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The Development of a Thermally Enhanced Emergency Fire Shelter

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Since its founding in 1905, the U.S. Forest Service has been responsible for maintaining public lands. The Forest Service and other public lands agencies respond to an average of 73,000 wildfires per year, and responding firefighters are required to carry a number of safety gear items, including the M2002 emergency fire shelter. The emergency fire shelter is intended to serve as a last resort means of protection in case a firefighter's escape route has been compromised in the face of an approaching flame front. No fire shelter deployment tragedy has been more costly than the 2013 Yarnell Hill fire in Arizona, where 19 members of the Granite Mountain Hotshots perished. After the tragedy at Yarnell Hill, the Forest Service decided to expedite the next redesign cycle of the fire shelter in order to improve its ability to withstand direct contact with flames. Engineers at NASA Langley Research Center have spent the better part of a decade developing flexible thermal materials for use in inflatable aerodynamic decelerators and have demonstrated their performance in the IRVE-2 and IRVE-3 flight programs (Inflatable Reentry Vehicle Experiment). NASA engineers recognized an opportunity to leverage their experience and knowledge with flexible thermal protection systems to potentially improve the fire shelter's resistance to direct flame contact, and have been working directly with the U.S. Forest Service to achieve this goal. They launched the CHIEFS project (Convective Heating Improvement for Emergency Fire Shelters) in 2014. Over the past three years, CHIEFS has screened over 270 unique material layups, and tested over 30 unique full scale shelter concepts in an effort to achieve a game changing improvement to the thermal protection of the fire shelter, while maintaining minimal mass and volume. This paper will discuss CHIEFS' 1st and 2nd generation fire shelter development efforts and test results.

I. Introduction

On June 30th 2013, 19 members of the Granite Mountain Interagency Hotshot Crew lost their lives in a wild fire outside of the town of Yarnell Hill, Arizona. The fire fighters were entrapped after weather conditions rapidly changed fire behavior, and were forced to begin clearing dense brush and other fuels in order to make a deployment

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site for their emergency fire shelters. The emergency fire shelter currently issued to wild land fire fighters, known as the (M2002), is an excellent design to efficiently reflect radiant energy; however, the shelter is not able to withstand prolonged exposure to direct flames. As a result, firefighters are trained to clear fuels away from the vicinity of their deployed shelter before flames encroach. According to the official incident investigation report, the crewmembers had less than two minutes to use chainsaws, shovels, and other tools to remove fuels from the Yarnell Hill deployment site[1]. It is apparent that this was not enough time to complete the task; the hotshots had not yet finished clearing the site when the flame front overtook them. Temperatures of over 1100°C (2000˚F) were evident at the site; there were no survivors. News of this tragedy spread around the country, and researchers at NASA Langley Research Center saw an opportunity to help prevent future tragedies like Yarnell Hill by utilizing their experience developing inflatable atmospheric decelerators to improve the shelter's ability to withstand exposure to flames.

For approximately the past 10 years, NASA Langley Research Center has been engaged in the development of Flexible Thermal Protection Systems (FTPS) for use on Hypersonic Inflatable Aerodynamic Decelerators (HIAD) for atmospheric entry[2, 3]. These inflatable decelerators could be exposed to peak cold wall heat flux values up to 100 W/cm2. The decelerator is constructed of an inflatable structure which is protected from heating by an outer FTPS covering. Maintaining an appropriate temperature on the inflatable structure throughout the duration of entry is the purpose of the FTPS. As the name suggests, FTPS differs from traditional rigid heat shield thermal materials in that it must be flexible; as a result, FTPS materials must be able to be folded and compressed when packed without serious deleterious effect to thermal protection when deployed. A typical inflatable heat shield FTPS concept is less than 25.4 mm (1 inch) thick with an areal mass of 3.1 kg/m^2 (0.6 lb/ft^2) for a 10 kJ/cm^2 integrated heat load earth entry trajectory. As a result, thin and lightweight designs with high thermal resistance are sought both by utilizing high performance materials and also by applying these materials to specific heating regions within the internal FTPS layup where they are optimally suited to inhibit heat transfer.

FTPS is composed of a stack of different thermal materials known as a "layup". The outer regions of the layup are exposed to higher temperatures than the inner regions of the FTPS which lie closer to the underlying inflatable support structure. For this reason, materials in the outer region should inhibit heat transfer best at relatively higher temperatures compared with the inner region. Heat transfer in high temperatures is dominated by radiant transmission; inner cooler regions predominantly focus on the inhibition of gas conduction and advection. The inner-most layer in the FTPS layup is the gas barrier which is designed to dead-head high temperature gas advection through the permeable insulation layers and protect the underlying structure from hot impinging jets.

In the fall of 2013, NASA Langley Research Center began the effort called Convective Heating Improvement for Emergency Fire Shelters (CHIEFS). CHIEFS operated on the premise that lessons learned, test methodology, and technological advances realized over the past decade of NASA FTPS development could be applied directly to the fire shelter application due to several key similarities between atmospheric decelerators and fire shelters. Both applications require durable flexible materials which can be packed to a minimal stowed volume, but be rapidly deployed for a single use to deliver predictable protection when exposed to a short duration and high intensity heat pulse. Despite the many similarities between FTPS technology for inflatable decelerators and fire shelter layups, several key differences were identified which made it necessary to focus the CHIEFS effort on developing a dedicated layup for the fire shelter application. The forest fire environment is different from that of atmospheric re-entry partly due to the presence of oxygen at the Earth's surface; several materials primarily composed of carbon – which exhibit desirable characteristics on decelerators where reduced oxygen levels are present – decompose exothermally upon heating in a fire shelter layup test. Also, peak re-entry heating occurs at high altitudes with corresponding low static pressures; so, radiation is a more dominant mode of heat transfer within FTPS layups for decelerators. Fire shelters would benefit from layups with more emphasis on addressing gas conduction and advection. Cost is an additional consideration for the fire shelter. Currently, the M2002 costs less than $400 per unit, and keeping the shelter within range of this price eliminates the use of many exotic materials which have been investigated for atmospheric entry. There are additional considerations for the fire shelter due to the fact that it is occupied by a human being during use. For example, it is not desirable to use materials with overly toxic, irritating, or otherwise harmful decomposition byproducts. Finally, mass and volume constraints on the fire shelter are significantly different than on the inflatable decelerator. The heating environment expected for the fire shelter is far lower – current decelerator candidates are tested to peak heating rates between about 5 and 10 times higher than average values reported in forest fire research – so the M2002 wall thickness of less than 1 mm makes direct application of a nearly 25.4 mm-thick decelerator layup inappropriate. Fire crew in the field are required to carry up to 18.1 kg (40 lb) of gear; and, according to a 2014 survey many firefighters already consider the 1.95 kg (4.3 lb) M2002 too heavy[4]. Significantly increasing convective protection without noticeably increasing shelter mass or packed volume has proven a challenging proposition.

CHIEFS began 2014 by conducting a series of small-scale laboratory convective tests at NASA Langley Research Center. By October 2014 CHIEFS had screened over 100 unique material layups and demonstrated significant improvement to the convective performance of the M2002 layup. The CHIEFS team met with USFS Missoula Technology and Development Center (MTDC) personnel and presented current research results at a Technical Interchange Meeting (TIM). MTDC had already been directed by the Washington Office Fire and Aviation Management (WO-FAM) to accelerate the lifecycle product review for the fire shelter and supporting components (a planned effort to assess technology available for a possible fire shelter revision), an action also taken largely in response to the Yarnell Hill tragedy, and responded favorably to the exploratory results presented by CHIEFS. In early 2015, NASA and the U.S. Forest Service entered into an Interagency Agreement and a free sharing of research findings, test collaboration, and support between the two agencies ensued.

After the TIM, CHIEFS resumed small-scale testing. With guidance from MTDC, the effort focused on the development of optimized light, medium, and heavy-weight layups. These shelters became known as the “Gen 1” fire shelters. The goal was to provide a shelter option that offered similar thermal protection to the M2002 but weighed less (lightweight), a shelter that weighed about the same as the M2002 but offered better protection (mediumweight), and an option that provided significantly better protection but was heavier (heavyweight). One of each of these Gen 1 shelters was exposed to controlled wild fire burns in the Northwest Territories of Canada in June 2015, and the remaining shelters were subjected to full-scale laboratory tests at University of Alberta in September of 2015. Based on discussions with USFS in October 2015 it was decided to begin work on a second generation of NASA fire shelters, known as “Gen 2”, with emphasis on using materials with less volatile and toxic decomposition byproducts, seams with better sealing capability, as well as a continuation of the push toward higher technology readiness level, durable, and affordable materials. The Gen 2 shelters focused on the target of a mediumweight shelter; the lightweight and heavyweight targets were dropped. The Gen 2 shelter development was conducted over the period of approximately one year with full scale shelter screening tests conducted at North Carolina State University (NCSU) in early March, late June, and early July 2016, and concluded with full scale testing of down selected concepts at the University of Alberta that September. This paper will focus on the Gen 1 and Gen 2 shelters and tests conducted at the University of Alberta only.

II. Full Scale Shelter Test Setup

Full scale shelter testing was conducted at the Protective Clothing and Equipment Research Facility (PCERF) at the University of Alberta in Edmonton, Alberta, Canada. The facility utilized a metal test enclosure built onto a trailer and placed outdoors for testing as shown in Figure 1. The shelter is positioned on a flat-bed test stand that has a 2.5 cm (1 in) thick layer of high temperature rigid insulation installed on the test bed floor. Gen 2 shelters were testing with a layer of approximately 2.5 cm (1 in) of soft Saffil batting over the rigid floor insulation. The thermocouples mounted in the shelters (typically between 9 and 15) were connected to a Measurement Computing Model 2416 data acquisition system (logging at 10 Hz), and then a galvanized sheet metal enclosure was installed over the test assembly as seen in the photograph. There are 8 propane torches which are spaced around the perimeter of the test bed: one at the head, one at the foot, and three evenly spaced on each side. For some of the Gen 1 tests and all of the Gen 2 tests a heavy chain was placed around the periphery of the shelter floor band to keep the shelter tight against the test bed floor and prevent flame ingress into the shelter from underneath. In the Gen 2 shelters, the traditional shelter floor was not installed, and instead a “racetrack” band was used which placed a 15.24 cm (6 in) of floor material to the *exterior* of the shelter so that chains placed onto the racetrack around the perimeter of the shelter walls could more effectively seal flames from entering the shelter from underneath.

Figure 1. PCERF Test Enclosure.

A thermocouple tree was mounted on the flat-bed test stand close to the location where the head of a firefighter would be positioned during an actual deployment (approximately 1 foot from the heated head end of the shelter). Two thermocouples were installed on this tree, at heights of 5.1 and 25.4 cm (2 and 10 in) above ground level. The lower thermocouple represents the temperature associated with the breathing zone of the fire fighter and was the most critical measurement during these tests. Limits of human tenability are assumed by the Forest Service to be breathing air temperatures of approximately 150°C; so, the main evaluation criteria for shelter testing is to determine the elapsed time until the 5.1 cm (2 in) thermocouple exceeds 150˚C. The longer the elapsed time, the better the overall performance of the shelter. Since the PCERF test facility was located outside, tests were only limited in duration to approximately 2 minutes in order to protect the test bed structure from excessive heat.

At the commencement of each test day, an M2002 shelter was tested; this test served as a calibration run and a baseline for performance of shelters tested that day. Often additional M2002 shelters were tested periodically throughout the day in order to provide additional baseline performance resolution.

III. Full Scale Gen 1 Shelters

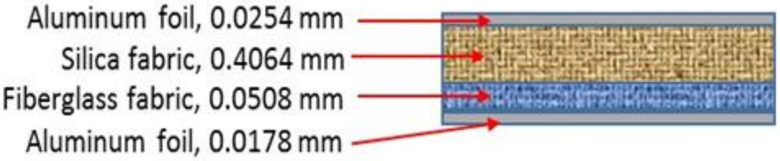


Figure 2. M2002 Wall Layup. *Construction of the existing fire shelter wall issued by the USFS.*

Figure 3. The Existing Fire Shelter (M2002). *Shown in the deployed configuration (left), and with a cutaway to display the firefighter inside (right).*

The existing M2002 shelter layup is the CHIEFS primary baseline for performance comparisons. This layup is shown schematically in Figure 2. The outer shell consists of a 0.4064 mm (0.016 in) thick silica fabric at 0.208 g/in^2 (9.5 oz/yd^2) laminated by Custom Laminating Corp. (Mt. Bethel, PA) to a 0.0254 mm (0.001 in) thick aluminum foil using a proprietary water based adhesive. The outer shell is installed on the shelter with the aluminum foil facing outward. The inner layup consists of a 0.0508 mm (0.002 in) thick fiberglass fabric with an areal mass of 0.030 g/in^2 (1.38 oz/yd^2) laminated to a 0.0178 mm (0.0007 in) layer of aluminum foil using the same adhesive, also from Custom Laminating Corp. The inner shell is installed on the M2002 such that the aluminum foil faces the shelter interior. The overall thickness of the shelter wall is 0.5004 mm (0.0197 in) with an overall areal mass of 0.34 g/in^2 (15.5 oz/yd^2). The overall shelter with the floor band, seams, and straps weighs 1.95 kg (4.30 lb) and has a packed volume of approximately 3441 cm^3 (210 in^3). The shelter is 218 cm (86 in) long, 39.4 cm (15.5 in) high, and 78.7 cm (31 in) wide when deployed. Two photographs of fully deployed M2002 shelters are shown in Figure 3.

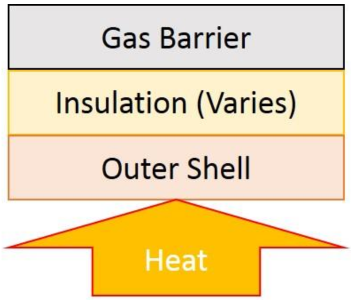


Figure 4. Basic Shelter Wall Layup Blueprint. *This schematic will orient the reader with the basic paradigm used in shelter wall construction.*

The Gen 1 shelter inner gas barrier was a polytetrafluoroethylene (PTFE) fiberglass fabric laminate with an areal mass of 0.085 g/in^2 (3.89 oz/yd^2). The Gen 1 CHIEFS shelters outer shell used a 0.065 g/in^2 (3 oz/yd^2) quartz fabric with 0.0254 mm (.001 inch) thick aluminum foil bonded to it using Custom Laminating Corporation’s silicone based adhesive and laminating process. The silicone based adhesive was a new trial formulation designed to withstand heating longer than the traditional water based adhesive (used in the M2002) before breaking down.

With the outer and inner laminates specified, the test effort was primarily directed towards evaluating the thermal performance of various candidate insulations to be used in between. A basic blueprint is shown in Figure 4. The three insulations used for Gen 1 CHIEFS shelters were all commercially available products: Pyrogel 2250, Saffil paper, and Technofire graphite intumescent felt. Pyrogel 2250 is an aerogel impregnated non-woven insulation and each layer has an areal mass of 0.235 g/in^2 (10.8 oz/yd^2). Saffil paper is an alumina non-woven insulation and each layer has an areal mass of 0.13 g/in^2 (6 oz/yd^2). TFP Tecnofire T6663-02 is a thin fiberglass felt impregnated with intumescent graphite particles which expand upon heating, and each layer has an area mass of 0.035 g/in^2 (1.6 oz/yd^2). A photograph showing the final Gen 1 layup designs (lightweight, mediumweight, and heavyweight) is shown in Figure 5. Shelters were constructed using the standard M2002 geometry as well as an alternate shape known as the “thermal pod”. The thermal pod targeted the geometric efficiency of a sphere to achieve a design that uses about 20% less surface area than the M2002, and also decreased the surface area to volume ratio of the shelter – a configuration favorable to slower heating of the interior environment. The thermal pod is shown in Figure 6. A description of the layups used in this test series is shown in Table 1, and a matrix of configurations for tested full scale Gen 1 fire shelters is shown in Table 2.

Figure 5. Gen 1 Layups. *From left to right: heavyweight, lightweight, and mediumweight.*

Figure 6. Thermal Pod Design. *Alternate CHIEFS shelter design with more efficient use of surface area.*

Table 1. Gen 1 Layups. *Layups specified in this table below were used in the fabrication of the walls on Gen 1 test shelters. Materials are shown for each layup in numerical order and from left to right starting with the material nearest the heat source and ending with the material on the surface of the shelter interior.*

Layup	Outer Shell	Insulation 1	Insulation 2	Gas Barrier
M2002	1. .001 in Al foil 2. H_2O based adhesive 3. 9.4 oz/yd^2 silica fabric	None	None	1. Fiberglass fabric 2. H_2O based adhesive 3. .0007 in Al foil
M2002 Sil	1. .001 in Al foil 2. Silicone based adhesive 3. 9.4 oz/yd^2 silica fabric	None	None	1. Fiberglass fabric 2. H_2O based adhesive 3. .0007 in Al foil
Lightweight	1. .001 in Al Foil 2. Silicone based adhesive 3. 3 oz/yd^2 silica fabric	TFP Graphite Intumescent Felt X 4	None	PTFE fiberglass fabric laminate
Mediumweight	1. .001 in Al Foil 2. Silicone based adhesive 3. 3 oz/yd^2 silica fabric	TFP Graphite Intumescent Felt X 4	Saffil Paper	PTFE fiberglass fabric laminate
Heavyweight	1. .001 in Al Foil 2. Silicone based adhesive 3. 3 oz/yd^2 silica fabric	TFP Graphite Intumescent Felt X 7	Pyrogel 2250	PTFE fiberglass fabric laminate

Table 2. Gen 1 Test Matrix. *One of each design was tested in a controlled wildfire in June 2015, the remaining shelters (as counted below) were tested in the September 2015 tests at PCERF.*

Shelter	Shelters Tested	Layup	Geometry	Wall Seam	Floor Seam	Mass (Av) lb (est.)	Packed Volume (Av) in^3 (est.)
M2002	3	M2002	M2002	M2002	M2002	4.30	210
M2002 Silicone	3	M2002 Sil	M2002	M2002	M2002	4.30	210
ML	2	Lightweight	M2002	M2002	M2002	4.16	175
TM	2	Mediumweight	Thermal Pod	M2002	M2002	3.74	212
TH	2	Heavyweight	Thermal Pod	M2002	M2002	6.23	567
MH	2	Heavyweight	M2002	M2002	M2002	7.97	708

IV. Full Scale Gen 1 Shelter Test Results

Fourteen fire shelters were tested at the full scale PCERF test facility in Edmonton in September of 2015. Two of each of the four CHIEFS designs and three of each of two versions of the M2002. The CHIEFS designs tested were the M2002 geometry constructed using the lightweight layup (ML), the thermal pod geometry constructed using the mediumweight layup (TM), the thermal pod geometry constructed using the heavyweight layup (TH), and the M2002 geometry constructed using the heavyweight layup (MH). The M2002 was tested as the baseline as well as the M2002 Silicone which is the same as the M2002 baseline shelter in every way except that the adhesive used to fabricate the laminates was the same silicone based adhesive used on CHIEFS shelters rather than the standard water based adhesive. The layups mentioned here are summarized in Table 1 and the shelters in Table 2.

Figure 7. Open flames within CHIEFS shelter. *Flames in this shelter are entering underneath the shelter floor band, this was a common point of flame ingress.*

During testing, it became evident that several shelters were experiencing open flames and even explosive flashes within the shelters. Flames often entered the shelter underneath the perimeter floor band (Figure 7) or near wall seams. Explosive flashes were noticed on a number of shelters. In certain cases flashes occurred after the test had completed and heating terminated. Video images indicate that there is a significant buildup of visible smoke inside of many shelters during heating; however, CHIEFS Gen 1 shelters retain this smoke throughout the test while the M2002 begins to vent smoke to the outside of the shelter after significant failure of the gas barrier aluminum prior to the conclusion of the tests. Figure 8 demonstrate the M2002 ventilation effect. It is likely that the smoke produced during thermal decomposition of all shelters is flammable. Gas samples taken within shelters during tests, as well as gasses captured in small scale laboratory thermal decomposition of shelter material samples, were analyzed using gas chromatography-mass spectrometry. Several flammable volatile components were identified originating with the adhesives used in the aluminum-fabric laminates. When heated, the water based adhesives produce several volatile organic compounds such as acetone, benzene, and toluene; the silicone based adhesive produces a number of flammable siloxanes in addition to volatile organics. Flashing and flames inside of shelters were shown to exhibit a marked effect on temperatures measured to indicate shelter performance. As the primary interest in this first round of full scale tests was the thermal resistance of the material layups to convective heating, shelters significantly influenced by internal flames were not included in the results. Results for shelters with minimal internal flshing are shown in Figure 9.

Figure 8. M2002 shelter self ventilating. *Approximately 20 seconds into the test the M2002 visibly accumulates flammable thermal decomposition byproducts (left); at the conclusion of heating – approximately 60 seconds into the test – the M2002 gas barrier is severely compromised and thermal decomposition byproducts easily ventilate outside of the shelter (right). This is likely the reason explosive flashes were not observed within the M2002.*

It should be noted that the M2002 outperformed the M2002 Silicone. As the only difference between the two shelters is the laminating adhesive, it can be argued that the silicone based adhesive has a deleterious effect on shelter thermal performance. All of the CHIEFS Gen 1 shelters used the silicone based adhesive. One way the USFS analyzes performance is by assuming that the maximum survivable breathing air temperature for a firefighter inside a shelter is 150 °C, and accordingly assessing the amount of time a given shelter design can provide a “thermally habitable” environment inside. Compared to the M2002, the CHIEFS Gen 1 ML shelter underperformed; however, the fairest comparison would be between Gen 1 shelters and the M2002 Silicone. Compared to the M2002 Silicone, the ML shelter provided a thermally habitable environment for a duration about 11% longer with 4% less mass and 17% less packed volume, and the TM shelter offered protection for about 116% longer with 3% less mass and about

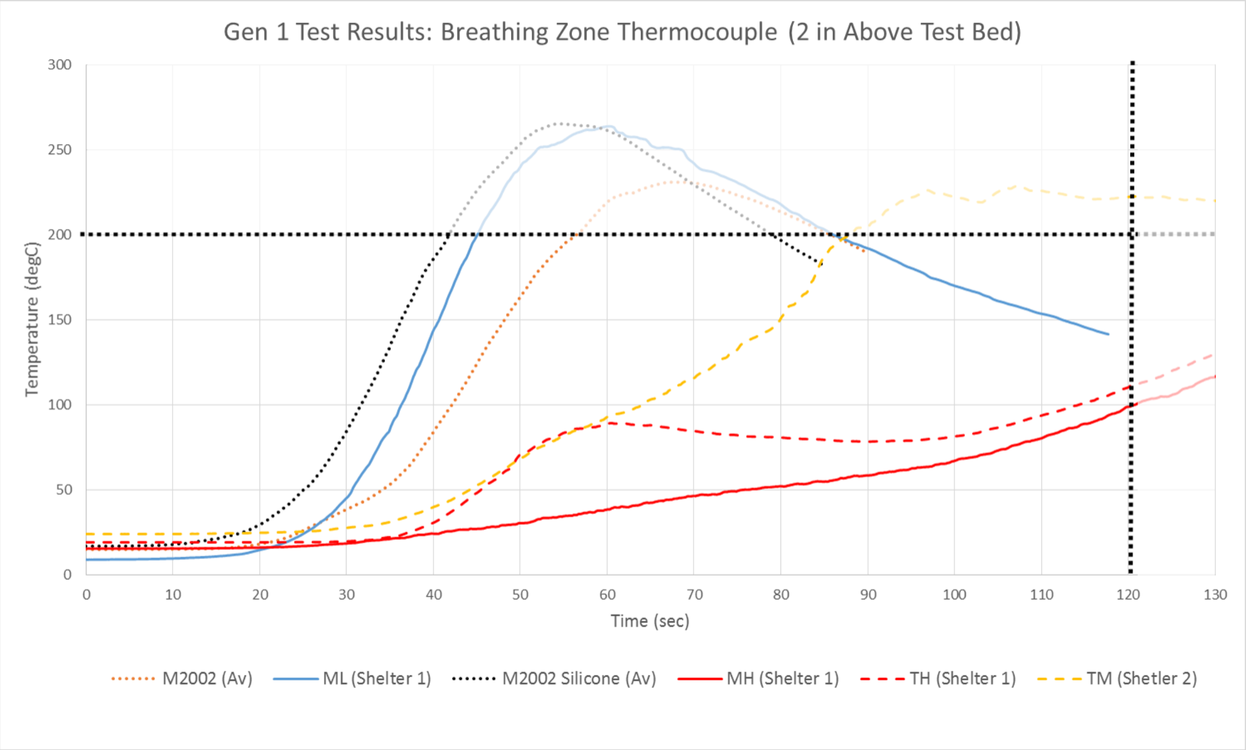


Figure 9. Gen 1 Test Results Summary. *Breathing air temperatures are shown as a function of time for tested shelters which did not experience significant internal flames or flashes. Heating was terminated after the breathing zone thermocouple reached 200 °C for all tests except MH and TH shetlers which were terminated at 120 s. 150 °C is considered by the USFS to be the maximum survivable breathing air temperature. CHIEFS Gen 1 shelters are most fairly compared to the M2002 Silicone results.*

the same packed volume. Both the TH and MH shelter tests were terminated at 120 seconds, the maximum time the test rig can endure, well before the thermally habitable limit was reached.

V. Full Scale Gen 2 Shelters

The baseline Gen 2 shelter gas barrier was the same polytetrafluoroethylene (PTFE) fiberglass fabric laminate with an areal mass of 0.085 g/in^2 (3.89 oz/yd^2) as the Gen 1 shelters. The existing M2002 inner liner was also tested in limited cases as a CHIEFS gas barrier. The Gen 2 CHIEFS shelters used a more robust 0.122 g/in^2 (5.6 oz/yd^2) silica fabric on the outer shell compared with Gen 1. This silica fabric is the same fabric as is used on the floor of the M2002. The fabric is bonded with 0.018 mm (.0007 in) thick aluminum foil using Custom Laminating Corporation's water based adhesive and laminating process, and is known as the "Single 7" (S7) laminate and has an areal mass of .168 g/in^2 (7.7 oz/yd^2).

Figure 10. UPF Insulation. *This lightweight fiberglass batting is the Gen 2 baseline insulation.*

The insulations evaluated in the Gen 1 shelters were replaced in favor of a more cost effective and practical fiberglass batting. This soft and light weight batting is produced by United Pacific Fiberglass (UPF) Corporation under the name Ultracore Aircraft Insulation (UAI), and referred to here as "UPF". The batting is produced in layers with densities between 5.4 to 10.9 kg/m^3 (0.34 to 0.68 lb/ft^3) and areal densities of 0.045 to 0.055 g/in^2 (2.1 to 2.5 oz/yd^2). The uncompressed thickness of the insulation is approximately 1.27 cm (.5 in); the insulation can be compressed to a thickness of about .5 millimeters (.013 in). A photograph of a sample of this insulation is shown in Figure 10. Several versions of the batting were tested in Gen 2 shelters including a version with intumescent graphite flakes imbedded directly into the insulation (shown in Figure 11). Additionally, small scale convective testing had provided evidence supporting a benefit to inserting a thin polymer film as an inner gas barrier between two layers of insulations within the layup itself. Multiple candidates were screened in small scale testing, but generic polyimide was selected as the material for this inner gas barrier on the Gen 2 full scale test shelters due to its low cost, weight, and beneficial thermal performance. The generic polyimide had a thickness of approximately .0254 mm (.001 in). Layups tested are shown in Table 3.

Figure 11. UPF Insulation with Embedded Intumescent Graphite Flakes.

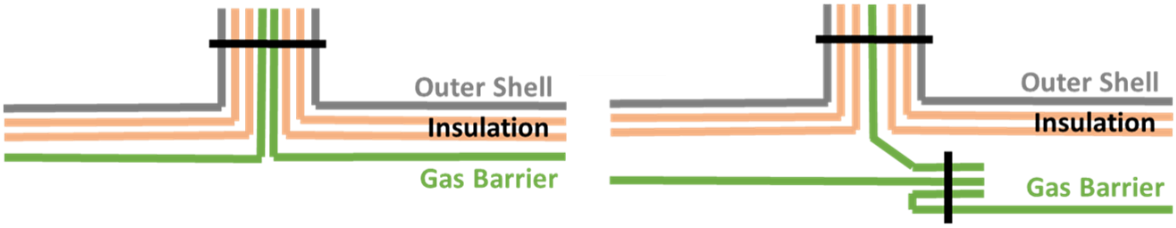


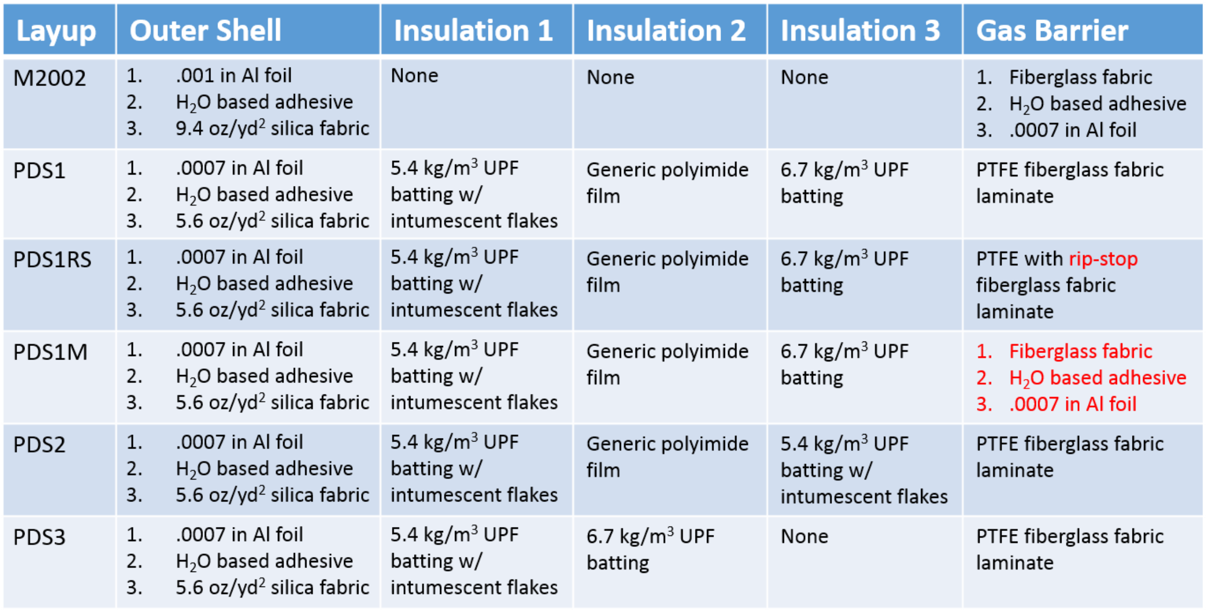
Figure 12. Gen 2 Wall Seams. *M2002 baseline (left) and R27 (right). The purpose of the R27 seam was to interrupt the continuous path from outside the shelter through the gas barrier created during stitching.*

In addition to material changes, Gen 2 efforts focused on developing and testing various wall seam designs in order to limit the deleterious effect of gas ingress noticed during the Gen 1 tests. A number of seam concepts were designed, and prior to the PCERF tests, the various seams were assessed for their effect on thermal performance during tests, especially by observing shelter interior video data, and also by considering the estimated impact on manufacturing costs and time. Ultimately 2 designs were selected for testing at PCERF, the baseline M2002 seam and a seam known as the R27 (Figure 12).

All shelters were fabricated using the standard M2002 geometry except for a novel design known as the “MW” concept. The MW shelter is very similar to the M2002 except that it is fabricated out of two full length sections of material so that there is only one seam running down the length of the shelter from head to foot along the centerline. This strategy reduces the total running length of seam which is intended to reduce shelter fabrication cost, potential gas ingress points, and shelter mass. A picture of the MW shelter is shown in Figure 13. All shelters were fabricated using a floor concept called a “racetrack”. The racetrack is actually not actually a floor, but rather a 15.2 cm (6 in) wide band of floor material (D7) which runs around the *outside* perimeter of the shelter rather than within the shelter. The intention is that by placing the heavy chains used in all recent tests on top of this band, the shelter floor is better sealed to gas ingress underneath the floor band than with previous tests. This configuration was desired because testing targeted thermal performance of the shelter materials rather than ancillary effects caused by the test bed. Chains were used in all tested shelters and the bed of the test rig was covered in a layer of 2.54 cm (1 in) Saffil batting to help further seal the floor band. Shelters were not individually packed, so no packed volume data is available; however, a CHIEFS shelter similar to the PDS1 was successfully packed into the M2002 carrying case using a hydraulic press in June 2016 (210 in^3). Shelter mass was measured for each shelter tested and a matrix of configurations for tested full scale Gen 2 fire shelters is shown in Table 4.

Figure 13. MW shelter. *The MW geometry is similar to the M2002 but uses less total running seam length.*

Table 3. September PCERF Gen 2 Layups. *Materials are shown for each layup in numerical order and from left to right starting with the material nearest the heat source and ending with the material on the surface of the shelter interior.*



Layup	Outer Shell	Insulation 1	Insulation 2	Insulation 3	Gas Barrier
M2002	1. .001 in Al foil 2. H_2O based adhesive 3. 9.4 oz/yd^2 silica fabric	None	None	None	1. Fiberglass fabric 2. H_2O based adhesive 3. .0007 in Al foil
PDS1	1. .0007 in Al foil 2. H_2O based adhesive 3. 5.6 oz/yd^2 silica fabric	5.4 kg/m^3 UPF batting w/ intumescent flakes	Generic polyimide film	6.7 kg/m^3 UPF batting	PTFE fiberglass fabric laminate
PDS1RS	1. .0007 in Al foil 2. H_2O based adhesive 3. 5.6 oz/yd^2 silica fabric	5.4 kg/m^3 UPF batting w/ intumescent flakes	Generic polyimide film	6.7 kg/m^3 UPF batting	PTFE with rip-stop fiberglass fabric laminate
PDS1M	1. .0007 in Al foil 2. H_2O based adhesive 3. 5.6 oz/yd^2 silica fabric	5.4 kg/m^3 UPF batting w/ intumescent flakes	Generic polyimide film	6.7 kg/m^3 UPF batting	1. Fiberglass fabric 2. H_2O based adhesive 3. .0007 in Al foil
PDS2	1. .0007 in Al foil 2. H_2O based adhesive 3. 5.6 oz/yd^2 silica fabric	5.4 kg/m^3 UPF batting w/ intumescent flakes	Generic polyimide film	5.4 kg/m^3 UPF batting w/ intumescent flakes	PTFE fiberglass fabric laminate
PDS3	1. .0007 in Al foil 2. H_2O based adhesive 3. 5.6 oz/yd^2 silica fabric	5.4 kg/m^3 UPF batting w/ intumescent flakes	6.7 kg/m^3 UPF batting	None	PTFE fiberglass fabric laminate

Table 4. September PCERF Gen 2 Shelters.

Shelter	Shelters Tested	Layup	Geometry	Wall Seam	Floor Seam	Average Mass lb
M2002	3	M2002	M2002	M2002	Racetrack	4.30 (est.)
PDS1-R27	3	PDS1	M2002	R27	Racetrack	4.69
PDS2-R27	2	PDS2	M2002	R27	Racetrack	4.91
PDS3-R27	2	PDS3	M2002	R27	Racetrack	4.51
PDS1-PFA	2	PDS1	M2002	PFA	Racetrack	4.89
PDS1RS-R27	2	PDS1RS	M2002	R27	Racetrack	4.52
PDS1-M2002-MW	2	PDS1	MW	M2002	Racetrack	4.36
PDS1-M2002	2	PDS1	M2002	M2002	Racetrack	4.62
PDS1M-R27	2	PDS1M	M2002	R27	Racetrack	4.47

VI. Full Scale Gen 2 Shelter Test Results

In general, Gen 2 shelters performance was reduced from Gen 1 shelters; however, the materials utilized were more practical for use in real fire shelters. Mass and volume figures converged on only minor changes from the existing M2002 shelter metrics. Figure 14 shows temperature plots in tested shelters for the thermocouple located 5.1 cm (2 in) above the shelter floor near where the firefighter would be breathing. The shelter with the best overall performance used the heavyweight layup (PDS2) with an averaged 72% improvement in duration of a "survivable" breathing air temperature and an average 14% increase in overall shelter mass compared with the M2002. However, all shelters offered a significant advantage over the M2002 so it may be that a slight decrease in thermal performance would be permissible so that a shelter could be selected with a more modest increase in mass. For example, the PDS1-M2002-MW shelters provided an average 45% increase in survival time with only an average 1% increase in mass compared with the M2002. It should be noted that other factors may be taken into consideration when grading the overall performance of a shelter beyond the breathing zone thermocouple data; but, these variables go beyond the scope of this writing.

Several observations can be made when observing Gen 2 test results. First, overall internal flashing and flames were reduced compared with the Gen 1 tests. There was no clear advantage observed in using the R27 seam; as a result, the simplest seam to manufacture, the M2002, appears to be the most attractive option moving forward. Second, the advantage of the internal polyimide gas barrier layer indicated in previous testing was not observed at PCERF 2016; in fact, results suggest a deleterious thermal effect. Both of the PDS3-R27 shelters were free of any internal combustion and exhibited a 59% improvement in survival time at the breathing zone thermocouple with only a 5% increase in shelter mass over the M2002. For this reason, the polyimide film would be dropped from shelter designs moving forward. Finally, the M2002 gas barrier (PDS1M layup) tended to fail catastrophically relatively early on during the testing of both PDS1M-R27 shelters. This effect is less obvious in the breathing zone thermocouple data; however, observing internal video data large sections of softened aluminum foil delaminate from the gas barrier and fall into the shelter interior at 79 seconds in the PDS1M-R27-1 test and 48 seconds into the PDS1M-R27-2 test. Note the early rise in the breathing zone thermocouple data evident on the PDS1M-R27-2 shelter. Interestingly, this phenomenon has only been observed in limited cases on the M2002 which uses the same gas barrier; most M2002 gas barriers become heavily oxidized and compromised but do not exhibit the same type of sectional delamination observed here. After the PDS1M-R27 tests, the material properties were investigated and it was found that the UPF was in a more significantly and completely deteriorated condition than the PDS1-R27 or the PDS1RS-R27, likely a consequence of the aluminum gas barrier's inability to shed heat via radiant energy into the shelter thus accelerating warm up of the overall layup as well as the subsequent catastrophic delamination.

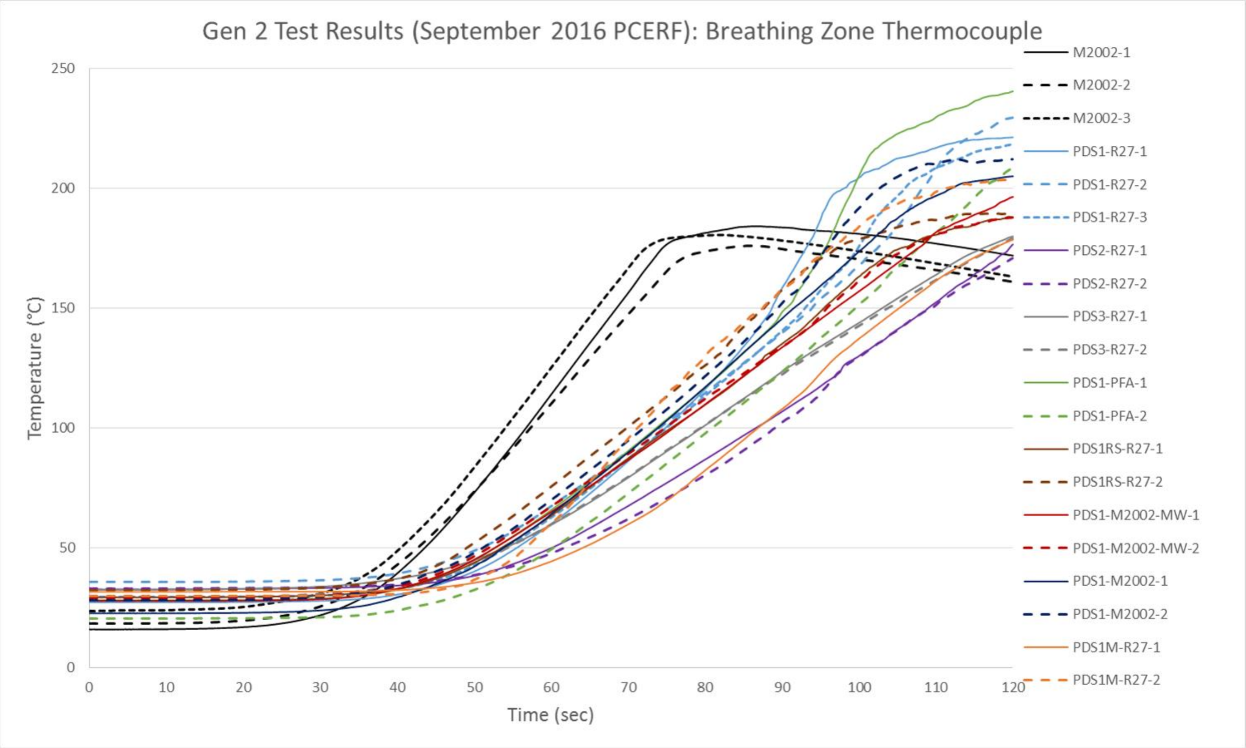


Figure 14. September 2016 PCERF Test Results Summary. *Breathing air temperatures are shown for all tested shelters. 150°C is considered by the USFS to be the maximum survivable breathing air temperature. Surprisingly, there was limited internal combustion and occurance was independent of seam design including the basic M2002 seam. On average, PDS1-M2002-MW shelters exhibited a 45% improvement in survival time at a 1% increase in mass, the PDS3-R27 shelters a 59% improvement in survival time at a 5% increase in mass, and the PDS2-R27 shelters a 72% improvement in survival time at a 14% increase in mass when compared to the M2002.*

VII. Conclusion and Future Work

After the tragic loss of 19 firefighters at the 2013 Yarnell Hill fire in Arizona, engineers at NASA Langley Research Center, experienced in the development of flexible thermal protection technology used on inflatable entry vehicles, sought to apply their expertise to the development of an emergency fire shelter better able to withstand direct exposure to flames. The effort took the form of NASA’s Convective Heating Improvement for Emergency Fire Shelters (CHIEFS) task. The primary target for CHIEFS was to produce an emergency fire shelter with a game changing improvement in convective (direct flame) resistance when compared to the existing M2002 fire shelter used by the US Forest Service. In order to succeed, CHIEFS shelters would need to keep within tight constraints. Gen 1 and Gen 2 fire shelters were developed which targeted thermal performance improvement with minimal increase in shelter packed volume, mass, cost, production of toxic or flammable thermal decomposition byproducts, and targeted a durable and easy to manufacture concept.

Gen 1 was the initial CHIEFS effort to develop and test a round of full scale fire shelter concepts. Fourteen fire shelters were tested at the full scale PCERF test facility in Edmonton in September of 2015. The CHIEFS designs tested were the M2002 geometry constructed using the lightweight layup (ML), the thermal pod geometry constructed using the mediumweight layup (TM), the thermal pod geometry constructed using the heavyweight layup (TH), and the M2002 geometry constructed using the heavyweight layup (MH). The M2002 was tested the baseline as well as the M2002 Silicone which is the same as the M2002 shelter in every way except that the adhesive used to fabricate the laminates was the same silicone based adhesive used on CHIEFS shelters rather than the water based adhesive. The M2002 geometry is the existing fire shelter shape issued by the USFS and the thermal pod is a novel CHIEFS design targeting the geometric efficiency of a sphere to achieve a design that uses about 20% less surface area than the M2002. Compared to the M2002, the CHIEFS Gen 1 ML shelter underperformed; however, the fairest comparison would be between Gen 1 shelters and the M2002 Silicone as the CHIEFS shelters were all fabricated using the silicone adhesive. Compared to the M2002 Silicone, the ML shelter provided a thermally habitable environment for a duration about 11% longer with 4% less mass and 17% less packed volume, and the TM shelter offered protection for about 116% longer with 3% less mass and about the same packed volume. Both the TH and MH shelter tests were terminated at 120 seconds, the maximum time the test rig can endure, well before the thermally habitable limit was reached.

Gen 2 shelters were developed as an effort to improve practical aspects of the shelter design and targeted the mediumweight volume and mass contraints. Materials which were too bulky, not durable enough, and produced undesirable thermal decomposition byproducts were removed from consideration. The thermal pod was removed following a survey conducted by the US Forest Service which indicated the design was unpopular with fire fighters. The MW shelter was introduced as an alternate design to the M2002 geometry. An alternate seam design, the R27, was introduced as an option to combat ingress of flammable gasses and decrease internal flashing and flames. 18 shelters were tested in September 2016 at PCERF in Edmonton, 3 M2002 shelters and 15 CHIEFS concepts. All shelters used the water based adhesive, and all shelters used the standard M2002 design except for 2 MW shelters. The baseline insulation was a fiberglass batting insulation known as UPF, and variations of the baseline unsulation configuration were tested including inserting a thin polymide film inside the layup. In general, thermal performance was decreased when compared with Gen 1 shelters; however, Gen 2 shelters were significantly more durable, manufacturable, and generally more ready for actual use in the field. On average, PDS1-M2002-MW shelters exhibited a 45% improvement in survival time at a 1% increase in mass, the PDS3-R27 shelters a 59% improvement in survival time at a 5% increase in mass, and the PDS2-R27 shelters a 72% improvement in survival time at a 14% increase in mass when compared to the M2002.

In future work, CHIEFS made use of lessons learned from Gen 2 shelter tests and implemented these changes into a new round of shelters tested at PCERF in April 2017. At the time of this writing, results are being analyzed and consequently these later tests are beyond the scope of this work. The lessons learned from Gen 2 tests include the following. First, there was no clear advantage observed in using the R27 seam; as a result, the simplest seam to manufacture, the M2002 was the only seam carried forward. Second, the use of the internal polymide film layer produced a deleterious thermal effect and was dropped from later designs. Finally, the M2002 gas barrier (PDS1M layup) tended to fail catastrophically relatively early on during the testing of both PDS1M-R27 shelters. After the PDS1M-R27 tests, the material properties were investigated and it was found that the UPF was in a more significantly and completely deteriorated condition than the PDS1-R27 or the PDS1RS-R27, likely a consequence of the aluminum gas barrier’s inability to shed heat via radiant energy into the shelter thus accelerating the warm up of the overall layup as well as the subsequent catastrophic delamination.

During Gen 2 testing, a strong irritating smoke was produced by the shelter decomposition. This was deemed unacceptable by the USFS. Further analysis showed the source of this irritant was the PTFE gas barrier which had been the baseline gas barrier material throughout Gen 1 and Gen 2 shelters. The only remaining gas barrier option for the then upcoming April tests was the existing M2002 gas barrier. The need to prevent the M2002 gas barrier delamination was made clear in Gen 2 testing. As a result, much effort after the September 2016 PCERF tests was committed to investigating alternate methods of manufacturing the M2002 gas barrier such that the catastrophic delamination does not occur. These efforts focused on either adhesiveless methods of bonding the aluminum foil to the underlying fiberglass fabric, or investigating alternate adhesives which can tolerate higher temperatures. This work is ongoing and at the time of this writing it seems likely that additional full scale testing will take place as the CHIEFS task continues to seek improved gas barrier integrity.

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John Morton-Aslanis and his team, under the direction of Dr. Roger Barker, at the North Carolina State University (NCSU) College of Textiles Thermal Protection Laboratory have generously offered their full-scale fire shelter test facilities to CHIEFS on multiple occasions. There has been a synergistic relationship between CHIEFS and the NCSU effort as Dr. Barker's team is also engaged in their own fire shelter development effort which is funded under the Federal Emergency Management Agency.

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