Aqueous Foam As A Less-Than-Lethal Technology For Prison Applications

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ABSTRACT

High expansion aqueous foam is an aggregation of bubbles that has the appearance of soap suds and is used to isolate individuals both visually and acoustically. It was developed in the 1920's in England to fight coal mine fires and has been widely used since for fire fighting and dust suppression. It was developed at Sandia National Laboratories (SNL) in the 1970's for nuclear safeguards and security applications. In late 1994, the National Institute of Justice (NIJ), the research arm of the Department of Justice, began a project with SNL to determine the applicability of high expansion aqueous foam for correctional applications. NIJ funded the project as part of its search for new and better less-than-lethal weapons for responding to violent and dangerous individuals, where other means of force could lead to serious injuries. The phase one objectives of the project were to select a low-to-no toxicity foam concentrate (foaming agent) with physical characteristics suited for use in a single cell or large prison disturbances, and to determine if the selected foam concentrate could serve as a carrier for Oleoresin Capsicum (OC) irritant. The phase two objectives were to conduct an extensive toxicology review of the selected foam concentrate and OC irritant, and to conduct respiration simulation experiments in the selected high expansion aqueous foam. The phase three objectives were to build a prototype individual cell aqueous foam system and to study the feasibility of aqueous foams for large prison facility disturbances. The phase four and five objectives were to use the prototype system to do large scale foam physical characteristics testing of the selected foam concentrate, and to have the prototype single cell system further evaluated by correctional representatives. Prison rather than street scenarios were evaluated as the first and most likely place for using the aqueous foam since prisons have recurrent incidents where officers and inmates might be seriously injured during violent confrontations. The very low density of the high expansion foam also makes it more suitable for indoor use. This paper summarizes the results of the project.

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2. AQUEOUS FOAM

The unique high expansion aqueous foam developed and evaluated for corrections applications is mechanically generated by the movement of a large volume of air through a screen that is continuously wetted by an aqueous solution of a synthetic foam concentrate. Foam concentrates contain surfactants that are chemically similar to those used in hair shampoo and liquid soaps. In military and security applications, aqueous foam has been used for tunnel denial and for riot control. Past SNL installations of aqueous foam security systems include Department of State embassies where the historic security threat includes mobs intent on ransacking and burning facilities[1]. In these applications, the aqueous foam not only impedes adversaries from moving about within the facilities, but also hinders them from starting fires in the foamed spaces.

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Once dispensed, aqueous foam acts like a viscous liquid. It can flow down halls and stairwells and needs to be contained. The longer a foam stands after being generated, the more it behaves like a solid. This is because the water drains out of the bubbles reducing the wall thickness, wall strength, and fluidity of the mass. High expansion aqueous foam is generally evaluated using two criteria: expansion ratio and drainage rate. Expansion ratio is defined as the ratio of the volume filled by the deployed foam relative to the storage volume of the water and concentrate consumed in generating the foam. Expansion ratios of 400:1 are typically used for security applications. Drainage rate is a measure of the foam's liquid retention capability. Immediately after a mass of foam is generated, liquid will begin flowing downward through the foam. As liquid drains from the foam, the bubbles become more fragile and the dissipation rate increases. SNL has developed foam concentrates specifically designed for security applications. Aqueous foam characteristics which can be tailored to an application include: flexibility in sizing (commercial systems are available with foam output of 50 to 37,000 cfm), sound attentuation, vision obscuration, fire suppression, irritant carrier capability, and foam sustainability.

3. TOXICOLOGY STUDY

Over thirty-six low-to-no toxicity foam concentrates were evaluated for physical foaming characteristics. The ones which met the physical characteristics deemed necessary for corrections applications were further evaluated for toxicological concerns. This led to the final selection of the foaming agent for prison aqueous foam applications, Stepan's Steol CA-330. The concentrate was also tested and shown to be a successful carrier for Oleoresin Capsicum (OC) irritant. OC irritant was selected because of its universal usage and acceptance by law enforcement agencies. Extensive review of the toxicology literature was documented for both the aqueous foam[2] and OC irritant[3]. A patent application was filed for the successful combined foam concentrate/OC formulation.

An evaluation of the toxicity literature[2] was done on the aqueous foam developed for the NIJ to determine whether there are any significant adverse effects associated with completely immersing individuals without protective gear in the foam. The toxicity of the aqueous foam developed for NIJ was determined by evaluating the individual components of the foam. The foam is made from a 2-5% solution of Steol CA-330 surfactant in water generated at expansion ratios ranging from 500:1 to 1000:1. Steol CA-330 is a 35% ammonium Laureth sulfate in water and contains trace amounts (<0.1%) of 1, 4-dioxane. The results of the study indicate that Steol CA-330 is a non-toxic, mildly irritating, surfactant that is used extensively in the cosmetics industry for hair care and bath products. Inhalation or dermal exposure to this material is not expected to produce significant irritation or systemic toxicity to exposed individuals, even after prolonged exposure. The amount of 1, 4-dioxane in the surfactant, and subsequently in the foam, is negligible, and therefore, the toxicity associated with dioxane exposure is not significant. In addition, aqueous foams have been used for applications that include immersing individuals in foam without protective equipment for various amounts of time. In general, immersion in aqueous foams similar to the one developed for NIJ has not resulted in acute, immediately life-threatening effects, or chronic, long-term non-reversible effects following exposure.

OC is an extract of the pepper plant used for centuries as a culinary spice (hot peppers). The results of the OC review[3] indicate that the effects of exposure to OC appear to be limited to the characteristic burning sensation expected of the capsaicinoids and do not result in permanent adverse effects or tissue damage. OC exposure can result in dermatitis, as well as mild to moderate adverse nasal, pulmonary, and gastrointestinal effects in humans. The primary effects of OC exposure include pain and irritation of the mucous membranes of the eyes, nose, and lining of the mouth. Blistering and rash have been shown to occur after chronic or prolonged dermal exposure, and ingestion of large doses may cause acute stinging of the lips, tongue, and oral mucosa and may lead to vomiting and diarrhea. However, prolonged or repeated dermal exposures and large oral exposures are not expected with the intended use of OC in aqueous foam. All effects following OC exposure are expected to be reversible following removal of the individual from the exposure. OC has been used extensively as a culinary additive and medicinal ointment, and there have been no reports of permanent adverse effects following repeated or prolonged exposure.

4. FOAM RESPIRATION SIMULATION EXPERIMENTS

Frequency, volume, and character of the aspirate are factors that determine the occurrence and extent of pulmonary complications following aspiration. Using the dog as a model for aspiration pneumonia, the current "at risk criteria" for aspiration pneumonia has been determined to be fluid volumes of greater than 25 ml (aspiration of 0.4.-0.5 ml/kg) with a pH of less that 2.5. The maximum quantity of foam that might be aspirated by an individual immersed in the SNL aqueous foam was studied[4]. Figure 1 shows the breathing simulator used to simulate the aspiration of the foam generated at expansion ratios in the range of 500:1 to 1000:1. Although the natural instinct of an individual immersed in foam is to cover their nose and mouth with a hand or cloth, thus breaking the bubbles and decreasing the potential for aspiration, this study was performed to examine a worst case scenario with mouth breathing only, and no attempt was made to block foam entry into the breathing port. Two breathing rates were examined: one simulating a sedentary individual, and one simulating an agitated or heavily breathing individual.

The results of this study indicate that breathing in aqueous foam without movement forms an air pocket around the nose and mouth within one minute of immersion. Maximal aspiration of the foam occurs in the first 3-5 breaths following immersion, with no additional foam aspirated with continued exposure. The maximum accumulated amount of foam that was estimated to be aspirated during a one-hour exposure to aqueous foam generated at an expansion ratio of 500:1, was 18 grams or 17.5 ml of collapsed foam. This is less than the 25 ml critical volume for risk of aspiration pneumonia. The potential for aspiration increases, however, under circumstances involving general anesthesia, intoxication with alcohol or drugs, seizures, strokes, and disorders of the esophagus and trachea, which may be of concern when dealing with an incarcerated individual.

5. PROTOTYPE AQUEOUS FOAM CELL EXTRACTION SYSTEM

Requirements for the aqueous foam cell extraction system were developed in conjunction with NIJ, the American Correctional Association (ACA), the Florida Department of Corrections (FDOC), and the Federal Bureau of Prisons (FBOP)[5]. Based on the developed requirements, a cart-mounted cell extraction aqueous foam system was developed and tested. Figure 2 shows the system in front of the mock cell and Figure 3 shows the cell filled with foam following a test of the system. The system[6] has two main components: a pressurized system to provide a specific solution flowrate to the nozzles of the foam generator and an electric-powered fan to generate the air flow which creates the foam. The pressure source is a carbon dioxide cartridge identical to the ones used in fire extinguishers. The prototype foam generator output is 12 inches in diameter and uses a transition sock and adapter to input foam into a cell foodslot as shown in Figure 3. Note that all the components of the cell extraction aqueous foam system are detachable from the cart for carrying up stairs and re-assembly. Electric power cord reels and water hose reels allow for operation of the system 50 feet from utility connections. The main requirements for the system were to fill a 500 ft^3 cell in 30 seconds and deliver foam expansion ratios from 500:1 to 1000:1.

6. FOAM PHYSICAL CHARACTERISTICS TESTS

Large scale physical characteristics testing of the SNL developed prison aqueous foam was completed in December 1995[7]. The aqueous foam for the testing was generated using the cart-mounted cell extraction system. Fifty-seven total tests were conducted with the first forty-five tests to determine the overall performance of the cell extraction system and the final twelve tests used to conduct the large scale foam physical characteristics tests series. The mock cell shown in Figure 3 was used for the tests. It was modified such that as the aqueous foam collapsed to wastewater within the cell, the wastewater was collected and disposed of using the sanitary sewer. The large scale foam physical characteristics testing included light attenuation, sound attentuation, drainage rate/collapse rate, foam knockdown, OC foaming and decontamination, and mock cell cleanup and disposal of wastewater.

For the light attenuation tests, a videocamera was placed within the mock cell and the cell was filled with aqueous foam of approximately 500:1 expansion ratio. As the foam flowed over the videocamera, the view became opaque and the amount of diffuse light present decreased slightly with foam depth. In an actual prison cell, which has fewer light sources than the mock cell, the amount of diffuse light present in the foam would be significantly decreased and the view within the foam would be much darker or black.

For the sound attenuation tests, a noise source was placed at two distances from a sound level meter within the cell and the cell was filled with approximately 500:1 foam. The freshly dispensed foam has a sound absorption of approximately 7 to 10 dBA per foot of foam. As the water drains out of foam, the sound absorption lessens until there is almost no attenuation. With the maximum sound attenuation level noted, an inmate in a foam-filled cell and an officer at the foodslot should be able to converse by yelling at each other. A megaphone would insure communication with the inmate in freshly made foam.

For the drainage rate/collapse rate tests, the mock cell was filled with foam and not disturbed while data was collected. In 10 minutes approximately 60 percent of the solution used to make the foam had drained out of the foam, and in 20 minutes approximately 80 percent. Because of the low humidity in the building where the tests were conducted, some of the foam solution evaporated prior to being collected in the catch tank In the same 20 minutes the foam collapsed approximately 15 inches in height, but because of the drainage had become relatively fragile.

Four types of foam knockdown tests were conducted and included pressurized air hose, water spray, carbon dioxide fire extinguisher, and flashbang grenade. For each, the mock cell was filled with approximately 500:1 foam. The tests were to determine the times necessary to rapidly knockdown the foam for emergencies. The flashbang grenade collapsed most of the foam in the cell in a few seconds and the foam attenuated the peak sound level of the grenade from above 170 dBA (without foam) to 152 dBA (with foam). The carbon dioxide fire extinguisher collapsed the foam in under a minute. The pressurized air hose and water spray both required several minutes to collapse the foam. Figures 4 and 5 depict carbon dioxide fire extinguisher and pressurized air hose foam knockdown tests, respectively.

Expansion ratios of 830:1 were achieved with OC-laced foam concentrate using a laboratory scale (50 cfm) foam generator. The large scale tests were to determine how well the cell extraction aqueous foam system would generate OC-laced foams. The output of the lab foam generator was not choked by having to discharge into a sock and adapter as the cell extraction system does. The cell extraction system was able to achieve an expansion ratio of 186:1 through the sock and adapter, and 345:1 with the sock and adapter removed.

The FDOC decontaminates OC sprayed cells by sending linens to the laundry, airing out mattresses for 24 hours and washing all cell walls with standard cleaning soap and water. For the OC-laced aqueous foam testing at SNL, the mock cell did not contain linens or a mattress. Decontamination and cleanup of the mock cell and cell extraction aqueous foam system was conducted with copious amounts of water. Wastewater generated from collapsed aqueous foam and from the decontamination process was disposed of via the SNL sanitary sewer system. Cleanup of aqueous foam using a wet/dry vacuum for cleanup of OC-laced foam is not recommended since it would tend to resuspend settled OC.

Based on the twelve physical characteristic aqueous foam tests and the forty-five overall aqueous foam performance tests of the cell extraction system, the following conclusions were drawn:

* A non-toxic foam formulation which met the required design characteristics was successfully developed for correctional inmate cell extraction applications. OC was successfully incorporated into the formulation at a 5% concentration and the OC-laced formulation produced viable aqueous foam.

* The prototype cell extraction aqueous foam system was successfully demonstrated to meet most of the requirements developed by the correctional team: it is lightweight and portable; it can be separated into components for handcarry up stairs and then quickly reassembled for use; it can be operated 50 feet from utility connections; it can fill a 500 ft^3 cell twice without refill; it can fill a 500 ft^3 cell in 30 seconds; it can produce up to 500:1 expansion ratio foam through the sock and adapter into the cell using the foodslot; it can produce OC-laced foam; it is easy to operate; it is easy to maintain; it is easy to clean after usage; it can be stored for long periods between usages; and, it is relatively low-cost.

* From the sound attenuation testing, an individual at a cell foodslot should be able to converse through the aqueous foam to an individual in the cell by yelling at each other. Other factors should improve the sound transmission through the foam; as the foam ages (drains), the sound attenuation decreases; and the target expansion ratio for cell extraction applications is 800:1 which starts out with better sound transmission than the 500:1 foams that

were used for the sound attention tests. To insure communication with an inmate in a cell just filled with foam, the officer at the foodslot should use a megaphone.

* Light attenuation test results were as expected. As the foam flowed over the videocamera within the mock cell, the view became opaque and the amount of diffuse light present decreased slightly with foam depth. In an actual prison cell, which has fewer light sources than the mock cell, the amount of diffuse light present in the foam would be significantly decreased and the view within the foam would be much darker or black.

* The cell extraction aqueous foam system required an increase in surfactant to make viable foam. As a result, the foam does not collapse as rapidly as required by the correctional team representatives or like that seen in the small lab experiments. However, the foam still drains rapidly enough that after several minutes it is sufficiently fragile that all of the tested knockdown techniques can be used effectively. The fastest foam knockdown technique was a flashbang grenade and required only several seconds. Other knockdown techniques tested were CO_2 fire extinguisher, pressurized air, and water spray, the latter requiring several minutes to complete the foam knockdown.

* Based on the effects of OC exposure to test personnel in limited protective gear, the dispensed foam with OC should be as effective as aerosolized OC. Because of the perceived OC foam effectiveness by test personnel, there is also a potential for reduction of the OC concentration used in the foam formulation. Lastly, decontamination procedures already in use in prisons for aerosolized OC should be suitable for an OC-laced aqueous foam.

* A cart-mounted cell extraction aqueous foam system appears to be a feasible hands-off deterrent for belligerent inmates in cell extraction situations. It can be used alone or as part of a graduated, use-of-force continuum. The system provides the ability to add OC into the dispensed foam to encourage compliance, to isolate the belligerent inmate from communicating with his peers, to diminish the light within the inmate's cell further isolating him, and to do the above without any hands-on restraint. However, the current prototype cell extraction aqueous foam system requires modifications to increase delivered foam expansion ratios and some foam reformulation work may be necessary to increase foam expansion ratios with OC-laced foam.

* Large scale, non-portable aqueous foam systems have been installed in Department of State (DOS) Embassies and have performed satisfactorily. The DOS systems were installed to protect facilities against crowd disturbances and arson. Many of the conclusions drawn in this project work are supported by experiences gained at the DOS installations.

7. LARGE FACILITY FOAM APPLICATION STUDY

This study[8] investigated the potential effectiveness and application of a large, facility-based aqueous foam system that could isolate large areas in the event of facility disturbances. Issues investigated by the study included: feasible usage scenarios, machine sizing, possible system designs and hardware configurations, foam system activation, foam system pressure safety, foam characteristics, deployable foam amounts, foam flowrates, foam deployment times, foam placement, foam sustainability, foam as a carrier for Oleoresin Capsicum (OC) irritant, foam knockdown for retrieval of inmates, protective gear for correctional officers entering foam-flooded areas, and cleanup. FDOC and FBOP sites were selected by NIJ for the study.

From the FDOC modular prison site plan, three buildings were identified for investigation as to the applicability of an aqueous foam system. Those buildings included the 132 Single Cell Housing Unit, the Health/Classification Building and the Food Services Building. Situations for study in the housing unit were dayroom fights, loss of wing control and loss of sallyport control. Areas to protect in the Health/Classification Building included the medical records area and vault, and the pharmacy and its secure storage. Large scale disturbances and inmate fights were the issues in the Food Services Building.

The FBOP has built some high-rise prisons in urban locations which house some of the nation's most dangerous inmates. In FBOP high-rise prisons, stairwells extend from the ground floor to the top floor and have an eight-foot wide landing on each floor with no barriers within the stairwell. When disturbances arise in the stairwell, regaining control of inmates is difficult. The study was to investigate an aqueous foam system for the stairwell that would serve as an OC carrier and would be capable of driving the inmates(s) either up or down the stairwell to a preselected location for retrieval.

The aqueous foam generators and design criteria proposed in this preliminary study appear to be feasible for the FDOC and FBOP applications evaluated. Many of the application and usage issues discussed in the physical characteristics testing section regarding the prototype aqueous foam cell extraction system apply equally well to the large facility disturbances study.

8. FUTURE STUDIES/RECOMMENDATIONS

Formal evaluations of the NIJ Aqueous Foam Project results are in progress. The benefits of the technology are being weighed carefully against the potential risks of application before proceeding with any further significant testing or development. As with other new technologies that might be suitable for less-than-lethal applications in law enforcement, legal liability presents a significant hurdle to be overcome. The following tasks are recommended for follow-on work:

* The prototype cell extraction aqueous foam system was not able to meet the full range of foam expansion ratios specified by the design requirements. By increasing the cell foam fill time to 75 seconds from 30 seconds, the system should fully meet the designed foam expansion ratios of between 500:1 to 1000:1. A follow-on effort should be defined to include modification of the existing system for a 75-second cell foam fill time, if deemed acceptable by correctional representatives.
* Some additional foam reformulation work may be required to meet the desired expansion ratios with OC-laced foam even after the above cell extraction aqueous foam system modifications.
* Based on the NIJ aqueous foam project work (foam toxicology study, aspiration tests in foam using a breathing simulator, and collected anecdotal immersion experiences[9]) as well as previous dog studies in aqueous foam, human subject testing in aqueous foam can be the next technical step. However, legal liability may remain a significant concern for a cell extraction system used in prison applications. Intermediate, in-depth animal studies might lessen application liability issues. NIJ and potential correctional systems users should evaluate the legal liability and policy issues as part of additional aqueous foam development work.
* Voluntary human subject effectiveness testing needs to be conducted to establish the specific quantities of OC irritant necessary to be effective in the OC-laced aqueous foam. Use protocols, specific applications scenarios, specific cleanup procedures, documentation of human exposure effects, inmate extraction procedures, knockdown techniques, minimizing officer exposure, and large facility use implications should also be studied as part of the follow-on project.

9. REFERENCES

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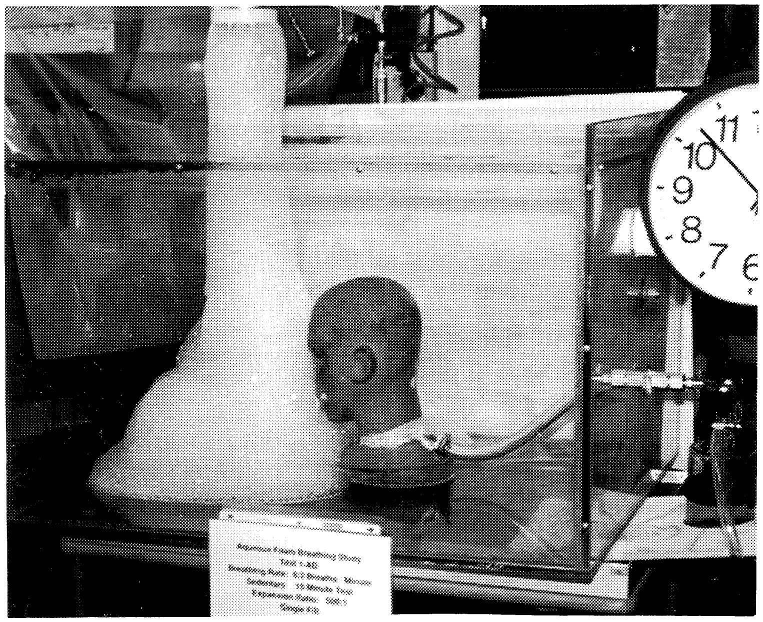

Figure 1. Aqueous Foam Respiration Simulation Experiment

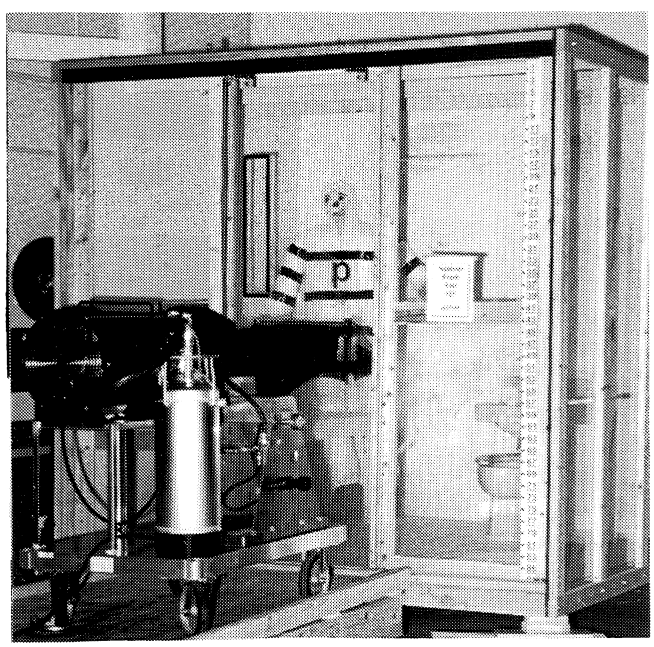

Figure 2. Prototype Aqueous Foam Cell Extraction System at Mock Cell

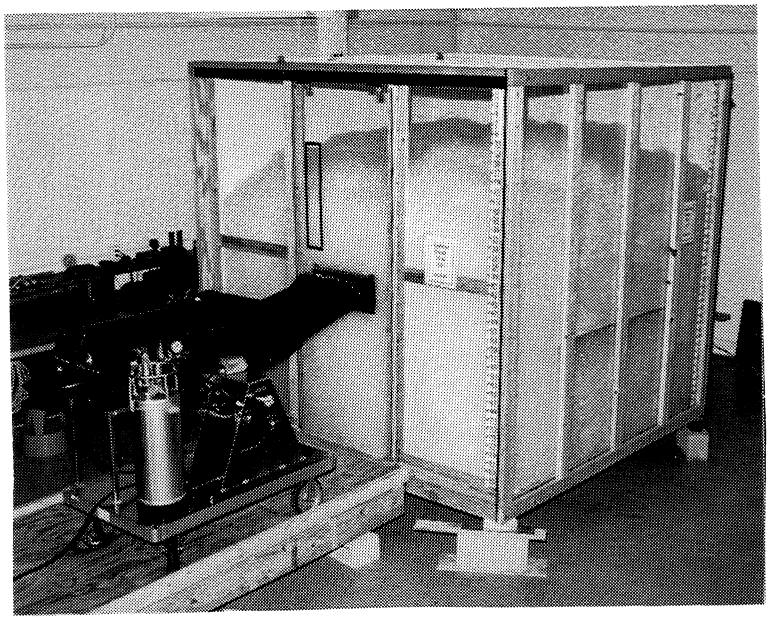

Figure 3. Mock Cell Filled With Aqueous Foam

Figure 4. CO_2 Fire Extinguisher Foam Knockdown Through Foodslot

Figure 5. Pressurized Air Hose Foam Knockdown Near Completion