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Breathing Air from Protein Foam

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Abstract

Protein foams can be used to extinguish fires. If foams are to be used to extinguish fires where people are present, such as in high-rise buildings or ships, then a method for allowing people to breathe in a foam-filled environment is needed. It is proposed that the air, used to create the foam be used for breathing. A canister that will break incoming air-filled foam has been designed for attachment to a standard gas mask, in order to provide breathable air to a trapped person. Preliminary results for the modified mask indicate feasibility of breathing air from air-filled protein foam.

Index Entries: Protein foams; egg albumin; canister; polypropylene sheet; airflow; breakthrough.

Introduction

Protein foams, such as egg albumin foam, are comprised of hydrophobic proteins that are efficient and inexpensive products for extinguishing smoldering or other difficult-to-put-out fires. These fires can even be those fed by large amounts of fuel such as in oil, coal, and chemical fires. These types of fires also have the ability to give off considerable heat, which creates resistance toward conventional fire suppression with water. Unlike water, protein foam has the ability to extinguish a fire through its ability to separate the oxygen supply from the fire. To exclude air from a fire, the foam must completely fill the fire zone and the fire zone must remain completely filled to allow cooling to proceed.

When people are present in fires such as those in warehouses, airplanes, ships, or even space capsules, an additional problem occurs: people

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cannot breathe freely because the protein foam used to extinguish the fire has excluded the air in the area of the fire. We propose here to begin to solve this problem by making that air in the foam available to the trapped persons by using a device to collapse the foam and simultaneously release the air for breathing. To implement the proposed solution, a breathing apparatus was constructed for the purpose of allowing a person to survive in the enclosed fire region until either help arrives or it is possible to escape.

The first breathing device tested was a surgical mask (typically found in drug stores) manufactured by 3-M. The mask was constructed of polypropylene and cotton fibers. It proved to be ineffective as a foam-breaking device, because the cotton fibers absorbed water from the albumin solution, impeding airflow through the mask.

The proposed alternative is a foam-breaking canister for use with a military type C-3 Chem/Bio Gas Mask *(1)*. When equipped with its standard filtering canister, this mask effectively protects the wearer's respiratory tract, face, and eyes against certain chemical and biologic agents such as HCN, SO_2, mustard gas, CN, GB, CS, CR, radioactive dust, and smoke from fires *(1)*. Here the mask was fitted with a 15-cm-high, 7-cm-diameter airtight steel can in place of its standard filter canister. The standard gel-activated carbon filter canister is not desirable because the material in the filter is not water resistant and makes breathing difficult once it begins to absorb the collapsed foam liquid. The airtight can was tested with a variety of combinations of water-resistant filters used to break the foam and simultaneously release the air for breathing and reject the water from the mask. Performance failure of the canister filter pack was defined as when either the entering protein foam or released water broke through the filter and reached the mask's breathing space. This mask was tested using foam of various bubble sizes, made from various concentrations of egg albumin.

Materials and Methods

Equipment

Egg albumin (lot no. CB 951) was purchased from Matheson Coleman and Bell. Fiberglass screen of 1×1 mm grid size was purchased from West End Hardware (Nashville, TN). Shop-Vac Foam Sleeve (905-85), D.C. May's Painter's Polypropylene Coveralls, and Phifer Super Solar Screening were purchased from Lowe's (Nashville, TN). TRONY SC1025ID5*1603 photocell was used in conjunction with an OPCOM laser pointer to determine the bubble collapse time. A 5-cm-diameter polyvinyl chloride (PVC) elbow was purchased at Lowe's.

Mask Design

A Chinese green tea steel cylinder 15 cm long and 7 cm in diameter was used as the framework for the foam-breaking canister. Foam-breaking screening devices were placed alone or in series inside the canister. The canister was attached (with an airtight seal made of duct tape) to the

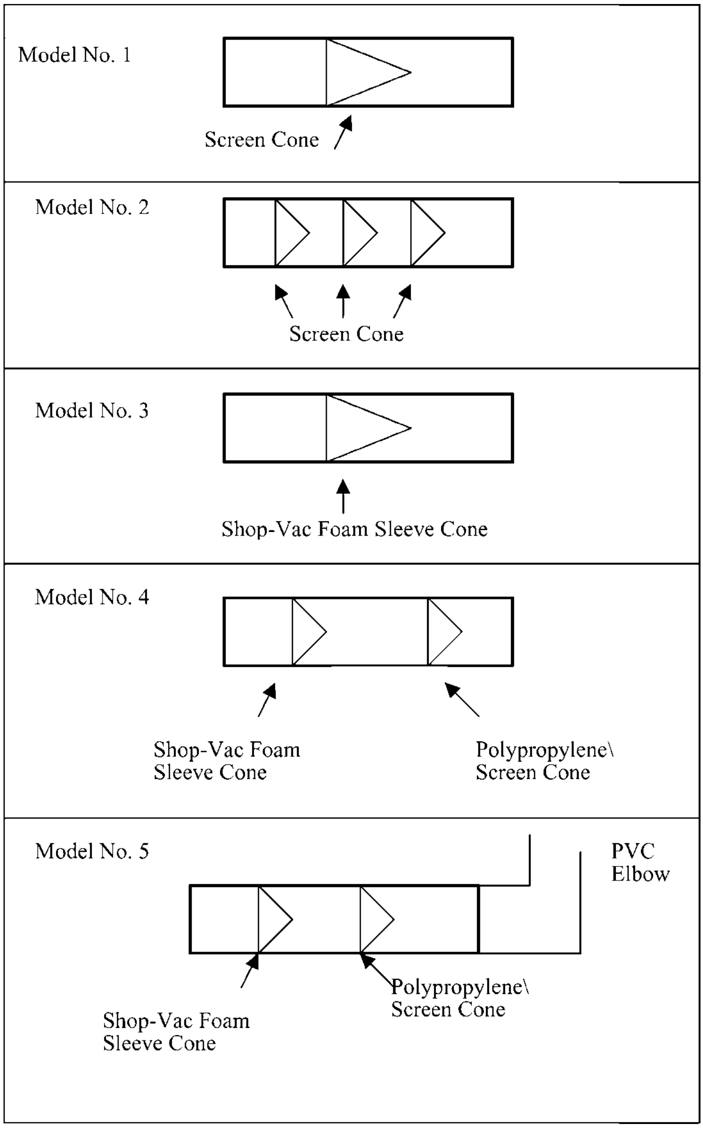

Fig. 1. Diagrams of each model as described in Materials and Methods. Each filtering device is labeled and indicated with an arrow. Diagrams are not drawn to scale.

air intake port of the gas mask. The other end was open and submerged in foam.

The foam-breaking devices included a 1 × 1 mm grid size fiberglass screen rolled into a cone, a piece of the foam sleeve rolled into a cone, and a polypropylene sheet, or a combination of the three. The foam sleeve is a porous material approx 1 cm thick with openings about 0.5–1 mm in diameter. The five canister models tested with the corresponding foam-breaking methods are illustrated in Fig. 1.

Table 1
Tested Canister Model Types and Corresponding Foam-Breaking Methods[a]

Model no.	Foam-breaking method used	Perceived resistance (Borg CR10 scale) (mean ± SD)
1	One 15-cm fiberglass screen cone	2 ± 0 (with and without foam)
2	Three 8-cm fiberglass screen cones loaded in series	2 ± 0 (with and without foam)
3	One 15-cm Shop-Vac foam sleeve cone	2.5 ± 0 (with and without foam)
4	One 10-cm Shop-Vac foam sleeve cone, one 10-cm polypropylene/ screen (skeleton) cone loaded in series	3.25 ± 0.35 (with and without foam)
5	One 10-cm Shop-Vac foam sleeve cone, one 10-cm polypropylene/screen (skeleton) cone, polypropylene sheet loaded in series, 5-cm-diameter PVC elbow	3.75 ± 0.35 (no foam)
6 (model 5 with foam)	One 10-cm foam sleeve cone, one 10-cm polypropylene/screen (skeleton) cone, polypropylene sheet loaded in series, 5-cm-diameter PVC elbow	8.5 ± 0.71 (foam)

[a]All perceived resistance values are based on evaluation by two of the authors (DA, DJ). There was no noticeable difference between the perceived resistance for both dry and wet foam-filled models for models 1–4. The perceived resistance with and without foam was noticeable for model 5 and is indicated above.

The model types for the foam-breaking canisters are described in Table 1 in the following format: the filtering devices are listed in the order that they are loaded, starting at the open end of the canister and moving in the direction of the mask. The foam-breaking method used for model 1 consists of a 15-cm fiberglass screen cone made flush with the canister wall with duct tape. The foam-breaking configuration used for model 2 comprises three 8-cm fiberglass screen cones loaded in series all made flush with the canister walls with duct tape. The foam-breaking configuration used for model 3 consists of one 15-cm-long Shop-Vac Foam Sleeve made flush with the canister walls with duct tape. The foam-breaking configuration for model 4 consists of an 8-cm-long Shop-Vac Foam Sleeve cone and an 8-cm-long fiberglass screen cone lined with a polypropylene sheet loaded in series. The two cones were made flush with the canister walls with duct tape. The foam-breaking method for model 5 consists of a 10-cm-long Shop-Vac Foam Sleeve cone, and a 10-cm-long fiberglass screen cone lined with a polypropylene sheet and a polypropylene sheet stretched across the canister loaded in series. The two cones were made flush with the canister walls with duct tape. The polypropylene sheet was stretched across the canister at the junction between the steel cylinder and a 5-cm-diameter 90° PVC elbow. The 90° PVC elbow was added in model 5 to increase drainage of solution resulting from broken foam.

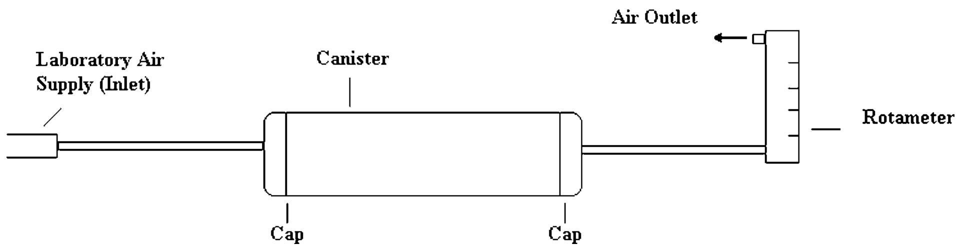

Fig. 2. Diagram of configuration used to measure airflow through freestanding canister.

Rate of Airflow Through Canister

Caps were placed on the ends of a 15- to 17-cm-diameter steel Chinese tea can in order to test the airflow rate through the canister separate from the gas mask. The canister was sealed to be airtight, as shown in Fig. 2. A laboratory air tube was attached and sealed to each cap. One air hose was attached to the laboratory air supply, and the other to an inline rotameter to measure the airflow rate. The outlet port of the rotameter was allowed to vent to the laboratory. A baseline measurement of airflow through the empty canister (control experiment) was run first. Foam-breaking devices were added to the canister as described for models 1–5. The corresponding airflow rates through the canister were then measured.

Perceived Resistance To Breathing For Model Types

It is important to be able to breathe comfortably through the mask, the filtering media and foam under a variety of conditions. The perceived resistance to breathing through the gas mask was tested with the Borg CR10 breathing scale *(2)* for perceived exertion. Using the mask equipped with the canister, the user took several breaths and reported a perceived exertion level on the Borg CR10 scale. It was established in preliminary experiments that the perceived exertion was about the same for the mask with or without the foam. Models 1–4 were therefore each tested without the introduction of foam for simplification. Model 5 proved to be an exception for testing. It was the only model that seemed to limit the number of breaths that could be taken when subjected to foam. After approx 70 breaths with the canister submerged in foam, the perceived exertion became too difficult for the subject to continue. Perceived exertion data were therefore considered with model 5 saturated with foam. The method used to determine this breathing ability is based on the self-assigned Borg CR10 exertion scale, which was originally conceived as a way to measure the respiration of individuals with impaired lungs.

Foam Collapse Time

The time required for natural foam collapse in a glass tube was determined to establish how fast the foam collapses and how wet the foam is. The speed of bubble collapse is important to know since much breakage is needed in the filter-aided mask to collapse the bubbles fast enough so that a person could survive on the air from the broken foam. It is important to consider foam wetness in choosing the appropriate filtering media. A 1.0 g/L stock solution of egg albumin protein was used in the experiments on foam collapse time. Collapse time was measured using laser light transmittance through the foam in a glass column in a dark room.

The laser beam was directed through the foam fractionation column and onto a TRONY photocell (housed in a Project Enclosure, purchased from Radio Shack, to shield from ambient light) connected in parallel to a voltmeter (Fig. 3). The voltage across a photocell is directly proportional to the intensity of the light striking the photocell *(3)*. The relative transmittance of the laser light through the column was thus determined by the voltage, as measured by the voltmeter, across the photocell as the foam collapsed. Scattered light from the laser and intruding outside light is assumed, which is why a maximum voltage (2.35 ± 0.13) was determined by shining the laser through the column without any foam. This maximum voltage was used as the control. The voltage across the photocell increased as the foam collapsed and more light reached the photocell. Once the solution was foamed, the voltage change across the photocell was measured every minute for 15 min. Percentage of transmittance was inferred by percentage of the maximum voltage at each minute. Percentage of collapse was then inferred from percentage of transmittance.

Foamate Liquid Recovery

Foam stability is related to water content in the foam. A strong or stable wet foam is best for extinguishing fires (zone 2 in Fig. 4), and a weak or unstable dry foam (zone 1 in Fig. 4) is best for breathing through the foam-breaking breathing mask. To measure the stability or strength of the foam, the volume of liquid in the foamate was measured as a function of time. Foamate liquid recovery was determined by foaming a 1 g/L egg albumin solution in a foam fractionation column to a foam height of 71 cm. This height was measured by reading off of a ruler placed on the foam fractionation column (Fig. 3). The height of solution in the base of the column was measured every 30 s up to a total run time of 15 min. The original solution height before foaming was used as the maximum liquid height value. Once the liquid was foamed, the height of the foam before it began to drain was used as the zero height value. Volume of foamate liquid recovery was determined by [the change in height (cm)] × π × [radius of the column (in cm)]^2 in mL of solution. Percentage of foamate solution recovery was determined by $V(t)/V_{max}$, in which $V(t)$ is the volume of foamate liquid recovered at any given time, t.

Testing of Mask using Foam

Three liters of a 1.0 g/L egg albumin solution was prepared and placed in a 5-gal open-top Nalgene container. Air entered via a sparger, which was

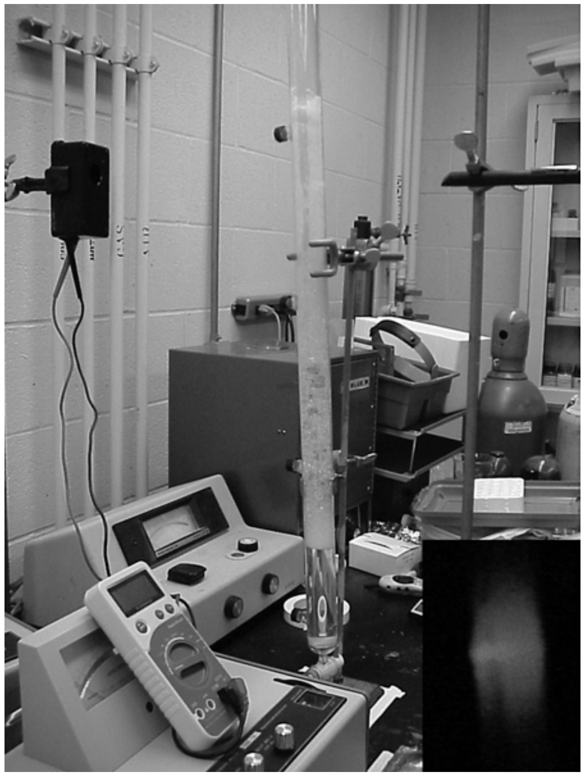

Fig. 3. Laser foam fractionation column setup. (**Bottom right**) Laser beam shining through foam in dark.

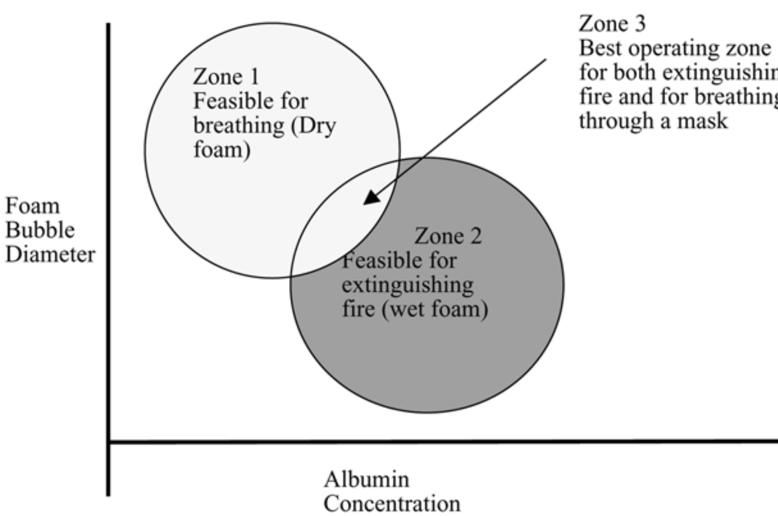

Fig. 4. Conceptual diagram of optimal zones both breathing through a foam-breaking mask (zone 1) and for extinguishing fires (zone 3). The overlapping region (zone 3) represents the best operating zone for extinguishing fires and for breathing through a mask.

made of approx 100 glass beads (about 4 mm in diameter) in a tightly wrapped nylon mesh at the bottom of the container. The sparger filled the 5-gal container with foam of bubble diameter of about 5–10 mm. The canister of models 1, 2, 3, 4, or 5 was attached to the mask. The canister, attached to the mask, was then vertically submerged in the foam in order to allow excess water to be drained. The user began breathing normally, pulling the foam into the canister. All model types broke the foam, providing breathable air to the user. The user continued to breath until "breakthrough" was achieved. Breakthrough is defined as the breath at which the foam penetrates the gas mask via the intake valve. The number of breaths required to reach breakthrough was then recorded. Model 5 was the exception. After approx 70 normal breaths, the perceived exertion became too great for normal breathing. The test was then stopped even though breakthrough was not achieved.

Results and Discussion

As shown in Table 1, the perceived resistance, evaluated by using the Borg CR10 scale *(2)*, was found to increase with model number with the exception of models 1 and 2 (whose resistances were found to be equal). The Borg CR10 value is the self-assigned value on a scale of 1–10, with 1 being very easy and 10 being very hard. In general, there is an increase in foam-breaking material loaded into the canister in each consecutive model type, and this increase leads to greater breathing resistance.

The evolution of foam-breaking models is described as follows: Model 2 was created in response to the achievement of breakthrough of model 1 after only one breath. The number of breaths until breakthrough increased to three (three times that of model 1) by placing three series screen cones of grid size 1×1 mm. Model 3 was then tried because models 1 and 2 were ineffective in limiting foam breakthrough of bubbles of small diameter (less than about 5 mm). The small cell size and thick nature of the Shop-Vac foam sleeve (the foam was required to travel through more than one cell) improved the effectiveness of the canister. It was observed that as foam was broken by the Shop-Vac foam sleeve, albumin solution began to accumulate in the foam sleeve cells. As the user inhaled, foam of bubble diameter smaller than the original foam (about 0.5–1.5 mm) was created behind the Shop-Vac foam sleeve cone owing to the coalescence of the solution that had accumulated there (Fig. 5). Model 3 achieved breakthrough at 39 ± 1 breaths. To combat this small-diameter foam, a second cone was installed to create model 4. This second cone consisted of a polypropylene-lined screen cone. It was observed that the second cone broke about 0.5- to 1.5-mm-diameter foam created from the Shop-Vac foam sleeve. In model 4, the second cone caused coalescence of the accumulated solution in a fashion similar to that that occurred in the Shop-Vac foam sleeve cones in models 3 and 4. The resulting foam diameter did not differ noticeably from about 0.5- to 1.5-mm-diameter foam

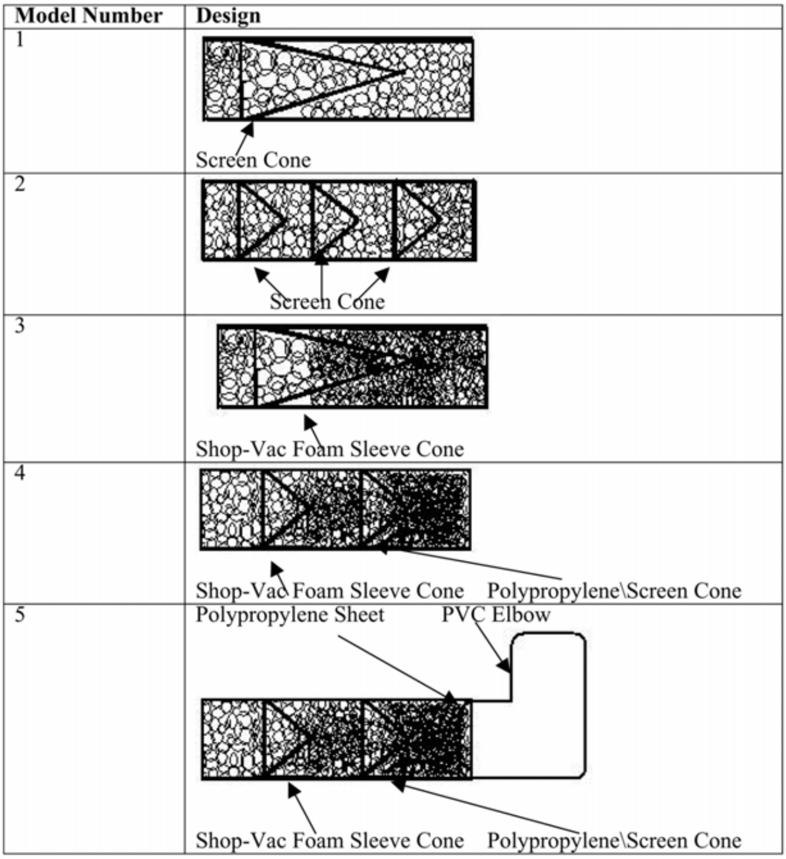

Fig. 5. Evolution of foam through each model as described in Results and Discussion. Foam flows from left to right. Denser bubbles indicate small-diameter foam. Each filtering device is labeled and indicated with an arrow.

created by the Shop-Vac foam sleeve cones. Model 4 achieved breakthrough after 127.5 ± 4 breaths. Model 5 was designed to provide additional breakage of about 0.5- to 1.5-mm-diameter foam resulting from the second cone in model 4. To help break this small bubble foam, a polypropylene sheet was stretched across the canister (Fig. 1). The 90° PVC elbow (Fig. 1) was added to exploit gravity for drainage. However, the PVC elbow was not enough to keep the polypropylene sheet from being saturated and in effect further restricting breathing. When about 0.5- to 1.5-mm-diameter foam resulting from the second cone in model 4 reached the polypropylene sheet, breathing resistance became too great for normal breathing after 77.5 ± 8 breaths. No foam breakthrough was reached using model 5.

As shown in Fig. 6, the perceived resistance to breathing (by a subject using the gas mask with the canister) is lessened as the airflow rate through the canister is increased. The flow rate through the canister, as determined

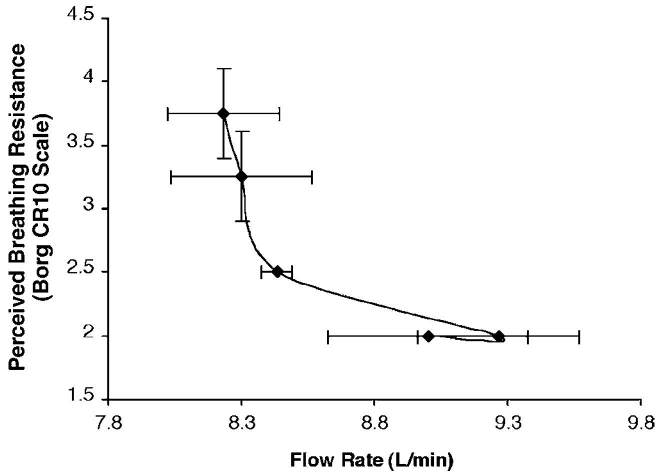

Fig. 6. Correlation of airflow through canister to perceived breathing resistance as determined using Borg 10 scale. The trend shows a decrease in flow rate with an increase in perceived breathing resistance.

by the method described in Materials and Methods, decreased as a function of perceived resistance as evaluated using the referenced Borg CR10 scale. Mask models 1 and 2 are exceptions to this trend. It is believed that this is owing to experimental error and is allowed within 1 SD of each mean airflow rate (Fig. 6). This confirms the typical resistance for each model type as approximated by the Borg CR10 scale.

The typical foam collapse time data, quantified in Fig. 7, describe how fast the foam can collapse. Figure 8 shows a typical drainage experiment. The photocell could be used to determine that approx 9% of V_{max} is achieved in 15 min. This implies that approx 9% of the laser light was transmitted to the photocell, confirming what is seen in a visual assessment (the foam does not look to be significantly collapsed). The data in Figs. 7 and 8 can be cross plotted to give Fig. 9. Figure 9, in turn, can be used to define whether there is wet foam or dry foam. The wet foams have little of their initial water drained, whereas the dry foams have much of their water drained. Foam wetness determines how well a person can breathe air from it and how well it can extinguish a fire (Fig. 4).

Mask model types 1 and 2 provide little perceived resistance but offer little foam-breaking ability and are therefore impractical since foam enters the mask almost from the first breath. Although mask model 5 offers a high level of bubble-breaking ability, the perceived resistance to breathing is beyond a feasible level (when filled with foam). This leaves mask model 4, which allows for many breaths (about 120) until foam breakthrough, combined with the characteristic of a perceived resistance that allows for comfortable breathing, as shown in Fig. 10. Model 4 is, therefore, the best overall canister of models 1–5.

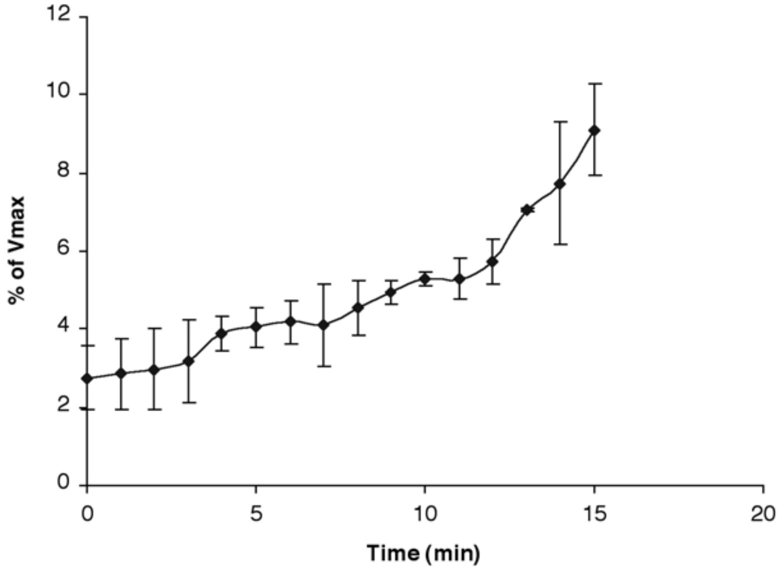

Fig. 7. Percentage of maximum voltage from photocell reading transmitted laser light with respect to time. The voltage across the photocell climbs to approx 9% of V_{max} (mean $V_{max} \pm SD = 2350 \pm 127.92$ mV) after 15 min. This is a measure of the resistance to the penetration of laser light through the foam in the column at approx 40 cm above the initial bulk liquid/foam interface. The initial solution contains an albumin protein concentration of 1 g/L. The solution is allowed to foam to a height of 71 cm above the initial bulk liquid/foam interface.

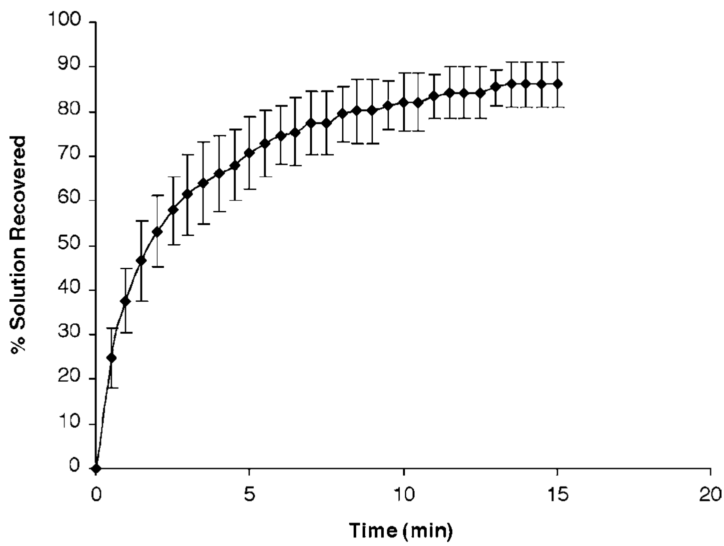

Fig. 8. Percentage of foamate liquid recovered (100 × Volume of albumin solution recovered/volume of albumin solution initially in foam). The percentage of foamate liquid recovered rises with respect to time and planes to approx 86% recovery. The foam was under the conditions given in Fig. 7.

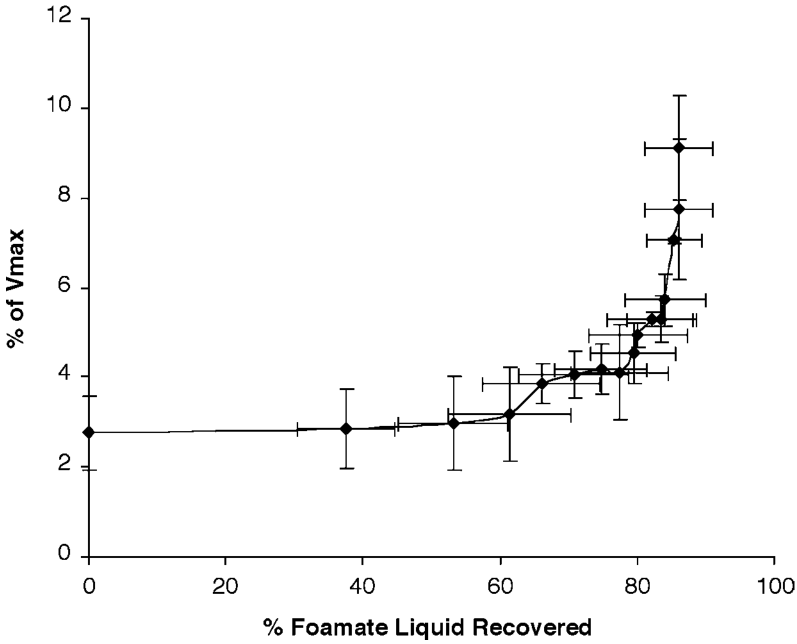

Fig. 9. Cross plot of percentage of foamate liquid recovered and percentage of maximum voltage from photocell reading transmitted laser light. This figure can be used to determine the relative foamate liquid content as a function of laser light transmittance.

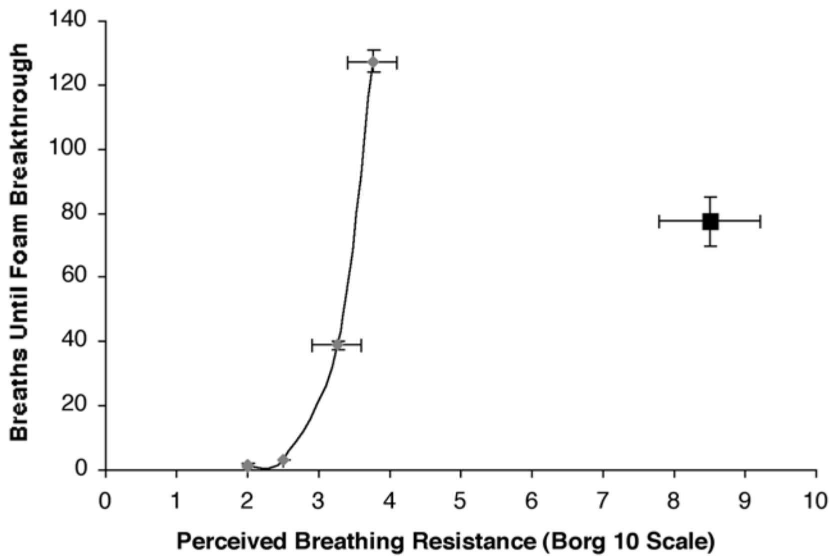

Fig. 10. Correlation of breaths until foam breakthrough into mask to perceived breathing resistance as determined using the Borg 10 scale. The trend shows an increase in breaths until breakthrough with an increase in perceived breathing resistance. The datum point to the right represents the type 5 model when saturated by foam. Model no. 5 did not reach breakthrough but exceeded a feasible breathing resistance on the Borg CR10 scale.

Conclusion

Further tests need to be run to design a canister model that allows for the breakage of smaller-diameter and wetter foams. We have shown that it is feasible to breathe air from an air-generated foam reaching 120 breaths in succession. Further work is needed to extend the working time and breakage ability of the canister-modified gas mask breathing device.

References

1. Snyder, D. (2001), C-3 Chem/bio Gas Mask. Gas Mask USA. (Website: www.gasmask usa.com)
2. Borg, G. (1998), *Borg's Perceived Exertion and Pain Scales*, Human Kinetics, Champaign, IL.
3. Daley, R. (2002), Exp 137: Electromagnetic Spectrum. *Lab on Legs: Energy and Change* March 28, 2002. CSIRO South Australia Education Programs. Available at Website: www.csiro.au/adelcsirosec/Pdf/Exp137.PDF. Accessed April 27, 2002.