GRAFOAM® CARBON FOAM AS A MULTI-FUNCTIONAL CORE MATERIAL

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Abstract

"Multi-functional" composite materials that combine the property and performance advantages of several different materials, have become the preferred choice of engineers and designers. Multi-functional materials reduce the size, weight, complexity, and overall cost of a system or design. GrafTech International and its subsidiaries ("GrafTech") have developed a patent-pending carbon-based foam, which can meet this need for a multi-functional material. GRAFOAM® carbon foam has an open cell structure that can be produced in densities from 0.032 g/cm^3 (less than one-fourth the density of balsa wood) to 0.56 g/cm^3. Among its useful characteristics carbon foam demonstrates:

- *Light weight*
- *High strength*
- *Impact resistance*
- *Fire resistance*
- *Excellent thermal insulation*
- *Electromagnetic shielding*
- *Sound dampening*
- *Corrosion and rot resistance.*

There is a demonstrated range of improvements in properties of GRAFOAM® carbon foam sandwich panels when compared to balsa panels presently being used.

1 Introduction

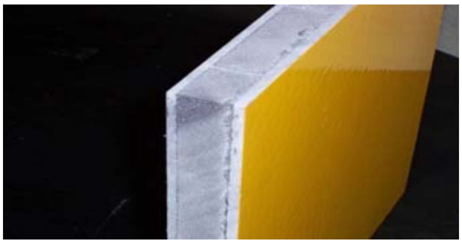
GrafTech has recently developed a breakthrough core material for composite structural panels utilizing our extensive experience in carbonaceous materials.

Using a proprietary new high temperature processing method, it is possible to manufacture large-size, cost-effective carbon foam blocks of excellent uniformity and quality. Figure 1 shows large-scale manufacture of carbon foam blocks. No other supplier of carbon foam has demonstrated the capability of producing blocks of this size in high volumes.

Figure 1: LARGE SCALE PRODUCTION OF GRAFOAM® PANELS

GrafTech has worked with partners to produce a multifunctional panel with attributes that can be engineered to provide a SafeTFoam™ panel solution for many needs.

Figure 2: SAFETFOAM™ PANEL



An extensive development and testing program has resulted in a revolutionary fire resistant multi-functional sandwich panel with attributes that can be tailored to a wide range of design requirements. Figure 2 shows one of the multi-functional panels resulting from this development effort. The carbon foam can be easily laminated with an extensive range of skin materials; the present work is focused on various fiberglass fire retardant laminates.

GrafTech's panels can be modified by changing web spacing, core thickness, fiberglass wrapping, and skin resin chemistry to produce a pre-determined set of properties for a panel. Mechanical strengths, fire resistance, shielding capabilities, and impact resistance are all controllable and predictable with models currently under development. Test panels have been produced with various reinforcement strategies in order to determine the operating envelope of strength, weight and cost.

2 Panel Development and Testing

2.1 Panel Development

Insulative carbon foams have been considered as a core material for composite panels for several years due to their multifunctional capabilities. Unlike other pitch or coal based carbon foams, insulative carbon foams are non-graphitizable with improved strength and low thermal conductivity. GRAFOAM® carbon foam is a further advance in this field based on the unique processing techniques employed and the wide range of densities (including densities ranging from 30 to 560 kg/m^3). GRAFOAM® is a registered trademark of UCAR Carbon Company, Inc. It also has a very uniform structure (within a block and from block to block) and a uniform cell structure. This leads to consistent and predictable mechanical and thermal properties. All of these attributes combined with scale of production have made GRAFOAM® carbon foam an attractive new core material.

GRAFOAM® carbon foam panels can be reinforced to meet the strength requirements needed in certain balsa wood applications. WebCore Technologies' (Miamisburg, OH) TYCOR® glass fiber wrapping process is used to produce the reinforced core panel as shown in Figure 3. Variables in the production process include web spacing, core thickness and fiberglass wrapping, to tailor the final panel properties.

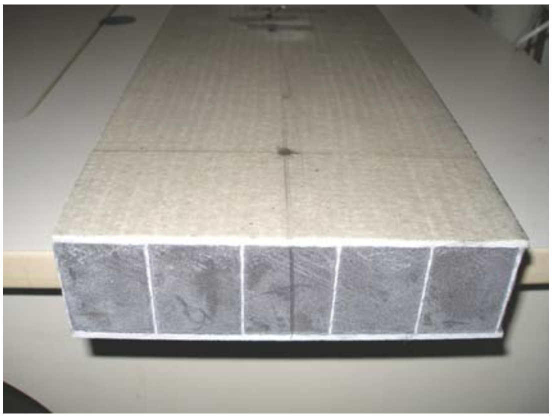


Figure 3: SAFETFOAM™ PANEL WITH WEB REINFORCEMENT

The foam material has been successfully processed as a core material by pultrusion, Vacuum Assisted Resin Transfer Molding (VARTM), and Fiber-Tech's (Washington Court House, OH) proprietary Wet Lay-up Vacuum Bag process (WLVB). Large panels with TYCOR reinforced carbon foam core have been produced via Fiber-Tech's process as shown in Figure 3. The panel product is marketed by the trade name - SafeTFoam™ panel. Panels of 2.5, 5.0 and 7.5 cm carbon foam core thicknesses can be produced. The resin used for the laminate is a proven fire resistant vinyl ester. These panels can be cost effectively produced in large sizes (up to 20 meters in length).

2.2 Panel Testing

GRAFOAM® carbon foam core materials have undergone an extensive testing program during the last 12 months, and this program continues as new applications are identified. Specific testing for each new application has been identified and completed. A series of mechanical tests have allowed GrafTech to characterize the SafeTFoam™ panel and to predict flexural, tensile, and shear strengths when modifying laminate, web, or core properties. Fire testing has been completed under various combustion conditions; again allowing prediction of fire and thermal performance. Also, a series of special tests (storm debris impact, EMI shielding, lightning protection, acoustic shielding and cyclic fatigue testing) characterizes our multi-functional capability. The optimum engineered panel can be produced for each application, meeting the customer's specifications at the right cost.

2.3 Panel Testing Results

A series of test results will be shown which illustrate the ability to characterize and predict panel performance based on the design. Figure 4, for instance, shows thermal and fire protection for a series of SafeTFoam™ panels of 3-inch core thickness relative to a standard 3-inch thick balsa wood panel with a similar laminate.

The balsa wood marine panel fails after prematurely under these fire conditions, whereas the carbon foam core panels continue to provide sustained fire protection.

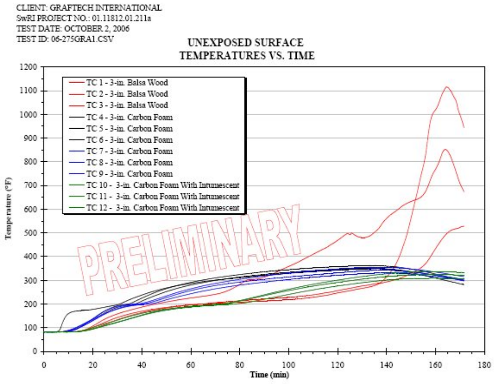


Figure 4: FIRE DATA

Other results show mechanical, impact, and acoustic properties relative to panel design. Most testing has been completed at Graftech's extensive R&D testing facility in Parma, Ohio; but other specialized testing has been completed at industry recognized testing facilities.

2.4 Fire Testing

GRAFOAM® carbon foam core materials panels are of extensive interest in the fire retardant market due to their capability to withstand sustained fire conditions at high temperatures. The carbon foam has been heat treated to temperatures in excess of 800°C in processing, and will not pyrolyze or sustain combustion at elevated temperatures. Unlike other sandwich panel core materials like balsa wood which break down into a char,

Figure 5: 7.5CM BALSA PANEL DESTROYED IN FIRE

the carbon foam will maintain it's structure with sustained thermal and fire protection. It will oxidize very slowly over time at temperatures above 300°C, but will not sustain combustion.

Figure 6: 7.5CM CARBON FOAM PANEL INTACT AFTER FIRE

Figure 4 is an illustrative example of a complete set of fire tests done at South West Research Institutes "Fire Technology Department Center" in San Antonio, Texas. Various fire tests were conducted to simulate fire-testing protocols in the small-horizontal test furnace. This is a 122 x 122cm furnace with capability to simulate ASTM E-119 and other standard fire conditions.

Figure 7: SWRI HORIZONTAL FIRE TEST FURNACE

Several fire test schedules were used to simulate different fire hazard conditions. One such schedule was used to simulate conditions currently being evaluated for mine safety shelters.

Table 1. Fire Test Schedule – Mine Shelter Application

Step	Time (min)	Temperature (°C)
1	15	1093
2	105	538
3	180	149

The schedule shown above has been proposed for mine safety shelter applications in the West Virginia coal mining industry, but no standard has been established as yet. Further changes in the standard can be modeled using the thermal information gained from these trials and the model discussed later in the paper.

It was shown that a 2.5 cm thick GRAFOAM® carbon foam composite panel (1.9 cm thick FPA-05 carbon foam core and 0.3 cm thick laminates on both sides with a web spacing of 3.8 cm) remains undamaged after experiencing these fire conditions. A comparable 7.5 cm thick balsa wood panel loaded in the same furnace under the same conditions completely charred and disintegrated (Figures 5 and 6).

Other fire testing, smoke development, flame spread, and non-combustibility testing trials were completed. These are summarized in Table 2. All the testing results demonstrate the sustained excellent fire protection of GRAFOAM® carbon foam. One example is illustrated by the cone calorimeter results at a Heat Release Rate (HRR) of 25 kW/m^2 in Figure 8, which show that the carbon foam does not contribute an exothermic heat flux due to burning. In addition, unlike most conventional polymeric cores, the carbon foam core does not emit toxic decomposition by-products. Similar results are obtained at Heat Release Rates (HRR) of 50 and 75 kW/m^2.

Figure 8: HEAT RELEASE RATE AT 25KW/M2

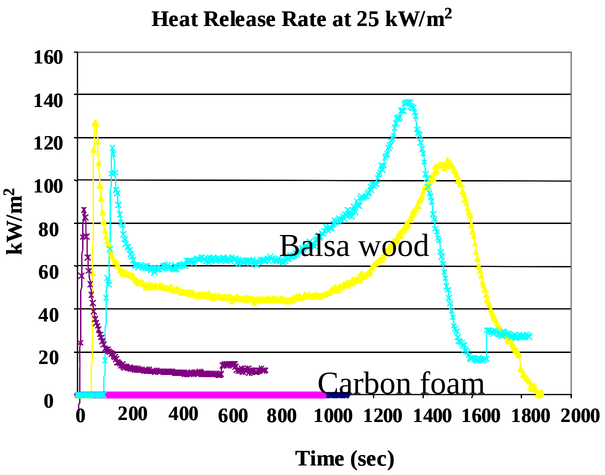


Table 2. Other Fire Testing Results

Test	Description	Result
ASTM E84	Flame Spread	0 - None
ASTM E84	Smoke Development	0 - None
ASTM E119	3.6 x 3.6m fire test 2000°C	Passed 4 hours
ISO 1182	Non-Combustibility	Classified non-combustible
Cone Calorimeter	Heat release rate at 25, 50 and 75 kW/m^2	Carbon foam 0 both cases (no exothermal)

2.6 Acoustic Testing

Carbon foam sound transmission, sound reduction, and sound absorption characteristics were also studied. Two testing programs were undertaken as described in Table 3.

Table 3. Acoustic testing results

Test	Description	Results
ASTM E90	Sound transmission Class	STC 42 (reduces transmission by 42dB)
ASTM C423	Noise reduction class	NRC 0.30; SAA 0.32 Classified as a sound absorber
Impedence tubes (10cm)	0-1600 Hz	Controlled by adding porosity
Impedence tubes 92.85cm)	500-6400 Hz	Controlled by adding porosity

There were two impedance tube setups: the large one was 10 cm in diameter and had a frequency range of 0-1600 Hz; and the smaller one was 2.85 cm in diameter and 500-6,400 Hz frequency range. Grades FPA-02, FPA-05, FPA-10, FPA-15 and

FPA-20 carbon foams of two thicknesses each were tested. The foam shows high transmission loss (between about -60 and about -20dB at the 100 to 1,600 Hz range). However, the absorption coefficient is between 0.1 and 0.2 at frequency around 6,400 Hz. The rigidity of carbon foam and its "closed" cell structure help explain the result. In order to further examine how the absorption coefficient is affected by open porosity on the surface of the carbon foam, 1 mm-diameter by 7 mm deep holes are introduced to the foam surface. Seven, 13, 25 and 37 holes were drilled on one face of the surface of FPA-10 carbon foam samples that introduced additional 0.9, 1.6, 3.0 and 4.6% porosity, respectively. The added open porosity was shown to drastically increase the absorption coefficient of the foam material. These results suggest that a desirable sound absorption effectiveness level can be designed into the foam material.

A second series of ASTM tests were conducted on a 10.16cm thick carbon foam panel. These measured the noise reduction in decibels and sound absorption coefficient of the material. The panel was demonstrated to have a 42dB reduction and acted as a sound absorber. The results indicated that acoustic shielding is another component of this material.

2.7 Electro-Magnetic (EM) Shielding

Grades FPA-02, 10, and 20 carbon foam samples of 6 to 25 mm thickness were subjected to the electro-magnetic wave with frequencies ranging from 100 to 3,000 MHz. Average values of the EM reflection and transmission coefficients over the frequency range were measured and percentage absorption calculated. For both the carbon foam Grades FPA-10 and 20 of various thicknesses, EM shielding is excellent, as indicated by the fact that the EM transmission is zero. Slight EM transmission for some FPA-10 tests are attributed to test errors due to sample fit. Low EM transmission (0.3-3.3%) is observed for FPA-02, primarily due to its highly porous nature having an approximate 98.5% porosity. Because the foam material is electrically conductive, the EM reflection is high for FPA-10 and 20. More EM wave penetration into the less dense, higher resistance FPA-02 foam allows more EM absorption. Further development is planned to engineer GRAFOAM® carbon foam to be a non-reflective absorber for applications requiring a low radar signature.

2.8 Mechanical Strength Testing

A series of flexural strength tests were conducted at GrafTech according to ASTM C 393 mid-span loading test method using 20.3 cm by 61.0 cm FPA-05 carbon foam panel specimens (3.8 cm web spacing) and the results are summarized in Tables 4, 5 and 6. Compared to pultruded balsa wood panels, the nominal 7.6 cm thick carbon foam panel shows a comparable flexural strength and also provides a 30% weight reduction.

Table 4. Flexural Strength Test Results – 2.5cm thick panels

Core Material	Description	Area Weight (kg/m^2)	Average Flexural Strength (MPa)
FPA-05 foam (80 kg/m^3)	3.2 cm thickness (2.5 cm thick carbon foam core & 0.3 cm thick laminates on both side)	22.5	34.2
Balsa wood (196 kg/m^3)	2.5 cm thickness (1.9 cm thick balsa wood core & 0.3 cm thick laminates on both sizes); pultruded	16.1	7.8

Table 5. Flexural Strength Test Results – 5.1cm thick panels

Core Material	Description	Area Weight (kg/m^2)	Average Flexural Strength (MPa)
FPA-05 foam (80 kg/m^3)	5.7 cm thickness (5.1 cm thick carbon foam core & 0.3 cm thick laminates on both side)	24.9	14.4

Table 6. Flexural Strength Test Results – 7.6cm thick panels

Core Material	Description	Area Weight (kg/m^2)	Average Flexural Strength (MPa)
FPA-05 foam (80 kg/m^3)	8.3 cm thickness (7.6 cm thick carbon foam core & 0.3 cm thick laminates on both side)	28.8	Test in progress
Balsa wood (302 kg/m^3)	8.9 cm thickness (7.6 cm thick balsa wood core & 0.65 cm thick laminates on both sizes); pultruded	40.1	6.5

A series of ASTM C297 (Flatwise tensile strength of sandwich constructions) and ASTM C273 (Shear properties of sandwich core materials) tests were also completed on the 2.54, 5.08, and 7.6 cm panels. These results are summarized in Table 7.

Table 7. Flatwise Tensile and Core Shear Stress Test Results – 2.54, 5.08 and 7.6cm thick panels

Panel Thickness (cm)	Flatwise Tensile (M Pa)	Core Shear Stress (longitudinal rib) (M Pa)	Core Shear Stress (transverse rib) (M Pa)
2.54	0.98	1.10	0.26
5.08	0.73	0.96	0.23
7.62	0.73	0.83	0.20

2.9 Lightning Testing

A preliminary series of lightning tests have been conducted under a European Union (EU) lightning materials program in the United Kingdom at Culham Lightning Center in Culham Oxfordshire. A lightning strike is typically a high amplitude direct-current pulse with a well-defined waveform. The pulse can be divided into four components. They can be categorized as shown in Table 4 below.

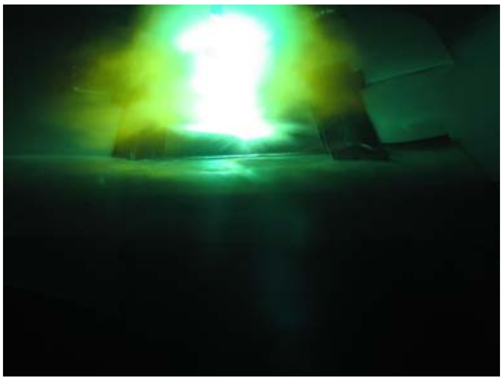


Figure 9: CARBON FOAM DURING 200000 AMP LIGHTNING STRIKE

The tests were conducted by a series of partners in the composites field who are interested in studying new and innovative materials with possible applications in the aerospace or marine fields. Preliminary testing was conducted on GRAFOAM® carbon foam by itself to determine how it would withstand high pulse – short duration (type A/D) lightning discharges as well as longer duration – lower amperage (type B/C) sustained discharges. Results are summarized in Table 8 below.

Table 8. Lightning Strike Test Results – 55x55x1cm panels

Strike Type	Description	Time	Current	Carbon Foam Result
A	Initial Strike	200usec	200000 A	Pass
B	Intermediate current	~200usec	11000A	Pass
C	Continuing current	0.75sec	900A	Pass
D	Restrike	200usec	100000 A	Pass

The foam would normally be constrained within a sandwich structure with a conductive laminate (such as an electrically conductive skin like a carbon fiber laminate). These preliminary tests showed that carbon foam has no difficulty in absorbing and dissipating the high pulse (short duration) or low pulse (long duration) strikes. There was no thermal damage to the foam.

Figure 10: CARBON FOAM AFTER 100000 AMP LIGHTNING STRIKE

2.10 Impact Absorption

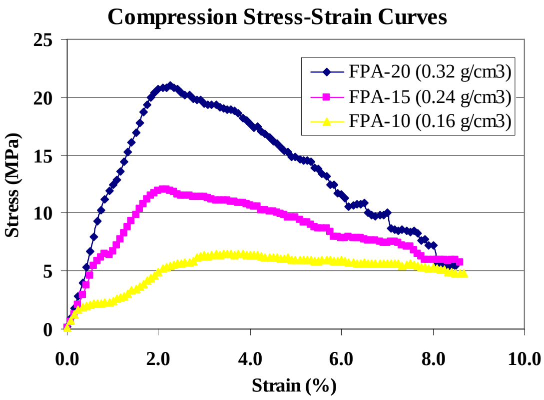


Figure 11: NON-CONSTRAINED COMPRESSIVE STRESS-STRAIN CURVES

The compressive strength of carbon foam increases with density, ranging from 6 MPa for 160 kg/m^3 up to 60 MPa for 560 kg/m^3. Although the carbon foam is rigid, it provides an impact adsorption capacity under a compression load. Figure 11 shows the non-constrained compressive stress-strain test results for Grades FPA-10, 15 and 20, of densities 0.16, 0.24 and 0.32 g/cm^3, respectively. All of the carbon foam grades have a plateau after reaching the maximum stress level at approximately 3% strain. These plateaus range from 6 to 10 to 15 MPa for Grades FPA-10, 15 and 20 respectively.

The crushing behavior of the carbon foam suggests progressive collapse of the foam cells up to a 60%-plus strain rate. Development efforts are in progress to produce carbon foam panels to take advantage of this property.

Figure 12: STORM DEBRIS IMPACT TESTING OF CARBON FOAM AT TEXAS TECH

Impact tests were conducted on 2.5 cm thick, 122 cm by 122 cm carbon foam sandwich panels (1.9 cm thick FPA-05 carbon foam core and 0.3 cm thick laminates on both sides with a web spacing of 6.4 cm) at the Texas Tech University Wind Research Center (Lubbock, TX). The testing is for simulated windborne debris. The primary simulations are impacts of a 5 cm x 10 cm cross-section wood board traveling along the board's longitudinal axis, striking the test subject perpendicular to the test subject face.

Table 9. Storm Impact testing Results – Texas Tech 122 x 122 x 2.5cm panel

Description	Projectile	Projectile Speed (mph)	Impact Force (ft-lbs)	Result
Hurricane envelope	Wood 5.1 x 10.2cm (4.1 kg)	34	350	Pass
Hurricane shelter (low speed)	Wood 5.1 x 10.2cm (6.8 kg)	66	2180	Pass
Hurricane shelter (high speed)	Wood 5.1 x 10.2cm (6.8 kg)	80	3200	Pass
Tornado	Wood 5.1 x 10.2cm (6.8 kg)	100 (= wind speed 250mph)	4964	Pass
> Tornado	Wood 5.1 x 10.2cm (6.8 kg)	125 (= wind speed >300mph)	7757	Pass

The hurricane test criterion for property protection uses a 4.1 kg 5 cm × 10 cm wood board projectiles, traveling horizontally at 54.4 km/hr (34 mph), which corresponds to a wind speed of 176-240 km/hr (110-150 mph). The tornado test criterion uses a 6.8 kg (15 pound) 5 cm × 10 cm wood board traveling horizontally at 160 km/hr (100 mph), which corresponds to a wind speed of 400 km/hr (250 mph). This is the criterion used in designing vertical surfaces for occupant protection.

The carbon foam sandwich panel passed all these tests, and also sustain projectiles in winds >300mph with the 6.8 kg (15 pound) projectile speed at 200 km/hr (125 mph).

Based on these results there is further interest in using carbon foam as a potential ballistic and blast panel; where constrained carbon foam would absorb blast and projectile energy behind an engineered strike plate. The carbon foam would also provide sustained thermal and fire protection in such an application. Testing work to evaluate this concept is presently underway.

2.11 Fatigue Testing

Cyclic fatigue test was conducted at West Virginia University (Morgantown, WV) on 2.5 cm thick carbon foam composite panels (1.9 cm thick FPA-05 carbon foam core and 0.3 cm thick laminates on both sides with a web spacing of 6.4 cm). Twenty (20) cm wide panel samples were subjected to 50,000 test cycles with the displacement range being about 30% of its ultimate value which roughly translates into ~30% of ultimate load since the specimen had nearly a linear straight line to failure. The carbon foam composite panels withstood this fatigue test without degradation. Although slight cracks in the carbon foam cells are noted, but there is no excessive cracking that could have led to compromise of the carbon foam cell structure integration.

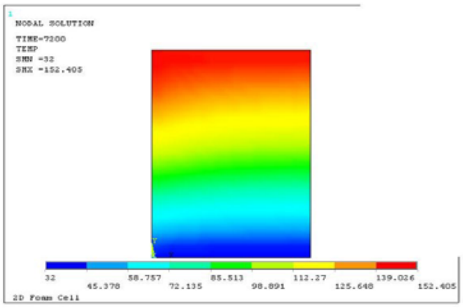
A second set of fatigue tests was conducted on FPA-10, 15 and 20 at 50 and 90% UTS levels by Tensile Testing Metallurgical Labs (Cleveland, OH) under the ASTM E 466 test standard. Up to 648,000 cycles were completed (30 Hz for 6 hours) on each specimen; no material failure was observed. These test results address common concerns about whether the rigid carbon foam can sustain cyclic load conditions. This is particularly important in the marine and aerospace industry where high fatigue applications are commonplace.

3 Modeling

3.1 Panel simulation

Finally, a series of computer models and engineering curves are being developed which use the test results to allow us to predict performance. Various finite element and static models have been used to understand performance. These models have been revised based on specific test results to ensure accuracy. Figure 13 shows typical thermal output from one model for a 2-inch thick panel.

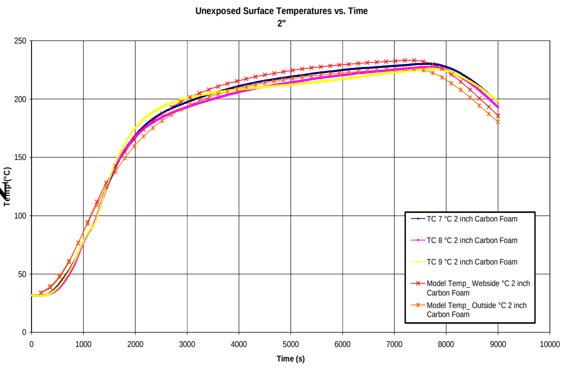
Figure 13: THERMAL MODEL OUTPUT



3.2 Model Tuning

The model predicts the thermal performance of a sandwich panel with carbon foam cores and various laminates, thereby enabling simulation-driven design to tune a product for a variety of applications. A commercial finite element method package was used to simulate the heat transferred through a panel consisting of fiberglass reinforced plastic skins and webs with a carbon foam core. The first test for the model was to design panels for a mine safe house capable of withstanding an initial blast of 50 psi and the predicted temperature profile that would follow such an explosion. The thickness of the carbon foam and fiberglass skin, as well as the spacing of the fiberglass webs were optimized to prevent the temperature inside the safe house from climbing above 90° F, ensuring the safe rescue of the trapped mine workers.

Figure 14: THERMAL MODEL CORRELATION TO ACTUAL TEMPERATURE DATA



The advantages of employing simulation-driven design are the time and cost savings awarded to the panel designer due to the ability to quickly test how altering materials and environmental conditions affect results. The accuracy of the model's predicted temperatures was confirmed using empirical data from a third party testing facility. Figure 14 shows actual time-temperature data for a 2.5cm SafeTFoam™ panel under ASTM E-119 fire conditions. The actual thermal performance of the composite panel was then analyzed and used to tune the panel model.

Using this data, maximum heat fluxes of the mine shelter under various fire conditions could be calculated. These are shown in Table 10.

Table 10. Maximum heat fluxes for Mine Shelter (various fire conditions)

Description	Max Heat Flux (1" wall) W/m2	Max Heat Flux (2" wall) W/m2
1093° C for 15 min, 538° C for 15 min, 204° C for 2 hrs	2233	928
204° C for 4 hrs, 27° C for 24 hrs	575	322
27° C for 3 days	575	322
538° C for 15 min, 204° C for 3 days	1344	549

Various thickness panels, web spacing, and laminates were then studied to optimize the recommended panel for the application. The most cost effective solution to provide the required fire protection coupled with the necessary blast and mechanical stress load could be predicted. The model will be an integral part of the SafeTFoam™ multifunctional panel package – providing the ability to engineer an optimized panel for all applications.

4 Applications

Wide ranges of applications have been identified for carbon foam. GrafTech has evaluated GRAFOAM carbon foam in three main application areas to date

- Tooling
- Multifunctional Core Material (sandwich panels)
- High temperature furnace parts

New applications are constantly being identified for carbon foam, and further extensive testing is underway to qualify the material for these uses. Recent applications that have been identified are:

- Abrasive material applications
- Acoustic shielding panels
- Filtration
- Electrochemical applications
- Fuel cells
- Marine joiner panels (bulkheads etc)
- Medical parts
- Metallurgical applications
- Military or emergency service protective clothing
- Vacuum insulating panels
- Lightning protection
- X Ray tables

New applications will continue to be identified which will utilize the unique and varied properties of this exciting new material.

5 Conclusions

GrafTech has developed a true multifunctional composite sandwich panel with the capability to engineer and predict performance for specific applications. Extensive development and testing has qualified GRAFOAM® carbon foam for a variety of core applications in sandwich panels. As civilian and military marketplaces continue to demand new materials with exacting thermal and fire resistance properties, carbon foam will be an attractive solution. There will be obvious weight savings in many applications as designers try to combine fire protection with other attributes in one composite panel.

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