder (NFPA, 2014).

Table 1

Foam agents with their associated properties (N/A = not available because agent is an aqueous solution, N/D = not determined).

Foam agent	Color	Odor	pH	Flash point (°C)	Density (g/cc)	Viscosity (cp)	Primary chemical components	Surfactant type	NFPA Code: Health	NFPA Code: Fire/flammablity	NFPA Code: Reactivity/ physical hazard
A	Colorless	Mild	7.5	100	1	N/D	Benzenesulfonic acid - 4-nonylphenol polyethoxylate	Anionic-nonionic	2	1	0
B	Light yellow	Slight	7.0–9.0	N/A	1.015	N/D	Butyl diglycol	Nonionic	1	0	0
C	Yellow	Mild	10.7	>200	1.017	10	Sodium olefin sulfonate	Anionic	1	0	0
D	Pale yellow	Bland	7.0–9.0	N/A	1.06	N/D	Sodium alpha olefin sulfonate	Anionic	1	0	0
Water	Colorless	None	7.5–7.9	N/D	1	1	Water	N/A	0	0	0

Table 2

Property results of foam agents using the Lafferty foam generator.

Foam agent	Concentration (%)	Water pressure (MPa)	Air pressure (MPa)	Nozzle	Expansion ratio	Drainage accumulation (mL)	Time (hh:mm:ss)
A	1.30	0.28	0.21	None	3.45	454	0:08:52
A	1.11	0.41	0.34	None	4.13	337	0:09:07
A	1.66	0.41	0.34	None	4.53	338	0:10:28
A	2.32[a]	0.28	0.21	None	5.00	311	0:10:04
A	1.11[b]	0.41	0.34	None	4.53	338	0:10:28
A	1.66	0.41	0.34	Veejet SS CO H3/4U	3.06	478	0:10:15
B	2.90	0.28	0.21	None	15.25	8	0:09:55
B	2.50	0.41	0.34	None	16.27	2	0:09:47
B	2.67	0.28	0.21	None	14.71	13	0:09:50
B	2.90	0.28	0.21	Veejet SS CO H3/4U	11.92	12	0:09:41
B	2.50	0.41	0.34	Veejet SS CO H3/4U	9.47	10	0:09:50
C	2.68	0.28	0.21	None	9.08	169	0:09:44
C	2.22	0.41	0.34	None	9.38	154	0:10:38
C	8.00	0.28	0.21	None	14.71	87	0:10:24
C	2.68	0.28	0.21	Veejet SS CO H3/4U	7.86	199	0:10:48
C	2.22	0.41	0.34	Veejet SS CO H3/4U	6.45	239	0:10:28
D	2.57	0.28	0.21	None	13.72	91	0:09:34
D	2.82	0.14	0.07	None	4.53	350	0:09:24
D	2.20	0.41	0.34	None	18.86	44	0:09:27
D	2.57	0.28	0.21	Veejet SS CO H3/4U	10.63	123	0:09:51
D	2.82	0.14	0.07	Veejet SS CO H3/4U	3.97	395	0:09:05
D	2.20	0.41	0.34	Veejet SS CO H3/4U	10.97	109	0:09:05

[a] Maximum siphon — no siphon regulation nozzle used.

[b] A mixed 1-to-1 ratio of water to thin foam agent.

Table 3

Summary of foam property testing results using the blower-air foam generator.

Foam agent	Concentration (%)	Water pressure (MPa)	Airflow power	Internal nozzle	Expansion ratio	Drainage accumulation (mL)	Time (hh:mm:ss)
B	2.17	0.21	Half	SS CO 50W	42.3	0.0	0:09:54
B	2.48	0.21	Half	SS CO 50W	39.2	0.0	0:10:00
B	2.32	0.21	Half	SS CO 50W	43.8	0.0	0:09:44
B	1.45	0.41	Half	SS CO 50W	34.4	0.0	0:09:08
B	1.53	0.41	Half	SS CO 50W	35.3	0.0	0:09:10
B	1.53	0.41	Half	SS CO 50W	30.0	0.0	0:09:13
B	1.32	0.21	Full	SS CO 50W	19.2	1.0	0:09:05
D	1.69	0.21	Half	SS CO 50W	60.2	5.5	0:10:33
D	1.45	0.21	Half	SS CO 50W	65.2	3.0	0:09:23
D	1.37	0.21	Half	SS CO 50W	56.1	7.0	0:08:56
D	1.62	0.21	Full	SS CO 50W	36.7	9.0	0:09:14
D	1.32	0.41	Half	SS CO 50W	40.4	13.5	0:09:12
D	1.61	0.41	Half	SS CO 50W	35.0	15.0	0:08:57
D	1.07	0.41	Half	SS CO 50W	34.3	14.5	0:08:56