AFRL-ML-TY-TR-2006-4571

FIRE RESISTANT COMPOSITE CLOSED CELL FOAM AND NONWOVEN TEXTILES FOR TENTS AND SHELTERS

Stephen C. Davis
Armacell LLC
7600 Oakwood Street Extension
Mebane, NMC 27302

Jennifer L. Kalberer
Applied Research Associates, Inc
P.O. Box 40128
Tyndall AFB, FL 32403

Final Report, January 2006

DISTRIBUTION STATEMENT A: Approved for public release; distribution unlimited.

Air Force Research Laboratory
Materials and Manufacturing Directorate
Airbase Technologies Division
139 Barnes Drive, Suite 2
Tyndall AFB, FL 32403-5323

NOTICE AND SIGNATURE PAGE

REPORT NUMBER AFRL-ML-TY-TR-2006-4571 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH THE ASSIGNED DISTRIBUTION STATEMENT.

__/s/______________________
VIRGIL J. CARR
Work Unit Manager

__/s/__________________________
RICHARD N. VICKERS
Chief, Deployed Base Systems Branch

__/s/______________________
WENDELL D. BANKS
Chief, Airbase Technologies Division

REPORT DOCUMENTATION PAGE			*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
31-07-2006	Final Technical Report	01-10-2004 03-01-2006

4. TITLE AND SUBTITLE	
Fire Resistant Composite Closed Cell Foam and Nonwoven Textiles for Tents and Shelters	5a. CONTRACT NUMBER: F08637-03-C-4009
	5b. GRANT NUMBER:
	5c. PROGRAM ELEMENT NUMBER: 62102F
6. AUTHOR(S)	5d. PROJECT NUMBER: 4347
Davis, Stephen C.; Kalberer, Jennifer L.	5e. TASK NUMBER: D2
	5f. WORK UNIT NUMBER: 4347D23A

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
Armacell LLC 7600 Oakwood Street Extension Mebane, NC 27302	AF06-01-31

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
Air Force Research Laboratory Materials and Manufacturing Directorate 139 Barnes Drive, Suite 2 Tyndall AFB, FL 32403-5323	AFRL/MLQD
	11. SPONSOR/MONITOR'S REPORT NUMBER(S): AFRL-ML-TY-TR-2006-4571

12. DISTRIBUTION/AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A: Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

Ref AFRL/MLQ Public Affairs Case #06-089. Report contains color images.

14. ABSTRACT

The objective of the overall effort is to develop a fire resisting elastomeric closed cell foam as a component of a nonwoven fabric -- foam composite for fabrication of rapidly deployed shelters. The foam component is designed to provide superior fire resisting properties and thermal insulation compared to current shelter materials. The present report summaries results of development work which led to a light weight, flexible foam with exceptional burn-through resistance and thermal insulation compared to current materials. The report also highlights tasks recommended for continued development work. Benefits of the unique nonwoven fabric - foam material for force protection are described.

15. SUBJECT TERMS

closed cell foam, shelters, fire protection, force protection

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Virgil Carr
U	U	U	UU	41	19b. TELEPHONE NUMBER *(Include area code)*

Reset

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

TABLE OF CONTENTS

FIGURES

TABLES

SUMMARY

Fire is a major cause of loss of assets in the US military both during war and peacetime. Tent cities are particularly susceptible to fire due to close proximity of housing and other shelters used for facilities as well as prolonged exposure to extreme environments such as those in the Middle East. The development of lightweight shelters is critical to the Air Force mission of providing prompt logistics support for forward base operations. Structures should have characteristics that enable these shelters to be flexible, and in the case of containing ignitable fuels and other assets such as aircraft, these structures are required to be fire resistant. A key property in providing resistance to fires is the ability of a structure to withstand heat fluxes for a relative long period of time.

This research is a continuation of fire resistant foam formulations developed in 2003. The efforts in 2004-2005 concentrated on optimizing closed cell foam and developing nonwoven fabric systems and methods to bond the fabric to foam. The objective of this project was to develop shelter material that was flame resistant, strong, insulating, lower weight and flexible over a wide range of temperatures.

Development of a closed cell foam and nonwoven textile was a collaboration of four different organizations including the Air Force Research Laboratory (AFRL) Fire Research Group, Armacell LLC (Armacell), North Carolina State University (NCSU) Nonwovens Cooperative Research Center (NCRC) and Georgia Tech Research Institute (GTRI). Each organization was responsible for specific tasks related to the overall objectives stated above. Armacell was responsible for optimizing foam physical properties, development of fire resistant (FR) foam and attachment of the foam to the nonwoven. NCRC was responsible for the development of FR nonwoven fabric and the attachment of the nonwoven to the foam. GTRI was responsible for testing the foam and composite components for intumescence, heat flux, tensile strength, tear strength and abrasion resistance. AFRL provided cone calorimetry and thermogravimetric analysis of the initial Armacell foam samples.

Four current Air Force shelter systems were used as a baseline to determine current fire retardant (FR) chemicals, weight, vertical flame resistance, insulation value and burn-through resistance. Two primary foam rubber systems, nitrile butadiene rubber (NBR) and ethylene propylene diene monomer (EPDM), were investigated. NBR and EPDM rubber were chosen based on their broad application range and low cost relative to other rubber choices. The closed cell foam that possessed the best overall properties was produced in quantity and bonded with the optimized non-woven textile candidate produced by NCSU.

Prototype closed cell foams developed during this research demonstrated the principle that elastomeric foams can be used as an insulating fire protection component for novel shelter material. A combination of the lightweight foam with strong, light weight non-woven fabric resulted in a new shelter material with promising properties.

The closed cell foam demonstrated excellent burn-through resistance and thermal insulation value compared to current shelter materials. Current shelter materials were shown to melt from a flame front, which would enable rapid fire propagation to adjacent structures. The closed cell foam did not melt, but rather formed a char barrier that

delayed burn-through by a minimum of 10 minutes. Superior thermal insulation values of closed cell foam were measured and calculations revealed significant heat loss reduction for shelter material containing only 0.1" thick closed cell foam. Current shelter systems contain up to 22% halogen, which results in the production of hydrochloric and hydrobromic acid when burned. Armacell formulated both EPDM and PVC/NBR foams that reduced the halogen content by up to 75% (5.4 wt%). The reduction in halogen will result in a reduction of acid gases produced during a fire event, making the off-gas less corrosive to the occupants and electronics. The use of PVC plastisol with a plasticizer having low flammability was demonstrated to be an effective adhesive to enable synthesis of the flame retardant fabric/foam composite shelter prototype.

The closed cell foam prototype developed in this work will require optimization to be field ready including weatherability, halogen reduction, thermal characteristics and adhesives. The PVC/NBR foams will require further stabilization to resist sunlight and heat degradation. In addition, improvements in low temperature flexibility are required. The EPDM foams developed met the exposure and flexibility requirements but did not meet the target fire properties. A significant reduction of halogen content (chlorine) was achieved but a further reduction to zero using the nitrile rubber foam system is possible. Future work should focus to further improve the thermal insulation properties of the foam/nonwoven composite via modification of the composition and/or structure. The PVC plastisol was used to form the final composite structure during this project is difficult to scale to full production. An alternative non-flammable adhesive will be required to be compatible with large scale production. The foam showed an excellent capability to store fire retarding materials and would be an excellent candidate for incorporation of self-decontaminating materials being developed by the AFRL Asymmetric Threat Protection Group, Tyndall AFB, FL. Other materials could be stored in the foam to generate properties to safeguard against a variety of chemical and biological agents for increased force protection. Flexible, light weight, high strength, thermal insulation composites are expected to have wide use beyond shelter applications.

1. INTRODUCTION

1.1 Background

Fire is a major cause of loss of assets in the US military both during war and peacetime. Tent cities are particularly susceptible to fire due to close proximity of housing and other shelters used for facilities as well as prolonged exposure to extreme environments such as those in the Middle East. On July 31, 2003 at Camp Champion, Kuwait, 21 tents were consumed in a fire within 20 minutes before military and Kuwaiti firefighters could respond.[1] The fire was thought to have been caused by faulty wiring in an empty tent. Eight soldiers were treated for smoke inhalation and numerous military personnel were displaced as a result of the total destruction of the tent housing. On May 24, 2005, 44 tents were lost in a fire at Camp Commando, Kuwait, totaling $1.5 million dollars in damage to military property and injuring 26 personnel (Figure 1).[2] The cause of the fire was linked to personnel smoking too close to the tents.

Figure 1. Tent City Fire at Camp Champion, Kuwait.

Air Force deployments require force protection capability that includes the airlift of a logistics infrastructure to have ready for combat assets within 36 hours of orders. The logistics footprint of such an aggressive deployment posture requires the use of materials and supplies that are lightweight, energy efficient and durable under extreme weather

[1] http://www.arcent.army.mil/news/archive/2003_news/july/fire.asp

[2] http://www.safetycenter.navy.mil/media/groundwarrior/issues/winter05/TentBurn.htm

conditions. A part of this logistic plan is to deploy crew and aircraft shelters that are manufactured with materials, which are capable of protecting deployed forces and assets. Fire resistant materials are part of the military's strategy to increase readiness while better protecting our warfighters and our material assets. The development of lightweight shelters is critical to the Air Force mission of providing prompt logistics support for forward base operations. Structures should also have characteristics that enable these shelters to be flexible, and in the case of containing ignitable fuels and other assets such as aircraft, these structures are required to be fire resistant. A key property in providing resistance to fires is the ability of a structure to withstand heat flux without igniting for a relative long period of time.

This series of reports addresses the research, development, test and evaluation of innovative intumescing closed-cell foam married with durable nonwoven fabric "sandwich" structures that are fire resistant, insulating, lightweight and meet the stringent requirements of the Defense Logistics Agency (DLA) with respect to physical and mechanical properties.

1.2 Objective

This research is a continuation of closed cell foam formulations developed in 2003[3]. The efforts in 2004-2005 concentrated on optimizing the closed cell foam and developing nonwoven fabric systems and methods to bond the fabric to foam. The objective of this project was to develop shelter material with the following key properties developed from DLA requirements listed in Tents Specs at a Glance[4]:

1. Flame resistance as measured with ASTM D 6413-99 Vertical Flame Test.
2. Strength (tear and tensile) suitable for shelter construction.
3. Thermal insulation value (10% improvement in R value vs. current shelter material).
4. Lower weight (10% reduction in weight of 21 oz/yd^2, with a target of 18.9 oz/yd^2).
5. Flexible at a temperature range of -40 to 120 °F. (Note: Armacell conducted fold testing on all foam samples as a means to quickly rule out poor performing materials. Each foam formulation was subjected to -40 °F temperatures, then folded to test for cracking. Samples that performed poorly were eliminated from further testing. The results are not reported in this document as this test was strictly used as an initial formulation screening method.)

1.3 Approach

Development of a closed cell foam and nonwoven textile was a collaboration of four different organizations including the Air Force Research Laboratory (AFRL) Fire

---

[3] Juan Vitali and Haskell Beckham. Fire Resistant Closed Cell Foams for Aircraft Shelters Technical Review. Interim Report. Defense Technical Information Center. March 2004. AFRL-ML-TY-TR-2005-4545.
[4] Defense Logistics Agency. Tent Specs at a Glance. http://warfighter.dla.mil/special/basecamp/specs.jsp.

Research Group, Armacell LLC (Armacell), North Carolina State University (NCSU) Nonwovens Cooperative Research Center (NCRC) and Georgia Tech Research Institute (GTRI). Each organization was responsible for specific tasks related to the overall objectives stated above. Three separate reports were prepared documenting the accomplishments of Armacell, NCRC and GTRI. Armacell was responsible for optimizing foam physical properties, development of fire resistant (FR) foam and attachment of the foam to the nonwoven. NCRC was responsible for the development of FR nonwoven fabric and the attachment of the nonwoven to the foam. GTRI was responsible for testing the foam and composite components for intumescence, heat flux, tensile strength, tear strength and abrasion resistance. AFRL provided cone calorimetry and thermogravimetric analysis of the initial Armacell foam samples. These results were used by Armacell to refine their candidate foams and will not be reported separately.

1.4 Foam Development Background

Armacell LLC is the global market leader in foams technology. The company invented Armaflex®, the world's best known and most trusted trademark in elastomeric foam insulation. With more than 50 years of experience in foams, Armacell now also manufactures Ensolite® and OleTex®, two of the most recognized trademarks in technical foams, following recent acquisition of those technologies. In addition, Armacell produces ArmaFoam®, a proven cost-effective solution for customized foam applications like underlayments, padding and gasketing.

Armacell LLC has five manufacturing locations in the U.S. with headquarters in Mebane, NC. Research and Development laboratories are staffed with specialized professionals for design and testing of closed cell elastomeric foam products. Armacell LLC is part of an extensive global network of manufacturing sites with 18 facilities in 11 countries. Global Research is headquartered in Mebane, NC. Detailed information can be obtained at www.armacell.com.

2. METHODS

2.1 Baseline Shelter Materials

AFRL obtained sample materials from four different shelter systems that had been deployed in the field or the desert for a period of time. These samples included a TEMPER tent that was deployed at the Silver Flag Exercise Site, Tyndall AFB, Florida; a California Medium Shelter, General Purpose (GP) Medium Shelter and a 4K Dome Shelter deployed in the Middle East. These samples were used as a baseline to determine current fire retardant (FR) chemicals, weight, vertical flame resistance, insulation value and burn-through resistance.

2.2 Elemental Analysis

Approximately 10 grams of sample were delivered to Elemental Analysis Incorporated (EAI) for analysis by Photon Induced X-ray Emission spectroscopy (PIXE). This was a non-destructive type analysis. See EAI Web site for additional information. http://www.elementalanalysis.com/pixe/

2.3 Foam Development

Organic based, flexible closed cell elastomeric foams are inherently flammable unless suitable fire retardants are included in their formulation. The industry is well known for employing flame retardants in the formulations of closed cell foams. The classes of flame retardants are[5]:

1. Endothermic water bearing inorganic compounds
    a. Aluminum trihydrate (ATH)
    b. Magnesium hydroxide (MgOH)
2. Halogen – Antimony
    a. Brominated organic compounds
    b. Antimony trioxide (Sb_2O_3)
    c. Chlorinated compounds (such as PVC (PolyVinyl Chloride))
3. Chlorinated paraffin
4. Nitrogen containing fire retardants
    - Intumescent
5. Phosphorous compounds
    a. Phosphorus based flame retardants
    b. Phosphate esters

[5] EFRA "Flame Retardants Frequently Asked Questions" (http://www.cefic-efra.com/pdf/FAQ_engl.pdf)

6. Others
    a. Borates
    b. Expandable graphite
    c. Stannates

In addition to the use of fire retardants, fire suppression can be improved by the choice of foam ingredients. The selection of foam ingredients is also the key to development of required physical properties such as weatherability, flexibility, strength, appearance, cell size and processability. Specific issues related to rubber, plasticizers and compatiblizers were studied.

2.4 Rubber

Two primary rubber systems, nitrile butadiene rubber (NBR) and ethylene propylene diene monomer (EPDM) were investigated, with each having advantages and disadvantages (Table 1). NBR and EPDM rubber were chosen based on their broad application range and low cost relative to other rubber choices such as chloroprene rubber (CR) or chlorosulfonated polyethylene.

Table 1. Comparison of NBR and EPDM Rubber properties.

Rubber	Advantages	Disadvantages
NBR	Oil resistant Compatible with PVC and other polar plastics Lower flammability	UV/Ozone stability Lower heat resistance Low temperature flexibility
EPDM	Good UV/Ozone resistance Low Temperature flexibility	Poor oil resistance Flammable Poor compatibility with polar plastics/plasticizers

Each system has a trade-off in properties such as oil resistance, outdoor exposure stability and low temperature flexibility. For this research effort, the most important criterion is the ability to formulate to meet the flammability requirement. Formulations based on NBR and EPDM were developed with the primary goal to pass the vertical flame test.

2.5 Plasticizers

Plasticizers were added to rubber compounds to control the viscosity, which enabled the compounds to flow to form shapes such as sheets and also to enable proper foaming to form the final closed cell foam product. The range of plasticizer choices is broad and the effectiveness of a particular plasticizer is very specific to the total compound formulation. Key issues in selection of a plasticizer were the compatibility with the compound, flammability of the plasticizer, effects on flexibility at ambient and sub-ambient temperatures and cost. The main groups of plasticizers considered were:

1. Aliphatic / paraffinic oils

2. Aromatic / naphthenic oils
3. Chlorinated paraffin oils
4. Phthalate ester oils
5. Epoxidized soybean oils
6. Phosphate ester oils

Screening experiments, consisting of small scale foam production and fire testing were carried out to identify optimal combinations of plasticizer and compound formulation.

2.6 Compatiblizers

Compatiblizers are ingredients, like soap, which bring two unlike chemicals together (such as oil and water in the case of soap). Compatiblizers contain functionalities compatible with the ingredients being brought together. Soap has a lipophilic section to attract fats and oils and also a hydrophilic group to attract water[6]. In this way, the soap (compatiblizer) can facilitate the extraction of fats and oils by water. In the same way, compatiblizers can facilitate the miscibility of un-like polymers, plastics or oils. A problem in formulating fire retardant foams is the combination of polar fire retardants with non-polar polymers, waxes or oils. Numerous compatiblizers were studied to enable stable combinations of non-polar compound ingredients with polar fire retardants to generate the optimal fire performance.

2.7 Sample Synthesis

Closed cell elastomeric foam samples were synthesized in the R&D laboratories at Armacell LLC in Mebane and Conover, NC. Small scale screening of additives were carried out using a two inch diameter two roll mill, compression forming sheets and batch curing in an oven. Larger scale formulations were mixed in 3 kg scale using a banbury mixer, 12 inch heated rubber mill and extruded into flat strips 6 inch wide and ¼ inch thick with a rubber extruder. Sections of these strips were cured and expanded in an oven. Closed cell foam samples produced were cut to size for laboratory screening vertical fabric fire tests. Additional samples were sent to GTRI for American Society for Testing and Materials (ASTM) testing.

2.8 Vertical Fire Test – Laboratory Screening

Initial fire testing was carried out in the laboratory using a vertical mounting bracket and a gas burner (Figure 2) following the procedures outlined in ASTM D 6413-99 Flame Resistance of Textiles (Vertical Test). The sample was suspended 19 mm above the top of the burner. A flame 38 mm high was applied to the test sample for 12 seconds while the afterflame, afterglow and any melting or dripping were timed and noted. No afterflame or afterglow lasting greater than two seconds was considered a pass. This test allowed each sample to be quickly evaluated to determine if the formulation met the

---

6 http://www.armacell.com/www/armacell/armacell.nsf/ansHTMLSeitenLookUp/US_Frame?OpenDocument&Link=http://www.armacell.com/www/armacell/armacell.nsf/8c7f80a2702ebd0480256a6200582c2f/97a19c2aede29e80c1256b1800697891?OpenDocument

flammability requirements. Samples that passed the initial fire test were provided to GTRI for complete ASTM D 6413-99 testing

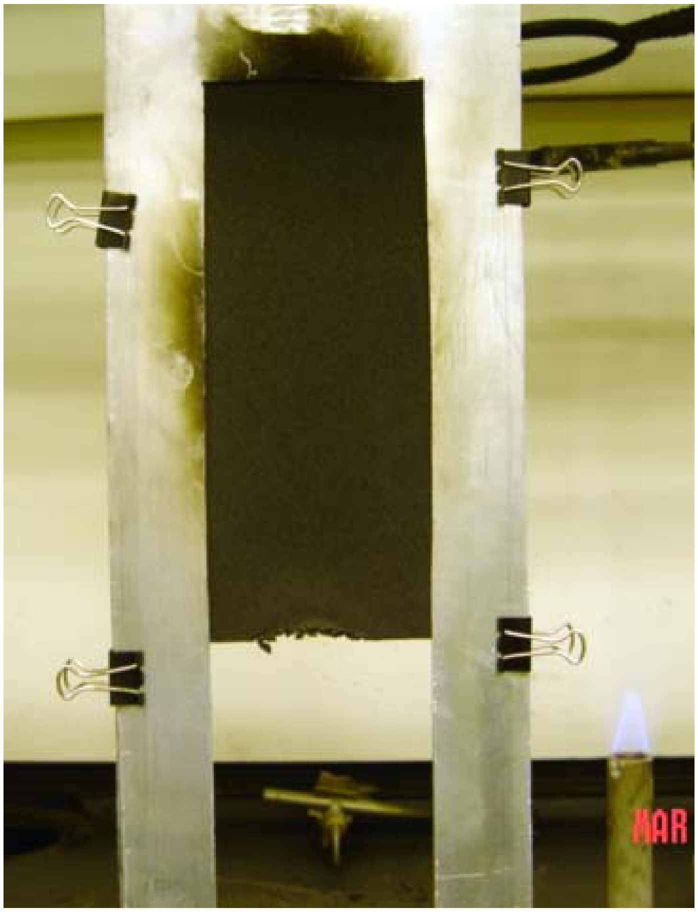


Figure 2. Laboratory Screening Vertical Fabric Test.

2.9 Thermal Insulation Property

Thermal conductivity of foam was measured using a Netzsch Heat Flow Meter Model: Lambda 2000. This instrument was not capable of measuring very thin samples due to geometric constraints. Instead, foam and fabric samples were placed on top of one inch thick fiberglass reference material. Change in total thermal conductivity due to the added layer (fabric or foam) was determined. Thermal conductivities were measured for one inch fiberglass board and the fiberglass board with either 0.10 inch thick foam or 0.02 inch thick nonwoven fabric coated with flame retarded PVC.

2.10 Burn-Through Resistance

To test the burn-through resistance and insulation value, a piece of 0.10 inch thick foam was mounted horizontally. A flame was placed underneath the foam and a piece of paper was suspended above the foam in line with the burner flame. The test set-up is shown in Figure 3.

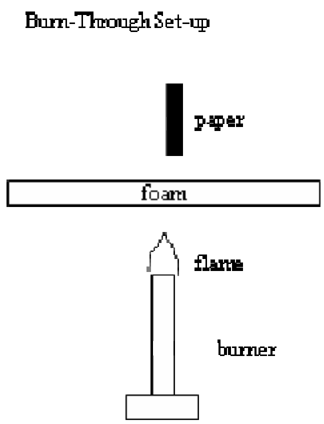


Figure 3. Schematic of Burn-Through Test Setup.

3. RESULTS AND DISCUSSION

3.1 Elemental Analyses of Existing Tent Materials

The four current shelter materials were tested using elemental analysis to determine the primary FR systems being used with the fabrics. Table 2 shows the percent by weight of the elements present in the shelter material. Samples of current shelter material showed 15 to 22 wt% halogen (Bromine and/or Chlorine) as well as antimony trioxide. The primary FR system was, thus, the halogen/antimony system. Many of these materials consisted of a polyester fabric coated with a fire retarded vinyl (PVC based) coating. Coatings can also be chloroprene based, which furnishes halogens for the FR system. Elemental analysis did not determine the source of the elements, however, the data showed that all of the four shelter materials contain high levels of halogen. In addition, the GP Medium shelter sample contained a high level of bromine, which is known to be more active than chlorine in fire suppression. High levels of aluminum were also seen. Aluminium trihydrate ($AL(OH)_3$) is a well known inorganic flame retardant. The TEMPER tent sample contained high phosphorous. The potential problem encountered with halogen containing materials is the production of hydrochloric or hydrobromic acid (HX) when burned. These corrosive gases can damage delicate electronics and are an inhalation irritant, therefore minimizing or eliminating the halogens in the shelter materials was a goal in the research for new shelter materials.

Table 2. Elemental Composition of Current Tent Material Samples.

WEIGHT PERCENT

	Temper Tent	4K Dome Tent	GP Medium Shelter	California Medium Shelter
Antimony	1.7	2.8	3.2	1.4
Chlorine	15.1	18.6	13.0	20.0
Bromine			9.3	
Aluminum	4.2	1.0	3.1	2.7
Iron		0.8	1.0	
Phosphorous	2.1	0.4	0.2	0.8
Barium	3.4	1.5		1.6
Zinc	1.4			

3.2 Foam Development

All four current shelter materials (TEMPER, GP Medium, California Medium and 4K Dome Shelter) were baselined for weight, vertical flame spread and afterflame (Figure 4). Three of four passed the fire test but one failed with a greater than two second afterflame The failure occurred with the GP Medium shelter material. This was surprising since it contained the active bromine in addition to chlorine and antimony. This failure may be indicative that degradation had occurred during field use. All four shelter materials melted in the heat of the flame cone.

The composite shelter material (including foam, nonwoven, coatings and adhesives) target weight was 18.9 oz/yd^2, with a target weight of 8 oz/yd^2 for the foam component. The foam development progress was graphically tracked to show sample identification, weight (oz/yd^2) and ASTM D 6413-99 vertical flame resistance data from GTRI (Figure 4 and 5). Formulations developed were based on either PVC/NBR or EPDM due to the broad applications of these foam types and their relatively low costs. For fuel and oil resistance, PVC/NBR based materials were chosen. For outstanding weatherability and low temperature flexibility, EPDM foams were investigated. The system that was chosen for the final prototype phase was based on which one met fire, physical and processability properties in time to scale to prototype phase. EPDM work focused on the choices of plastic phases, plasticizers, fillers and fire retardants. The vertical fire test became increasingly difficult to pass with thinner samples. This is analogous to the flammability of a 2 inch x 4 inch wood board versus a piece of paper. The paper, due to the high surface/volume ratio, burns very quickly and is easy to ignite. The board has a high mass and is difficult to ignite. Initial EPDM formulations were tested at GTRI using ¼ inch thick samples, which did not pass the vertical fire test. Thicker samples were determined to be too heavy for use as a shelter component. Results also showed that lower density material, such as 4 lbs/ft^3 (pcf), did not pass the vertical flame test (Figure 4 and 5). A target of 6 – 8 pcf was chosen to give a foam weight of 7 – 11 oz/yd^2 at 0.10 inch thickness. Some samples shown in Figure 4 that met the weight/fire criteria were

AF-CL0, AF-S and AF-T. While these three PVC/NBR based formulations passed the vertical flame test, they had insufficient low temperature properties and too large cell size for shelter applications. Further development work resulted in formulations in both EPDM and PVC/NBR that passed the fire test, had lower density and fine cell structure. These included AF-Q1, Q2 for EPDM systems and AF-U2 for PVC/NBR systems. The EPDM foams required the addition of a brominated fire retardant system to enable lower density, thinner gauge samples to pass the vertical flame test. Sample U2 was a PVC/NBR based foam containing a proprietary intumescent fire retardant based on ammonium polyphosphate.

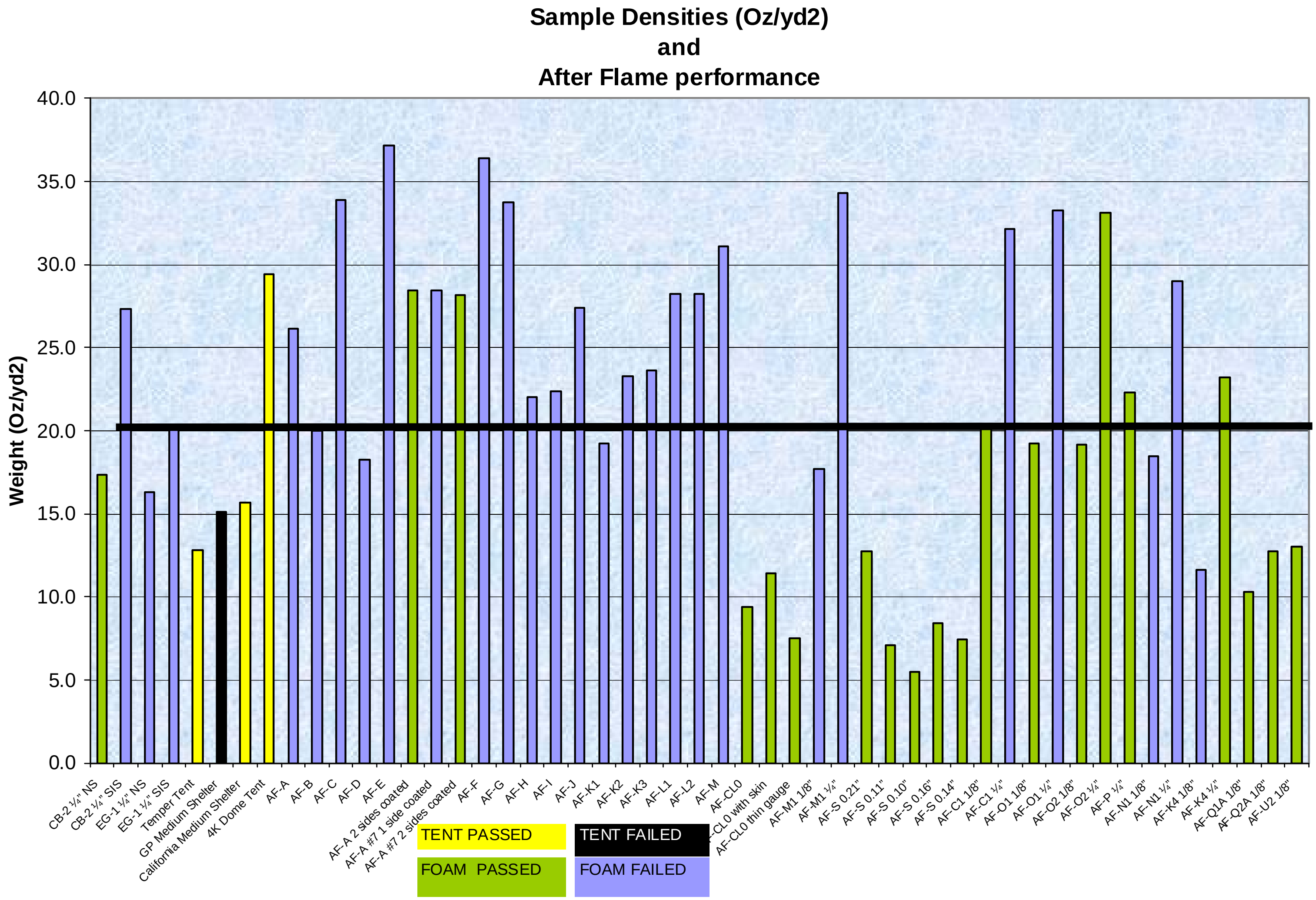


Figure 4. Flame Performance as a Function of Weight for Various Foam Formulations.

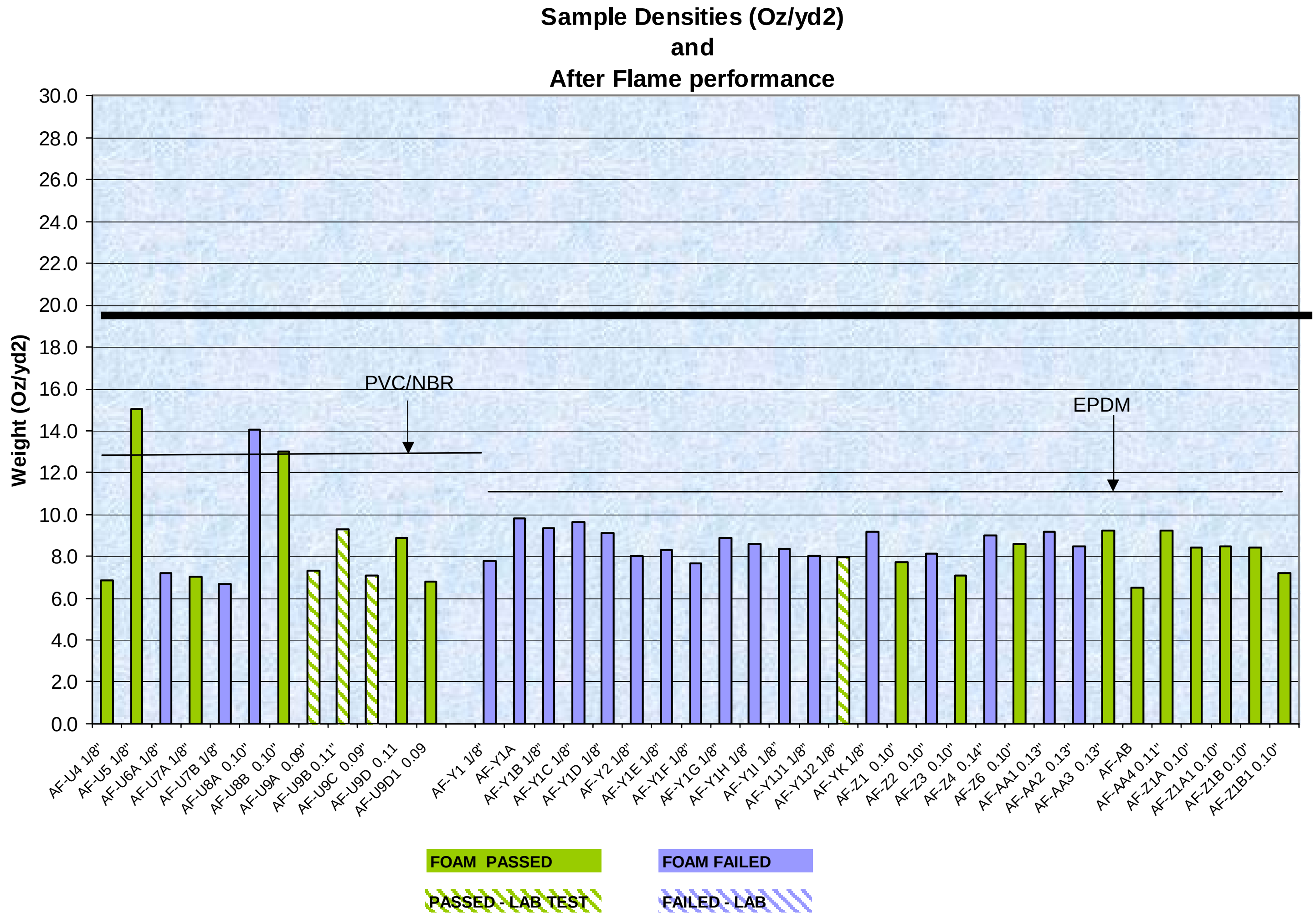


Figure 5. Flame Performance as a Function of Weight for Various Foam Formulations.

Further development of the EPDM formulas led to the series AF-AB and AF-Z1. These samples optimized plasticizer flammability and minimized halogenated fire retardant. The AF-Z1 series passed the fire test and had densities close to 8 oz/yd^2. These samples contained only 9 wt% halogen (Br). Additional work led to EPDM sample AF-Z1B1. This sample contained only 7 wt% halogen, which is a 50 to 70% reduction in halogen compared to existing shelter materials. Figure 6 shows EPDM AF-Z1B1 after 12 seconds of exposure to a flame. The foam showed minimal damage.

Figure 6. Sample AF-Z1B1 EPDM Foam after 12 seconds flame in laboratory screening test.

Examples of a passing and failing fire result for EPDM foam are shown in Figure 7 and 8, respectively. Figure 8 showed that the burning occurred on the foam surface as volatile components in the foam formed during sample heating, migrated to the surface and ignited. Figure 9 and 10 show examples of a passing and failing PVC/NBR foam formulations. The sustained burning (Figure 10) was observed in formulations lacking intumescent fire retardant and with use of plasticizers with higher alkyl content (more flammable). These observations led to formulations that minimized the plasticizer flammability and optimized levels of intumescent fire retardant leading to successful fire tests (Figure 9).

AF-Q1 AF-Q1A AF-Q2

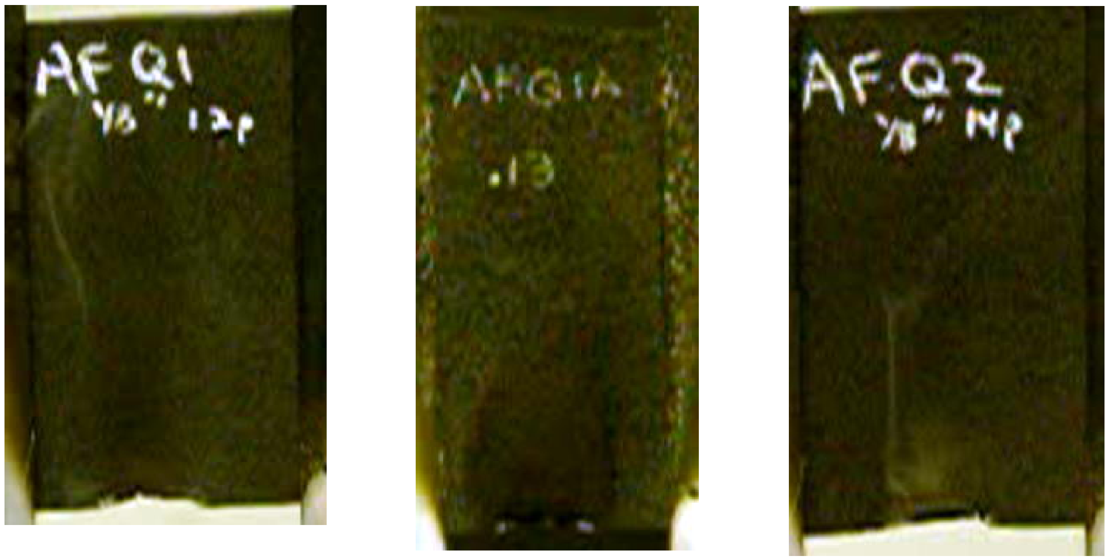


Figure 7. Examples of EPDM Foam Passing Fire Screening Test (afterflame < 2 seconds).

AF-Y2 AF-Y1A AF-Y1b

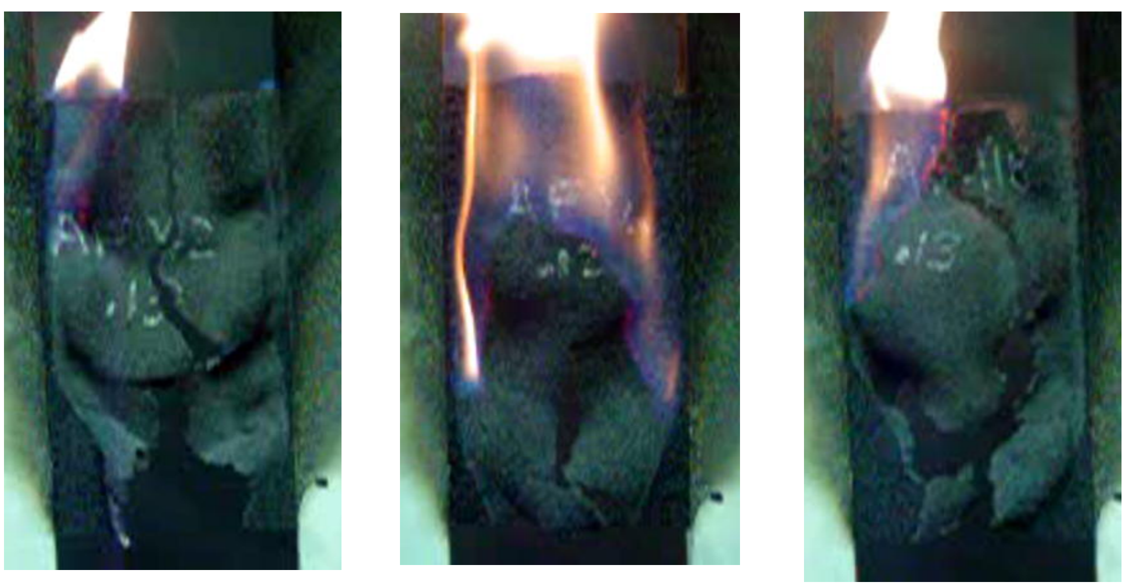


Figure 8. Examples of EPDM Foam Failing Fire Screening Test (afterflame > 2 seconds).

AF-U9D3 AF-U9D3A AF-U9D3B

Figure 9. Examples of PVC/NBR Foam Passing Fire Screening Test (afterflame < 2 seconds).

AF-U5 AF-U6 AF-U6A

Figure 10. Examples of PVC/NBR Foam Failing Fire Screening Test (afterflame > 2 seconds).

Development of PVC/NBR formulas continued based on the favorable results of sample AF-U2 (Figure 4). Further formulations resulted in test passes, at still lower sample weights as illustrated in Figure 5. The PVC/NBR series AF-U9D , which was based on AF-U2 but with optimized intumescent content, provided excellent results in fine cell size, passing fire test, low weight (6 – 8 oz/yd^2) and low halogen content (5.4 wt% Chlorine). The halogen content represents a 66 – 75% reduction over the shelter materials analyzed in this study. Figure 11 shows a comparison of material damage after 12 second flame exposure.

Prototype Foam | California Medium Shelter Material

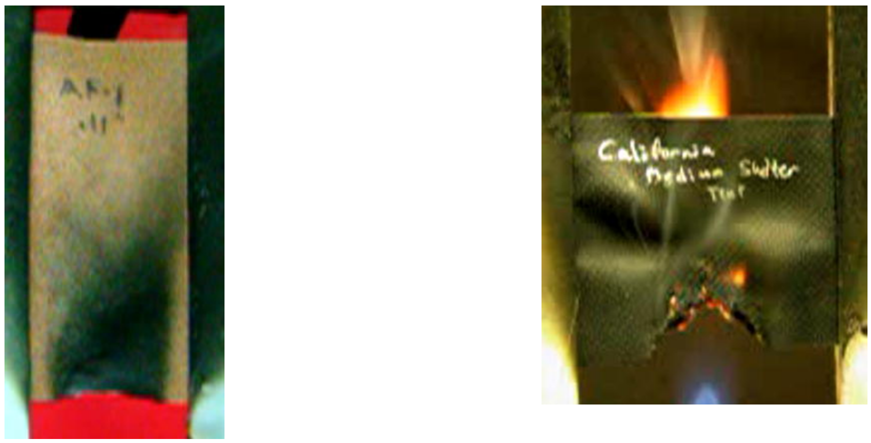


Figure 11. PVC/NBR Prototype Foam vs. Shelter Fabric After 12 Second Flame Exposure.

Images of 22 laboratory samples tested using the screening method are shown in Appendices A and B. Appendix A shows images of burns resulting from 12 second flame exposure on EPDM based samples. The images were recorded to illustrate the extent of sample damage due to the burning if the flame did not self extinguish. Some formulations failed to produce samples adequate for fire testing, therefore, gaps exist in the sample numbering. The images also attempt to capture the smoke evolution produced by sample burning. Appendix B contains images of fire tests on PVC/NBR based foams.

Figure 12 shows images of fire test on the final prototype coated nonwoven fabric and PVC/NBR AF-U9D foam composite, which self extinguished within two seconds to pass the vertical flame test. After successful vertical flame testing of the final composite structure, the foam component was produced at factory scale.

Nonwoven side after 12 second flame

Foam side after 12 second flame

Figure 12. Screening Fire Test of Nonwoven and PVC/NBR Foam Composite.

3.3 Adhesives (PVC Plastisols)

Once a coated nonwoven fabric and foam were developed that passed the fire test, the next step included the development a non-flammable adhesive to adhere the two materials without contribution to flame spread. NCRC utilized various hot melt adhesives, such as polyolefin films and co-nylon blow-down web, to adhere the fabric and foam. During vertical fire tests, the heat from the flame melted the adhesive, which caused delamination. The delamination exposed the flammable adhesive to the open flame resulting in a failed vertical fire test. A search for a non-flammable adhesive led to the use of PVC plastisols. These well know suspensions of PVC powder in a plasticizer, fuse to form a solid when heated. The heat causes the plasticizer to dissolve in the PVC to form a flexible, plasticized PVC film. The foam and/or fabric surfaces were lightly coated with plastisol and the layers adhered by heating, which caused the PVC to fuse. The use of non-flammable plasticizers resulted in a non-flammable plastisol adhesive. Adhesion was considered adequate if the foam sustained damage upon pulling the layers apart. Lab scale vertical flame testing showed minimal damage to the fabric/foam system after 12 seconds of flame exposure (Figure 12).

3.4 Scale-up to Produce Material for Shelter Prototype

In order to produce sufficient foam, adhesive and coated nonwoven for construction of a small shelter, larger quantities were produced. The foam was produced by utilization of the Armacell factory sheet line in Conover, NC. Trials were conducted to produce 60 inch wide x 1.25 inch thick continuous rolls 50 feet in length. Process conditions scaled up successfully using laboratory data and production scale experience. The 1.25 inch thick rolls were skived into 50 foot rolls, 0.10 inch thick using a continuous skiver with a vacuum belt which holds the foam in place during the cutting. Thickness was controlled between 0.90 and 0.11 inch with the center at 0.10 inch thickness.

The fine cell structure, which is a key factor in the performance and aesthetics of the foam, was maintained in the factory production.

Plastisols were produced in gallon quantities and delivered to NCRC along with the final foam samples for tent construction.

3.5 Thermal Insulation Property

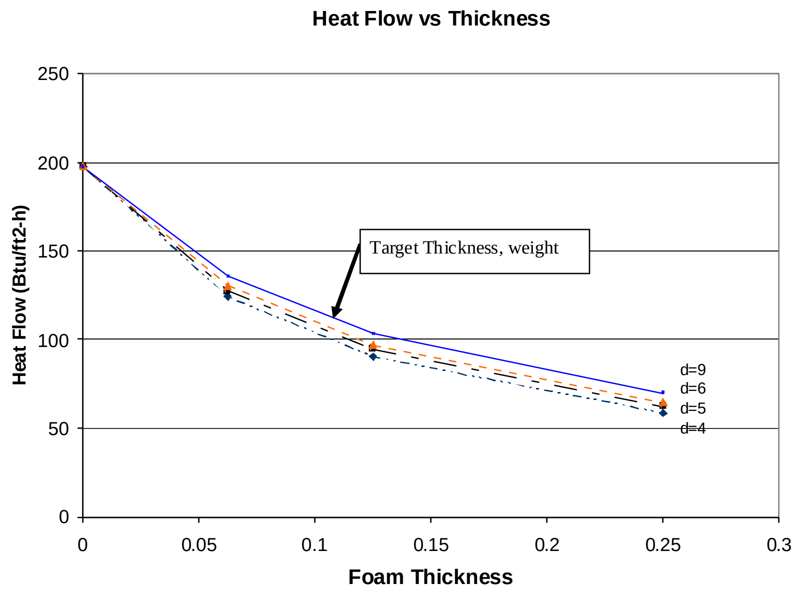
The results in Table 3 show low thermal conductivity for the foam (0.04 W/m°K or 0.28 BTU.in/ft^2.hr.°F) suggesting that the thermal conductivity of the foam component is at least 2.5 times lower than fabric alone.

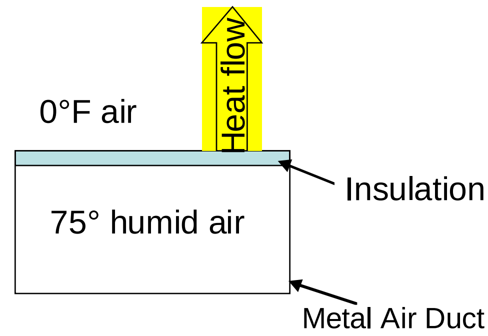
Table 3. Estimated Thermal Conductivity of Foam vs Fabric.

Material	Observed Thermal Conductivity (W/m°K)	Calculated Thermal Conductivity of Foam (W/m°K)	Calculated Thermal Conductivity of Fabric (W/m°K)
1 in. Fiberglass	0.0333		
1 in. fiberglass + 0.10 in. Foam	0.0337	0.040	
1 in. fiberglass + 0.02 in. NW Fabric	0.0336		0.10

Calculation of heat flow using Armacell ArmWin calculation program was carried out using the model of a duct with insulation on the outside, 75 °F humid air inside and an outside temperature 0 °F. The worst case scenario was presented with the air inside moving and outside air blowing at 15 mph. This model was representative of a heated shelter in the winter. A reduction in heat flow was shown when the duct was covered with increasing thickness of closed cell foam (Figure 13). The arrow points to the heat loss rate when using 0.1 inch thick insulation (with thermal k = 0.28 BTU in/ft^{2}hr °F) with a target weight of 6 – 8 oz/yd^2. Under these severe conditions, the calculations showed a 50% reduction of heat flow from 200 btu/ft^{2}hr to 100 btu/ft^{2}hr. In the case of still air inside and outside, the calculations predicted a 23% reduction in heat loss. The use of closed cell foam in shelters to reduce heat loss in addition to fire burn-through protection will enable the new designs to be more energy efficient.

- Calculated heat flow





Weight for 8 pcf foam

Insulation thickness (in)	Weight (oz/yd)
0	0
0.06	6
0.13	12
0.25	24

Figure 13. Thermal Insulation.

3.6 Burn-Through Resistance

The California Medium shelter material was used as a baseline for burn-through resistance. The shelter material melted away from the heat of the flame, which prevented flame spreading and burned a hole through the sample within 10 seconds of flame exposure (Figure 14). PVC/NBR AF-U9D foam formed a char and only the edge of the material was damaged. These data suggested that burn-through resistance, in addition to insulation value, were also much greater for the foam compared to the current shelter material. After five minutes of exposure, the foam formed a hard char and was glowing red hot but provided sufficient insulation so that the paper on the opposite side did not ignite (Figure 15). After 10 minutes the paper still had not ignited but some cracks appeared in the foam (Figure 16). After 10 minutes, the foam was removed and the paper was immediately consumed (Figure 17). This delay in flame burn-through translates into valuable time to extinguish a shelter fire and prevent propagation to adjacent structures.

Figure 14. California Medium Shelter after 10 seconds of Flame Exposure.

Figure 15. Foam After Five Minutes of Flame Exposure.

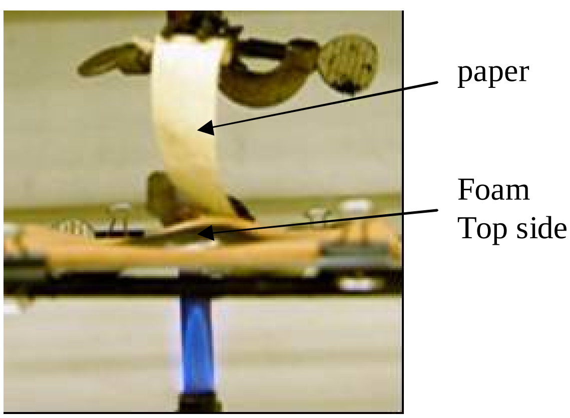


Figure 16. Foam After Ten Minutes of Flame Exposure.

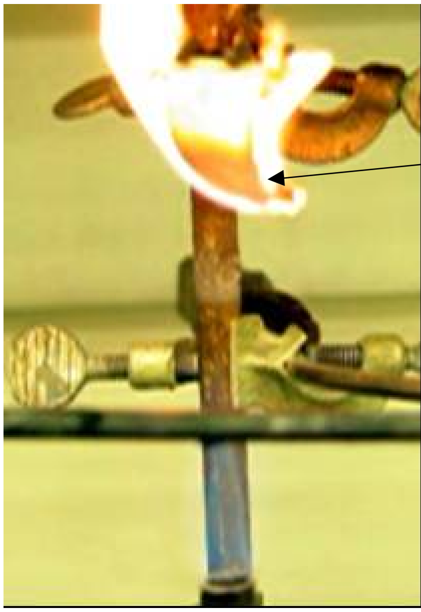


Figure 17. Paper Igniting After Foam Removed.

4. CONCLUSIONS

Prototypes developed during this research demonstrated the principle that closed cell elastomeric foams can be used as an insulating fire protection component for novel shelter material. A combination of the lightweight foam with strong, light weight non-woven fabric resulted in a new shelter material with promising properties.

The closed cell elastomeric foam prototype developed in this project passed the targeted fire test, ASTM D 6413-99 Flame Resistance of Textiles (Vertical Test). In addition, the closed cell foam demonstrated excellent burn-through resistance and thermal insulation value compared to current shelter materials. Current shelter materials were shown to melt from a flame front during the ASTM D 6413-99 test. In a shelter application the melting would enable rapid fire propagation to adjacent structures. The closed cell foam did not melt, but rather formed a char barrier that delayed burn-through by a minimum of 10 minutes. The delay in burn-through translates to increased time for fire suppression or evacuation of personnel from shelters.

Superior thermal insulation values of closed cell foam were measured and calculations revealed significant heat loss reduction for shelter material containing only 0.1" thick closed cell foam. A contributing factor to the excellent thermal insulation property of the foam is the development of very small cell size which reduces convective heat transfer. The fine cell structure, elastomeric composition, and thin gauge resulted in a very flexible foam component for the targeted shelter composite.

Current shelter systems contain up to 22% halogen, which results in the production of hydrochloric and hydrobromic acid when burned. Armacell formulated both EPDM and PVC/NBR foams that reduced the halogen content by up to 75% (5.4 wt%). The reduction in halogen will result in a reduction of acid gases produced during a fire event, making the off-gas less corrosive to the occupants and electronics.

The use of PVC plastisol with a plasticizer having low flammability was demonstrated to be an effective adhesive to enable synthesis of the flame retarded fabric/foam composite shelter prototype.

5. RECOMMENDATIONS

The foam prototype developed in this work requires optimization to be field ready including weatherability, halogen reduction, thermal characteristics and adhesives. Further work is recommended to improve the weatherability.

The PVC/NBR foams require further stabilization to resist sunlight and heat degradation. In addition, improvements in low temperature flexibility is required. The EPDM foams developed met the exposure and flexibility requirements but did not meet the target fire properties.

A significant reduction of halogen content (chlorine) was achieved but a further reduction to zero using the nitrile rubber foam system is possible. This would significantly reduce the toxic and corrosive gases generated during a fire and provide a safer environment for both personnel and assets.

Prototype materials demonstrated superior insulation values compared to current shelter materials. Future work should focus to further improve the thermal insulation properties of the foam/nonwoven composite via modification of the composition and/or structure. Flexible, light weight, high strength, thermal insulation composites are expected to have wide use beyond shelter applications. These novel composites are expected to have a significant role in energy savings, which would reduce logistics requirements for deployments.

A non-flammable adhesive via a PVC plastisol was used to form the final composite structure during this project. However, this system is difficult to scale to full production. An alternative non-flammable adhesive will be required to be compatible with a large scale fabrication.

The closed cell foams showed an excellent capability to store fire retarding materials and would be an excellent candidate for incorporation of self-decontaminating materials being developed by the AFRL Asymmetric Threat Protection Group, Tyndall AFB, FL. Other materials could be stored in the foam to generate properties to safeguard against a variety of chemical and biological agents for increased force protection.

Appendix A: EPDM Based Test Samples Laboratory Screening Fire Photographs

AF-E

AF-J

AF-K1

AF-K2

AF-K3

AF-K4

AF-L

AF-C1

AF-N1

AF-O1

AF-O2

AF-P

AF-Q1

AF-Q1A

AF-Q2

AF-Q2A

AF-R1

AF-V1

AF-V2

AF-W1

AF-X1

AF-Y1

AF-Y2

AF-Y1A

AF-Y1b

AF-Y1C

AF-Y1D

AF-Y1I

AF-Z1

AF-Z1A1

AF-Z1B

AF-Z1B1

AF-Z1B3

AF-Z2

AF-Z3

AF-Z4

AF-Z6

AF-AA1

AF-AA2

AF-AA4

AF-AA5

AF-AA6

AF-AB

Appendix B: NBR Based Test Samples Laboratory Screening Fire Photographs

AF-U

AF-U2

AF-U4

AF-U5

AF-U6

AF-U6A

AF-U7

AF-U7A

AF-U7B

AF-U8A

AF-U8B

AF-U9A

AF-U9B

AF-U9D

AF-U9D2A

AF-U9D3

AF-U9D3A

AF-U9D3B

AF-U9D4

AF-S

AF-T