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14. ABSTRACT
This research aims to develop, analyze, and evaluate a new type of structural element that will enhance the crashworthiness of naval vehicles by providing outstanding energy absorption with minimal weight. The structural element is an array of concentric fiber reinforced flexible matrix composite tubes with extension- twist coupling and ultra-high Poisson's ratio. The tubes are configured to crush or shear internal foam as a means of absorbing energy. This interim report includes technical progress, plans, publications, and various administrative matters. In the current period, work has focused on evaluating the deformation behavior of foams and flexible matrix composites designed to crush foam as an energy absorbing mechanism during tensile loading.

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1. Overview of Project

The proposed research aims to develop, analyze, and evaluate a new type of structural element that will enhance the crashworthiness of naval vehicles including fixed wing and rotary wing aircraft, land vehicles, and littoral vehicles by providing outstanding energy absorption (EA) with minimal weight. The envisioned structural element is an array of concentric fiber reinforced composite tubes with extension-twist coupling and ultra-high Poisson's ratio. The tubes are joined with threads and/or lightweight closed-cell core materials which fracture and crush as tensile force is applied to the tubes. By combining multiple energy dissipation mechanisms, the specific energy absorption (SEA) of the structural element will be maximized and, after iterations based on experimentation and analysis, is expected to be superior to current energy absorbing structural elements. Little is known about the various mechanisms of energy absorption in this type of structural element and how these mechanisms interact with each other to govern the overall performance in a crash event. This project aims to devise methods of fabricating the novel energy absorbing tubes, analyze the operative mechanisms of energy absorption and their interaction, select materials and configurations for the best performance, test the tubes at stroke rates resembling those likely to be encountered in nominally survivable crashes of naval vehicles, develop mechanism-based analytical models of EA behavior using experiments as guidance, evaluate environmental durability, and validate/improve the analytical models using experimental data. Upon completion of the proposed basic research program, a new class of energy absorbing material for improved crashworthiness of naval vehicles will be demonstrated, the behavior of this type of material will be better understood through validated analysis methods developed over the course of the work, and data and analytical tools will be available for advancing the technology to the stage of practical development. In the long run, this research may benefit the needs of the US Navy by exploring means of improving the safety of vehicles and saving the lives of Navy personnel involved in crashes.

The approach is organized into three tasks:
- Task 1. Evaluate mechanisms of energy absorption.
- Task 2. Develop analytical models for the observed deformation and damage mechanisms.
- Task 3. Validate and improve the models with a comprehensive set of experiments encompassing loading and environmental conditions encountered by the Navy.

2. Summary of Activity

In the current reporting period, major progress has been made in Tasks 1 and 2. This progress is outlined below.

2.1. Task 1 - Evaluate mechanisms of energy absorption

Experiments were conducted in order to evaluate the energy absorbing mechanisms of foam-filled composite tubes. Two types of foam-filled flexible matrix composite (FMC) tubes were investigated:

- A balanced $\pm\theta$ angle-ply FMC tube which, due to a high Poisson's ratio, undergoes a large transverse contraction as tension is applied longitudinally. This device is denoted *crush tube*. As tension is applied, the tube contacts and exerts radial compression on foam

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situated in its interior region. Energy is dissipated by crushing the foam and damaging the tube.

- A pair of concentric off-axis unidirectional FMC tubes that have extension-twist coupling of mutually opposite sign and foam placed in the thin annular gap between the two tubes, denoted *sandwich core device*. During longitudinal tension, these tubes twist in opposite directions and exert shear stress onto the annular foam. Energy is dissipated by shear-failing the foam (by fracture or plastic deformation) and damaging the tubes.

2.1.1. Crush Tubes

Manufacturing methods and some test results for the FMC crush tubes and polyurethane foam filler were reported in the Dec. 2009 report. In this reporting period, a comprehensive set of mechanical property data was obtained for foams of various densities so that an analytical model for predicting force-stroke characteristics of a crush-tube device containing such a range of foams can be validated.

Figure 1 shows representative uniaxial compressive stress-strain curves for polyurethane closed-cell foams of three different densities. Multiple specimens of each type have been tested to ensure meaningful results. Material properties measured for individual tests are shown in Tables 1,2, and 3 for 48, 128, and 240 kg/m^3 foam densities, respectively.
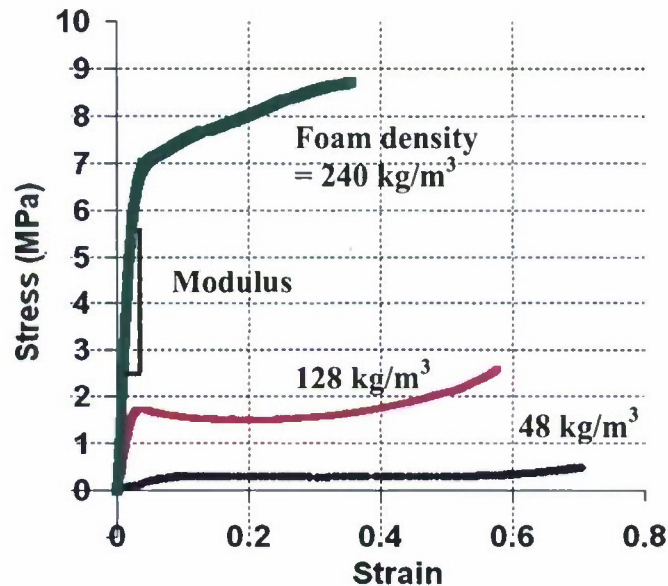

Figure 1. Typical uniaxial compressive stress-strain curves for polyurethane foams

Table 1. Mechanical properties of 48 kg/m³ polyurethane foam, from uniaxial crush tests.

	10-1	16-3	24-1	24-3	U2	Average	Std. Dev.
Crush stress, MPa	0.264	0.291	0.312	0.313	0.3	0.30	0.02
Elastic modulus, MPa	9.53	7.6	9.3	11.1	7.35	9.0	1.54
Poisson's ratio	N/A	0.1506	0.2073	0.155	N/A	0.171	0.03
Full compaction strain, m/m	0.52	N/A	N/A	N/A	N/A	0.52	N/A

Table 2. Mechanical properties of 128 kg/m³ polyurethane foam, from uniaxial crush tests.

	U5	L5	U7	L7	8PR1	8PR2	8PR3	8PR4	8FC1	8FC2	Average	Std. Dev.
Crush stress, MPa	1.22	1.16	1.46	1.30	1.48	1.52	1.39	1.41	1.6	1.5	1.40	0.14
Elastic modulus, MPa	36.0	39.2	49.1	41.7	31.2	65.7	60.7	68.6	83	70.5	54.6	17.46
Poisson's ratio	N/A	N/A	N/A	N/A	0.1894	0.1751	0.2106	0.3207	N/A	N/A	0.224	0.07
Full compaction strain, m/m	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.30	0.30	N/A

Table 3. Mechanical properties of 240 kg/m³ polyurethane foam, from uniaxial crush tests.

	15PR1	15PR2	15PR3	15PR4	Average	Std. Dev.
Crush stress, MPa	7.76	8.5	8.28	7.85	8.10	0.304
Elastic modulus, MPa	257.2	321.7	301.7	317.4	299.5	25.531
Poisson's ratio	0.2158	0.3211	0.259	0.1985	0.249	0.047
Full compaction strain, m/m	0.25	N/A	N/A	N/A	0.25	N/A

In the current reporting period, additional crush tubes of ±30, ±35, ±45, and ±60 deg. fiber angles were tested. These were made with AS4D/L100-C21 FMC tubes and polyurethane foams of 48 and 128 kg/m³ density. Tensile force-displacement characteristics were measured for the tubes based on a 25.4-mm-long gage length, which was shorter than the actual gage length of the specimen. The area under the force-displacement curve gives the energy absorbed by the device. Specific energy absorption (SEA) and volumetric energy absorption (VEA) were calculated up till the displacement that fully compacted the foam. SEA is found by dividing the absorbed energy by the mass of the 25.4-mm-long tube gage section, whereas VEA is found by dividing by the volume enclosed by the gage section including the space occupied by the foam inside it.

Force-displacement curves for crush tubes with different ply orientations are plotted in Figs. 2 and 3, while the numerical results are summarized in Table 4. It can be seen that a ±60 deg. tube exhibits highest specific energy absorption (SEA) and volumetric energy absorption (VEA) among the devices tested. It can also be deduced from Table 4 that, with an increase in density of foam, the SEA and VEA for a particular fiber orientation decrease. This decrease is largely attributed to the fact that the full compaction strain decreases with the increase in foam density—thus decreasing the energy absorbing stroke of the device. Therefore, the devices pose an interesting optimization problem depending upon the design and operational constraints specified by Navy.
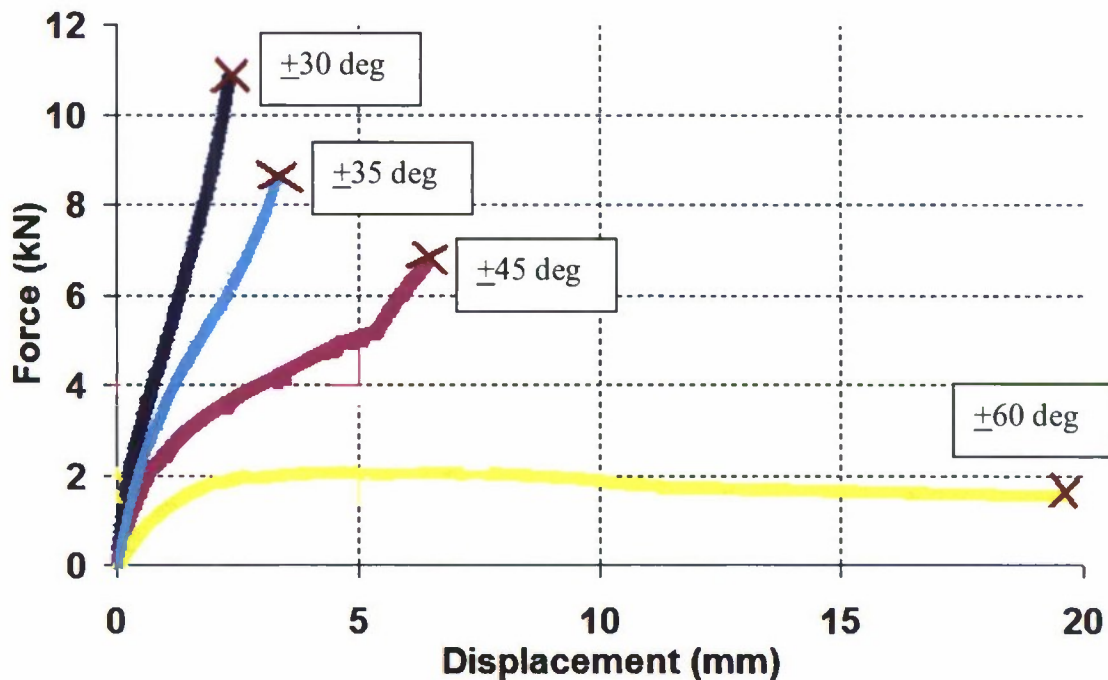

Figure 2. Typical force-displacement curves for FMC crush tubes with 48 kg/m^3 foam and various fiber angles. Tube thickness = 1.14 mm, radius = 1.05 cm, gage length = 2.54 cm. "X" indicates full compaction of foam.
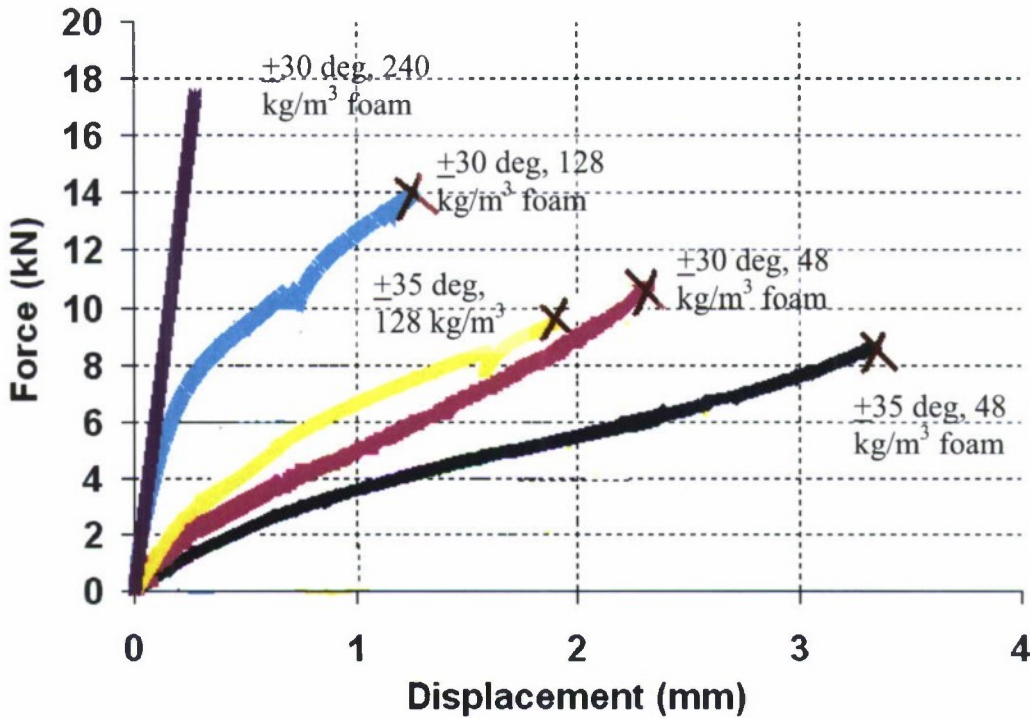
Figure 3. Typical force-displacement curves for FMC crush tubes with various fiber angles and foam densities. Tube thickness = 1.14 mm, radius = 1.05 cm, gage length = 2.54 cm. "X" indicates full compaction of foam.

Table 4. Specific energy absorption (SEA), volumetric energy absorption (VEA), and full compaction strain of FMC crush tube devices with two different foam densities in the core.

Tube Layup	48 kg/m^3			128 kg/m^3		
	SEA (J/g)	VEA (MPa)	Full comp. strain	SEA (J/g)	VEA (MPa)	Full comp. strain
± 30 deg	4.5	1.34	0.092	2.76	0.89	0.053
± 35 deg	6.31	1.92	0.132	3.7	1.17	0.076
± 45 deg	8.4	2.57	0.262	N/A	N/A	0.153
± 60 deg	12.2	3.86	0.781	N/A	N/A	0.453

2.1.2. Sandwich Core Device

The main activities on sandwich cores devices during this reporting period were aimed at characterization of shear strengths of sandwich foams of various densities using an in-house designed shear test apparatus. The shear strength is necessary to model the behavior of twist-extension-coupled FMC tubes with sandwich foam between the concentric tubes. The foams used were two kinds of polyurethane foam (FOAM iT, Smooth On Inc., Easton, PA) with mass

densities of 48 kg/m^3 (3 lb/ft^3) and 128 kg/m^3 (8 lb/ft^3) and a polyvinyl chloride (PVC) foam (DivinyCell, Diab Group International) with mass density of 80 kg/m^3. The polyurethane foams are the pourable, self-expanding type that cure in about two hours at room temperature. The PVC foam is purchased in pre-formed sheets.

The shear test specimen involved a rectangular foam specimen (61 mm x 50 mm x 5 mm) bonded with Lord 7650 urethane adhesive (Lord Corp, Cary, NC) on both faces to pre-cured unidirectional AS4/L100-C21 FMC laminas of similar planar dimensions. The FMC/foam sandwich specimen is bonded to two rectangular steel plates using a room-temperature curing epoxy adhesive (Devcon Plastic Welder) so that the assembly can be loaded with a universal testing machine. The specimen is shown in Fig. 4. The specimen is designed in accordance with ASTM C 273/C 273M, Standard Test Method for Shear Properties of Sandwich Core Materials (ASTM, C 273/C 273M, 2007).

Figure 4. Shear test fixture and foam specimen

As tensile load is applied to the plates as shown in Figs. 5 and 6, a mode II type shear failure is induced in the specimen. Failure may be in the foam, in the FMC, or at either the foam/FMC or FMC/steel interface. The last failure mode is not desired, however, since our interest is in the shear strength of the foam or the foam/FMC interface.

Figure 5. Test Fixture: Front

Figure 6. Test Fixture: Back

The shear stress-strain response of a typical specimen is shown in Fig. 7. Included in this graph is a 48 kg/m^3 polyurethane foam specimen tested in the as-cured condition and another tested following thermal aging. Due to the significant effect of aging, as we noted in the Dec. 2009 report with the same foam material tested in compression, aged properties for all the foams will be used henceforth. The peak in the curve corresponds to the point where foam begins to fracture. The shear modulus is found by fitting a straight line in the 0.2%-0.6% shear strain range. Figures 8 and 9 show the shear stress versus shear strain curves for 128 kg/m^3 polyurethane foam and 80 kg/m^3 PVC foam, respectively. The former result is contaminated with electrical noise on account of the low strains to failure. Material parameters obtained from shear tests are summarized in Table 5.
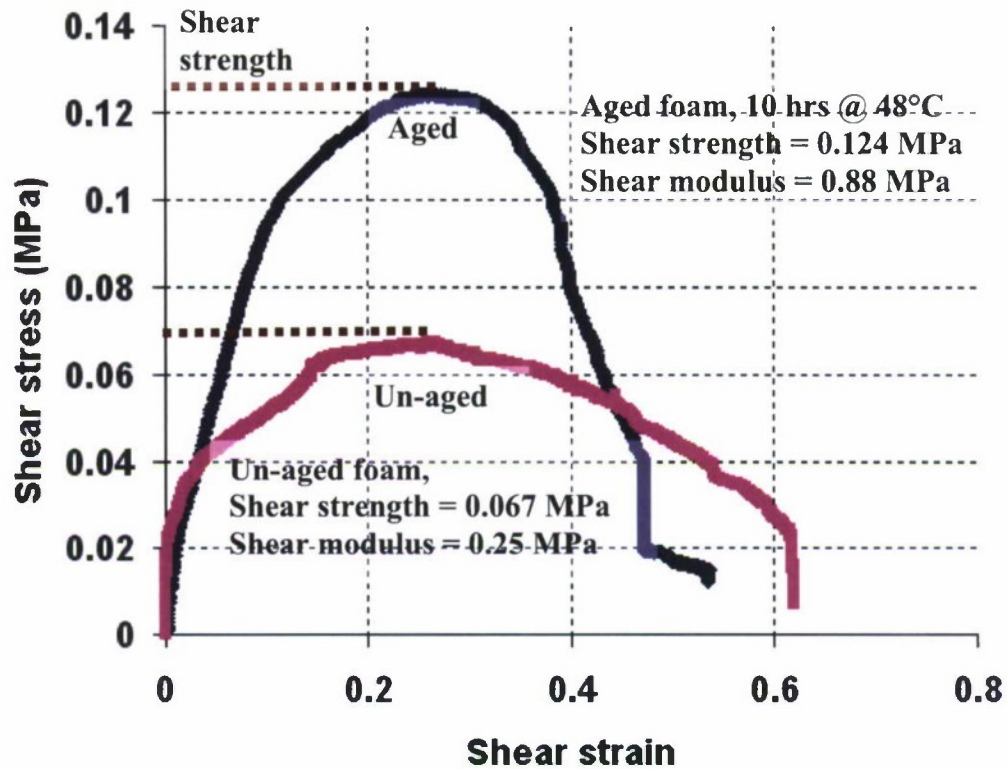
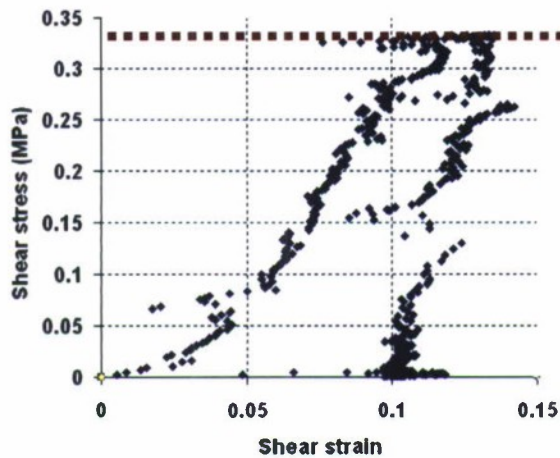Figure 7. Shear stress vs .shear strain curves of a 48 kg/m^3 polyurethane foam

Figure 8. Shear stress vs. shear strain curves of
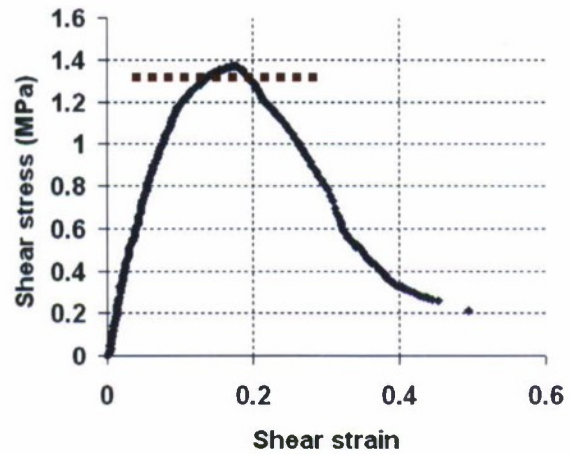a 128 kg/m^3 polyurethane foam

Figure 9. Shear stress vs. shear strain curves of
an 80 kg/m^3 PVC foam

Table 5. Shear properties of sandwich foams

	48 kg/m^3 polyurethane	128 kg/m^3 polyurethane	80 kg/m^3 PVC
Shear modulus (MPa)	0.88 MPa	3.89 MPa	16.78 MPa
Shear strength (MPa)	0.124 MPa	0.332 MPa	1.37 MPa

2.2. Task 2 - Develop analytical models for the observed deformation and damage mechanisms

Based upon the experimental findings a non linear analytical model is being developed. The foundations of the model is found in the work by Adkins and Rivlin (1952), who worked on large elastic deformations of thin shells, Hart-Smith and Crisp (1967), who studied the kinematics and deformations of thin rubber membranes, and Shan, Bakis et al. (2006), who used a nonlinear strain energy formulation to analyze nonlinear-elastic finite axisymmetric deformation of flexible matrix composite membranes. The modified strain energy formulation developed based on these publications is shown in Eq. 1.

$$W = \frac{1}{2}Q_{11}\varepsilon_{11}^2 + \frac{1}{2}Q_{22}\varepsilon_{22}^2 + 2Q_{66}\varepsilon_{12}^2 + Q_{12}\varepsilon_{11}\varepsilon_{22} +$$
$$\frac{1}{3}Q_{111}\varepsilon_{11}^3 + \frac{1}{4}Q_{1111}\varepsilon_{11}^4 + \frac{1}{3}Q_{222}\varepsilon_{22}^3 + \frac{1}{4}Q_{2222}\varepsilon_{22}^4 + \sum_{n=1}^{m}\frac{2^n}{n}Q_{666n}\varepsilon_{12}^n \tag{1}$$

In Eq. 1, the terms in the top row are linear terms that are evaluated from lamina tests. The terms in the second row are the nonlinear terms which need to be evaluated using crush tube force-displacement data like that shown in Figs 2 and 3. It was found that the number of nonlinear terms in the summation term of Eq. (1) needed to match the experimental results varied with fiber orientation of the crush tubes. The parameters obtained for one case were not applicable for all angle-ply laminates. Further development of the model is underway to better match the experimental results. It is suspected that a strain-energy-based formulation may not be sufficient to predict the entire force-displacement curve because of damage occurring in the tube in the stroke range of interest. Currently, the onset of this damage is being predicted using conventional lamina failure theories (Tsai-Wu, maximum stress, etc.).

3. Plans for Next Reporting Period (1 Jun. – Aug 30, 2010)

Task 1
- Fabricate and test sandwich core specimens with thicker tube walls to enable shearing of the foam before tube wall failure. This may require re-designed grips.

Task 2
- Continue to refine the analytical model for crush tubes based upon experimental findings.
- Begin to model the mechanism of energy absorption in a sandwich core tube device using experimental results.

Task 3
- No activity scheduled or planned.

4. Project Schedule and Milestones

Task	2009 Q3	4	2010 1	2	3	4	2011 1	2	3	4	2012 1	2
1. Mechanisms	-----------	----------										
2. Analysis					----------	----------						
3. Validation									----------	--------		
4. Report		*		*	*	*		*	*	*		†

*Reporting milestone; † Final report.

5. Budget Information

Budget information has been compiled through the end of May 2010. The total budget is $285K. Rounding errors prevent the numbers below from being completely self consistent.

Recv'd from ONR to-date	Planned expenditures to-date	Actual expenditures to-date	Balance
$124K	$95K	$70K	$55K

6. Upcoming Events

None

7. Publications and Patents

None

8. Presentations & Interactions

We are discussing the merits of various foam cores with industry representatives. Dr. Gordon Kahle, Principal Research Scientist, Cytec Engineered Materials, Olean, NY, is working with us in formulating polyurethanes of various stiffnesses for potential use in making FMC tubes by filament winding.

9. Degrees Awarded

Mr. Todd Henry, an undergraduate researcher working on this project, finished his B.S. degree in Aerospace Engineering and will be continuing his graduate education in the same department.

10. Cited References

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