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Multipurpose Spall Protective, Energy Absorbing Hybridsil® Materials for Military Vehicle Interiors

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ABSTRACT

Through Army SBIR funding, NanoSonic has designed a next-generation multipurpose Spall Protective, Energy Absorbing (SPEA™) HybridSil® material that has the potential to provide vehicle occupants with pioneering combinatorial protection from 1) fragmentation behind-armor debris (BAD), 2) high velocity head / neck impact, and 3) fire during underbody blast, crash, and rollover events. This innovative multilayered ensemble consists of highly flame resistant, energy absorbing polyorganosiloxane foams, molded ultrahigh molecular weight polyethylene panels, and carbon fiber reinforced polymer derived ceramic composites. The technical foundation for this effort was provided through independent 1) MIL-STD-662 FSP ballistic testing with The Ballistics and Explosive Group at Southwest Research Institute (SwRI); 2) FMVSS 201U head impact testing with MGA Research Incorporation; and 3) ASTM E1354 fire resistance testing with the Fire Technology group at SwRI. Fragment simulating projectile (FSP) testing completed in accordance with MIL-STD-662 indicates NanoSonic's down-selected HybridSil SPEA composite has an exceptional V50 value of 5,000 ft/s against 0.30 cal FSPs. Promisingly, FMVSS-201U testing on NanoSonic's HybridSil SPEA material indicates it has a HIC(d) value of 626.3 and thus meets Ground Vehicle Systems Center's (GVSC) performance objective of < 700.

1. INTRODUCTION

Through Army SBIR funding, NanoSonic has designed and empirically optimized a next-generation multipurpose Spall Protective, Energy Absorbing (SPEA™) HybridSil material that will provide vehicle occupants with pioneering combinatorial protection from 1) fragmentation behind-armor debris (BAD), 2) high velocity head / neck impact, and 3) fire during underbody blast, crash, and rollover events.

NanoSonic's Phase I optimized HybridSil SPEA composite has been iteratively optimized and uniquely designed to afford a previously unavailable combination of high velocity ballistic protection, head impact protection, and fire resistance. Having established a strong empirical foundation independently tested and validated with MGA Research Incorporation and Southwest Research Institute (SwRI), this technology is positioned to provide soldiers with state-of-the-art multipurpose protection during combat missions upon advancement and completion of a Phase II SBIR program.

At this phase of technical maturation, fragment simulating projectile (FSP) testing completed in accordance with MIL-STD-662 indicates NanoSonic's down-selected HybridSil SPEA composite has desirable V_{50} performance of 5,000 ft/s against 0.30 cal FSPs. The V_{50} value is the velocity necessary for a projectile to penetrate a material with 50 percent probability.

Importantly, NanoSonic's optimized layup also achieved GVSC's Federal Motor Vehicle Safety Standard (FMVSS) 201U head impact protection goal. This objective was a Head Injury Criteria (HIC (d)) value < 700. FMVSS 201U testing involves firing a free motion anthropomorphic head form equipped with an internal tri-axial accelerometer at an upper interior automotive component (i.e. roof, pillar, headliner, rail) and analyzing the data to establish a HIC (d) value. This value is calculated by averaging head form acceleration during a deceleration timeframe after target impact. For OEM vehicle safety compliance, HIC(d) values have to be under 1,000 (higher values reflect greater probability for brain injury).

Further, the extreme fire resistance and low smoke toxicity of this highly promising material has been validated through ASTM E1354 cone calorimetry testing. NanoSonic's down-selected HybridSil SPEA material also meets GVSC cost threshold of $\leq$ \$100 / sq. ft, has a current areal density of 2.5 lbs / ft^2, and thickness of 1.50".

In support of larger scale Phase II performance validation and vehicle integration R&D, the HybridSil EA foams and composite materials used to construct is Phase I optimized multilayered composite (Figure 1). were continuously designed for an immediate pilot scale manufacturing transition, as well as practical vehicle integration strategies, through upgrade kits at Army depots and direct insertion during new vehicle manufacturing. HybridSil resins have a current production capacity of 8,000 lbs. / day, an MRL of 6, and have been integrated onto combat active DoD platforms for trial demonstrations.

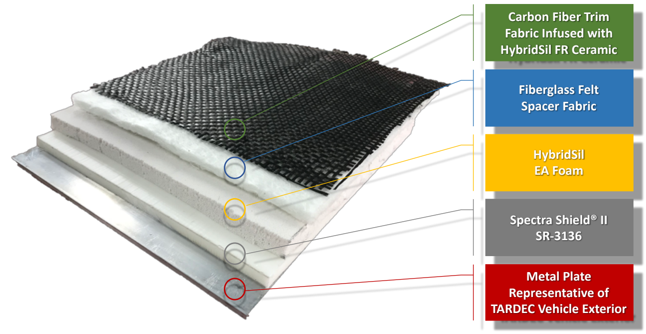

Figure 1: HybridSil SPEA design for MIL-STD-662F V_{50} ballistic testing against 0.30 cal fragment simulating projectiles (FSP).

2. MIL-STD-662F V_{50} Ballistic Testing

MIL-STD-662 V_{50} ballistic testing against 0.30 cal fragment simulating projectiles (FSP) was completed by the Ballistics and Explosives Engineering group at Southwest Research Institute (SwRI). Three unique HybridSil SPEA configurations were tested as 12" x 12" panels that were 0.75" to 1.5" thick. Three panels were provided for each configuration (9 total panels tested), and each panel was shot three times to generate a nine-shot sequence for V_{50} determination of each design. The metal strike face employed for all samples was 0.125" thick high hard steel (46100). The areal density of the systems ranged from 2.5 to 3.5 lbs. / sq. ft. (excluding the metal strike face).

MIL-STD-662F data indicates NanoSonic's HybridSil SPEA panels have 4-shot V_{50} averages of 5,041 $\pm$ 134 ft/s; 4,986 $\pm$ 18; and 5,064 ft/s $\pm$ 97. A summary of the V_{50} data for each sample is included in Table 1. A Vision Research Model Phantom v711 digital high-speed video camera (HSV) was used to measure the velocity of the 0.30 cal FSP just prior to impacting the strike face, and

Figure 2 shows the velocity computation and images of the projectile after FSP penetration.

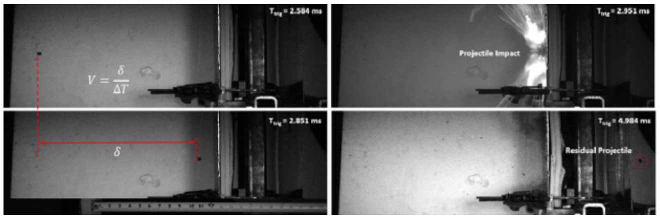

Figure 2: High speed video images obtained from SwRI's Phantom v711 digital high-speed video camera (HSV). Images provided by SwRI team members.

When considering the average V_{50} for all configurations was ~ 5,000 ft/s and this value is within the spread range of the sample set, it is concluded the 0.30 cal FSP ballistic performance of NanoSonic's HybridSil SPEA samples was not influenced by the density of the EA foam interlayer and thus dominated by the Spectra Shield panel.

Configuration A		
Test ID	V_s (ft/s)	Result
T7	5,101	Fail
T5	5,090	Fail
T9	5,006	Pass
T8	4,967	Pass
T6	4,804	Pass
T4	4,653	Pass
T2*	4,514	Fail
T3	4,248	Pass
T1	4,158	Pass
V_{50} Type	V_{50} (ft/s)	Spread
4-shot	5,041	134

Configuration B		
Test ID	V_s (ft/s)	Result
T16	5,135	Fail
T10	5,100	Fail
T15	4,999	Pass
T11	4,981	Pass
T12	4,981	Fail
T14	4,981	Fail
T17	4,969	Fail
T13	4,967	Pass
T18	4,867	Pass
V_{50} Type	V_{50} (ft/s)	Spread
4-shot	4,986	18
6-shot	4,980	32
8-shot	4,981	233

Configuration C		
Test ID	V_s (ft/s)	Result
T27	5,141	Pass
T22	5,129	Fail
T19	5,101	Fail
T26	5,072	Pass
T21	5,032	Pass
T23	4,985	Fail
T24	4,968	Pass
T25	4,912	Pass
T20	4,844	Pass
V_{50} Type	V_{50} (ft/s)	Spread
4-shot	5,064	97
6-shot	5,077	156

Table 1. MIL-STD-662F strike velocity data and V_{50} computations for NanoSonic's three HybridSil SPEA design variations.

3. FMVSS-201U HIC (D) Head Impact Testing

FMVSS-201U head impact testing was completed by MGA Research on the HybridSil SPEA configuration with an areal density of 3.0 lbs/ft. Since 0.30 cal FSP V_{50} performance was not influenced by the density / morphology of the HybridSil EA foam interlayer, NanoSonic's head impact sample set included the HybridSil EA foam that had previously demonstrated a HIC (d) value of 626.3

This layup is representative of Configuration A employed for 0.30 cal FSP ballistic testing that afforded an average V_{50} value of 5,041 ft/s. Images of Configuration A before head impact testing are included in Figure 3.

Figure 3: FMVSS-201U testing of HybridSil SPEA materials affording a 0.30 cal FSP V_{50} of 5,041 ft/s. This sample set afforded a very promising HIC (d) value of 626.3.

Promisingly, FMVSS-201U testing on NanoSonic's HybridSil SPEA material affording a V_{50} of 5,041 ft/s indicates it has a HIC(d) value of 626.3 and thus meets the GVSC performance objective of < 700. A summary of the HIC data measured by MGA is included in Table 2, and the accelerometer data for the X, Y, and Z-axes during head form impact is included in Figure 4.

HIC Type	HIC Value	Time 1 (ms)	Time 2 (ms)	Delta-T (ms)
HIC 36	609.55	79.2	82	2.8
HIC 15	609.55	79.2	82	2.8
HIC (d)	626.28	79.2	82	2.8

Table 2. HIC data provided by MGA Research on NanoSonic's Phase I optimized HybridSil SPEA material.

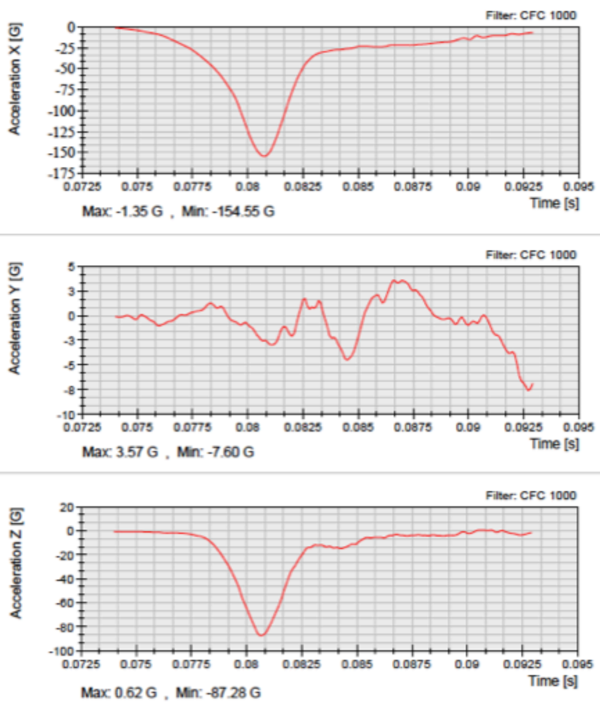

Figure 4. X, Y, and Z-axes accelerometer data during head form impact on NanoSonic's down-selected HybridSil SPEA material.

Of critical importance for repeated head impact protection during blast, crash, and roll-over events, it was noted by MGA researchers that NanoSonic's HybridSil SPEA materials did not reveal any signs of damage following high velocity head impact testing. An image of HybridSil SPEA sample panel following testing is shown in Figure 5.

Figure 5: HybridSil SPEA panel following FMVSS-201U high velocity head impact testing.

4. Cone Calorimetry Testing

In addition to having a 0.30 cal FSP V_{50} value of 5,041 ft/s and meeting GVSC's HIC (d) performance objective of <700, ASTM E1354 cone calorimetry testing completed by the Fire Technology group at SwRI indicates NanoSonic's Phase I optimized HybridSil SPEA material has excellent fire resistance and low heat release rates upon exposure to a 50 kW/m^2 heat flux. Cone calorimetry testing was completed on 4" x 4" samples (1.50" thick).

Four HybridSil SPEA samples were tested and the averaged results are included in Table 3. As expected, the average heat release rate was found to be very low at 14.7 kW/m^2. Further, the average weight loss after testing was 0.15 weight percent indicating negligible combustion or smoke production occurred.

PARAMETER	AVERAGE VALUE
Heat Flux (kW/m^2)	50
Exhaust Flow Rate (l/s)	N/A
Specimen Thickness (mm)	N/A
Exposed Area (m^2)	N/A
Initial Mass (g)	257.0
Final Mass (g)	256.6
Sample Mass Loss (kg/m^2)	0.1
Average Mass Loss Rate (g/s*m^2)	1.5
Time to Ignition (s)	20.5
Time to Flame Out (s)	38.3
Peak Rate of Heat Release (kW/m^2)	20.5
Average Rate of Heat release (kW/m^2)	14.7
Heat Release Rate at 60 seconds (kW/m^2)	12.1
Heat Release Rate at 180 seconds (kW/m^2)	7.5
Heat Release Rate at 300 seconds (kW/m^2)	5.3
Total Heat Released (MJ/m^2)	0.4
Average Effective Heat of Combustion (MJ/kg)	9.7
Average Specific Extinction Area (m^2/kg)	159.6
Total Smoke Released per Unit Area (m^2/m^2)	20.9
Total Smoke Production (m^2)	0.2

Table 3. ASTM E1354 cone calorimetry data on NanoSonic's Phase I Optimized HybridSil SPEA material. Testing was completed at a heat flux of 50 kW/m^2

5. CONCLUSIONS

NanoSonic's Phase I optimized HybridSil SPEA composite has been iteratively optimized and uniquely designed to afford a previously unavailable combination of high velocity ballistic protection, head impact protection, and fire resistance. Having established a strong empirical foundation independently tested and validated with MGA Research Incorporation and Southwest Research Institute (SwRI), this technology is positioned to provide soldiers with state-of-the-art multipurpose protection during combat missions upon advancement and completion of a Phase II SBIR program.

During the Phase I effort, fragment simulating projectile (FSP) testing completed in accordance with MIL-STD-662 indicates NanoSonic's down-selected HybridSil SPEA composite has a V_{50} value of 5,000 ft/s against 0.30 cal FSPs. Importantly, this material also achieved FMVSS 201U head impact protection objective of an HIC (d) value < 700. Further, the extreme fire resistance and low smoke toxicity of this highly promising material has been validated through ASTM E1354 cone calorimetry testing. NanoSonic's down-selected HybridSil SPEA material also meets GVSC cost threshold of $\leq$ \$100 / sq. ft, has a current areal density of 2.5 lbs / ft^2, and thickness of 1.25".

By providing vehicle design engineers with a multipurpose automotive component that functions as both an interior trim energy absorption and spall liner material, NanoSonic's envisions considerable transition interest within the military vehicle market during Phase II and III efforts. A Phase II program will provide a pivotal funding bridge enabling more rigorous BAD fragmentation testing with larger test specimens and more demanding threats, further FMVSS-201U head impact optimization, extensive FST testing, optimization of vehicle roof and foot well integration strategies, and pursuit of Phase III integration pathways through performance specification fulfillment within an array of military vehicles such as the Bradley, MATV, Stryker, HMMWV, and NGCV.