Low-Velocity, Multi-Hit Impact Performance of Basalt Fiber SC-15 Composites

by Steven E. Boyd, Ryan P. Emerson, Travis A. Bogetti, and David M. Spagnuolo

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Steven E. Boyd, Ryan P. Emerson, Travis A. Bogetti, and David M. Spagnuolo
Weapons and Materials Research Directorate, ARL
### 4. TITLE AND SUBTITLE
Low-Velocity, Multi-Hit Impact Performance of Basalt Fiber SC-15 Composites

### 6. AUTHOR(S)
Steven E. Boyd, Ryan P. Emerson, Travis A. Bogetti, and David M. Spagnuolo

### 14. ABSTRACT
A low-velocity, four-quadrant impact testing protocol is currently under development to evaluate the damage tolerance and durability of thick-section composite plates. With this protocol, multi-hit impact data is reduced to distinguish materials that are stiff and exhibit low rates of degradation during the four-hit test of each material specimen. This reduced data is displayed on a single Ashby-type chart, allowing composites of different matrix and reinforcement types to be compared and ranked. The present research focuses on the impact performance of two-dimensional (2-D) basalt fiber fabric compared to 2-D S2-glass fiber-fabric composites. Basalt fibers and fabrics are currently of interest because of their comparable mechanical properties to S2-glass, competitive cost (a price point between that of E-glass and S2-glass), and natural fire resistance. Basalt-fiber composites are touted as a competitive replacement in composite applications where carbon fiber and S2-glass are unwarranted. This research investigates the impact performance of two basalt fabrics, one manufactured by Martintek USA, LLC and one by BGF Industries, Inc. Sets of panels using 2-D basalt fabric infused with SC-15-toughened epoxy are subjected to four-quadrant impact under clamped and simply supported boundary conditions and are compared directly to panels manufactured with S2-glass fabric. Comparisons are drawn using the multi-hit protocol and damage areas measured using C-scan. The S2-glass composite slightly outperformed the basalt fiber composites in almost all metrics considered. The results also indicate that the BGF material outperforms the Martintek material.

### 15. SUBJECT TERMS
basalt fiber, low velocity impact, damage tolerance, durability
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We would like to thank the following government contractors for their assistance in the data acquisition and analysis supporting this work: Bradley Lawrence for general impact testing; and Aristedes Yiournas and Jordan Wagner for ultrasonic scanning of impact samples. We would also like to thank Jim Wolbert for processing the S2-glass and basalt-fiber composites used in this study.
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1. Introduction

Durability and damage tolerance are terms that are often used for describing material degradation and ultimately must be associated with a specific application or loading spectrum. The Boeing Compression After Impact Test (1, 2) is a well-established durability and damage tolerance characterization method for low-velocity single impact on “thin” section aerospace composites (e.g., tool drop, bird strike). This method has been used for decades by the U.S. Air Force, with great success for developing and ranking new materials for high-performance aircraft applications (e.g., stiffness critical thin-sectioned wing skins with high damage tolerance requirements).

Successive (or multiple) impact on thick-section composite laminates represents a unique loading environment for many of the U.S. Army’s structural composite applications, including ground and air vehicle platforms. This load spectrum is not typically encountered or addressed by other branches of the U.S. Department of Defense (e.g., Air Force, Marines, or Navy) or even the commercial sector. Compared to single-event impact, the response of composite laminates subjected to multiple impacts has received relatively little attention in the literature (3–5). Most of the cited literature for multiple impacts deals with thin-sectioned composite laminates rather than thick-sectioned composites (e.g., greater than 2.54 cm) (6–14).

In 1991, with the dissolution of the Soviet Union, research interest in basalt fibers increased as previous research results became declassified and supplies of basalt opened to commercial ventures. The U.S. Army Research Laboratory (ARL) has been recently monitoring the growing research developments and literature based on the use of basalt fibers in matrices traditionally reinforced with either glass or graphite. This effort was recently increased with a proposal through Foreign Technology (and Science) Assessment Support (FTAS) Program (FTAS03-11 [15]). The proposal focused on the comparative properties of basalt woven fabrics with that of current Army systems using similar S2 woven materials. This investigation would provide the Army with an alternative or substitute material for S2 glass if needed. Typical mechanical and ballistic properties were evaluated for the FTAS (15) as a part of a separate research effort, but ARL wanted to include durability data as well, since a significant amount of data is available for S2-glass. The basalt fiber is made from volcanic rock and its natural ingredients a significant cost savings can be achieved over S2-glass.

This research uses the low-velocity impact (LVI), four-quadrant testing protocol to distinguish the impact performance and durability of basalt fiber fabric composites vs. S2-glass fabric composites (a detailed explanation of the approach may be found in references 16–18). Two manufacturers’ basalt fiber fabrics are used in this research. The Martintek USA, LLC, and BGF Industries, Inc., basalt fabric composites are compared against each other and S2-glass fabric
composites. Data from the impact testing includes force-deflection plots, out-of-plane deflection, damage area, and residual composite stiffness after impact as well as a ranking assessment of impact performance using the Ashby-type ranking criterion.

2. Experimental

2.1 Impact Samples

Two basalt fiber fabrics were investigated in this research. The first fabric is a two-dimensional (2-D), 5 × 5 (warp × weft tows per square inch) basalt fiber fabric plain weave (PW) with a fabric areal density of 25 oz/yd² and was manufactured by Martintek USA, LLC (a division of JB Martin, Leesville, SC). The second fabric is a 2-D, 5 × 5 basalt fabric PW with a fabric areal density of 24.5 oz/yd² and was manufactured by BGF Industries, Inc. (Greensboro, NC). The S2-glass fabric is a 2-D, 5 × 5, roven weaving with a fabric areal density of 24 oz/yd² and is manufactured by AGY. The basalt fiber fabric was stacked to 22 plies (layers of 2-D fabric) in a quasi-isotropic orientation [(45/0)₅/₄₅]₅ and infused with a SC-15 toughened epoxy (Applied Poleramic Inc., Benecia, CA). The composite panels were infused using room temperature vacuum-assisted resin transfer molding (VARTM), cured, and post-cured according to manufacturers’ recommendations for SC-15. A large composite panel (89 × 89 cm) was manufactured out of which four smaller, 40.6- × 40.6-cm samples were cut using a water jet cutting machine. Table 1 lists the average thickness, weight, and density of the impact samples.

<table>
<thead>
<tr>
<th></th>
<th>S2/SC-15</th>
<th>BAS BGF/SC-15</th>
<th>BAS MTK/SC-15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness (cm)</td>
<td>1.51 ± 0.01</td>
<td>1.47 ± 0.01</td>
<td>1.35 ± 0.01</td>
</tr>
<tr>
<td>Weight (g)</td>
<td>4218 ± 9.3</td>
<td>4499 ± 9.2</td>
<td>4152 ± 13.0</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>1.798 ± 0.012</td>
<td>1.854 ± 0.013</td>
<td>1.868 ± 0.016</td>
</tr>
</tbody>
</table>

2.2 Fiber Burn-out

Fiber burn-out testing was conducted on four 2.5- × 2.5-cm samples of each large composite panel according to ASTM 2734 (19). Results for fiber, matrix and void fraction of each composite are presented in table 2.

<table>
<thead>
<tr>
<th></th>
<th>V_f (%)</th>
<th>V_m (%)</th>
<th>V_v (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S2/SC-15</td>
<td>48.2 ± 0.3</td>
<td>50.7 ± 0.7</td>
<td>1.1 ± 0.7</td>
</tr>
<tr>
<td>BAS BGF/SC-15</td>
<td>50.8 ± 0.2</td>
<td>48.5 ± 0.2</td>
<td>0.7 ± 0.1</td>
</tr>
<tr>
<td>BAS MTK/SC-15</td>
<td>52.5 ± 0.6</td>
<td>46.7 ± 0.5</td>
<td>0.8 ± 0.1</td>
</tr>
</tbody>
</table>
2.3 Drop Tower

An Instron Dynatup model 8110 impact test system was used for these experiments. The impactor was a 50-cm hemispherical tup and the strain-gage based load cell had a capacity of 222.4 kN (50 kips). Force data during each impact were recorded for 25 ms at a sampling rate of 270 kHz. Tup displacement was calculated by converting the force to tup acceleration and numerically integrating twice with respect to time.

2.4 Impact Table

The impact table fixture used in the impact testing is shown in figure 1. The all-steel fixture consists of a 3.8-cm-thick, 50.8-cm square table, bolted to a 2.5-cm-thick base plate with four 5.1-cm diameter, 30.5-cm-long legs. The top plate is 2.5 cm thick held in place with 16 2.2-cm-diameter high-strength steel bolts. Because this research was conducted before the conclusion to use only simply supported boundary conditions for all future impact testing, both clamped and simply supported boundary conditions were used in this study (18). Figure 1 illustrates the simply supported condition with the addition of the adapter plate (designed to snugly fit into the inner opening of the square table), four 1.3-cm steel rod supports which rest in machined “v” grooves in the adapter plate, and a 0.3-cm-thick, 2.5-cm-wide strip of soft rubber resting between the sample and top steel plate. The entire assembly is secured with sixteen hand tightened bolts to minimize rigid-body motion of the sample after impact and rebound. For the clamped condition, the adapter (with rods) and rubber are removed and the sample is clamped between the top plate and lower table with bolts installed with a pneumatic wrench.

Figure 1. Exploded-view illustration of the impact table, with detail showing a side-view cross-section of one side of the simple support.
2.5 Impact Location and Energy

Figure 2 illustrates the locations of impact for all samples in this investigation. Impacts were conducted one-at-a-time to permit non-destructive evaluation of each panel after each impact. Mass and height of the impactor were 227.4 kg and 96 cm, respectively, yielding an impact energy of 2141 J and velocity of 4.34 m/s.

2.6 Non-Destructive Evaluation

The samples were removed from the impact table and ultrasonically c-scanned before and after each impact with a transducer frequency of 0.5 MHz and spatial resolution of 1 mm. These scans were used to track the evolution of damage in the sample. Delamination was observed as the predominant damage mode in the samples. All scans reported in this work were performed with the scanner operating in through-transmission mode. This approach provided an accurate determination of the extent of delamination across the full dimension of the samples.

3. Results

3.1 Force vs. Displacement

Representative force-deflection curves are given for S2-glass and basalt fiber composites subject to clamped and simply supported boundary conditions in figures 3–5. The curves of the S2-glass and basalt fiber composites contrast in several ways. The S2-glass composites have a higher peak load of about 140–160 kN, the curve displacements (total integrated plate deflections) are less at 3–3.5 cm, and the S2-glass curves have a clearly discernible degradation in stiffness per
impact. The S2-glass composites sustain higher peak loads vs. the basalt fiber composites. Given that both composites exhibit similar accumulation of c-scan damage area per impact (see figures 6–10), this indicates that the S2-glass composites are slightly more damage tolerant. Also, the S2-glass peak load values are retained over all impacts whereas the basalt fiber composite peak load values of 110–140 kN decrease noticeably as damage accumulates (especially for the simply supported case). However, the basalt fiber composites are able to absorb more energy from the impact event (see figures 6b vs. 6a) and yet display a similar damage area accumulation per impact to the S2-glass composites. The impact energy of 2.1 kJ caused more localized shear deformations and back face perforations and yielded greater sample deflections of 3–4 cm for the basalt composites.

Figure 3. Force vs. displacement for S2/SC-15 for (a) clamped and (b) simply supported boundary conditions.

Figure 4. Force vs. displacement for BAS-BGF/SC-15 for (a) clamped and (b) simply supported boundary conditions.
Figure 5. Force vs. displacement for BAS-MTK/SC-15 for (a) clamped and (b) simply supported boundary conditions.

Figure 6. Energy absorbed during the impact for (a) S2/SC-15 and (b) BAS-BGF/SC-15; both with simply supported boundary conditions.

Figure 7. C-scan image showing progression of delamination in a S2/SC-15 sample under simply supported boundary conditions.
Focusing on figures 4 and 5, there is a key difference between the basalt fiber composites force-deflection behavior with clamped and simply supported boundary conditions. With the clamped condition, impacts two and three followed a similar path in the rebound portion of the curve with the fourth impact much more deflected. With the simply supported condition, impacts two and three are separated more and impacts four and three overlap. Observed inconsistencies like this in the rebound phase of the force-deflection curves indicate that the choice of boundary condition is influencing and perhaps altering the impact response of the samples. To what extent may be
explained by performing a modeling study of the two separate boundary cases; regardless, one of the main conclusions of Boyd et al. (18) was to continue future testing with only simply supported boundary conditions.

3.2 Damage Evolution – Ultrasonic Scans

Representative c-scan images of the BGF basalt fiber, Martintek basalt fiber, and S2-glass fiber composites are shown in figures 7–11 subject to either simply supported or clamped boundary conditions. Direct comparison with the S2-glass composite damage progression shown in figure 6 with any of the representative corresponding basalt composites regardless of boundary conditions (figures 8–11) indicates a very similar pattern of damage progression. The basalt composites demonstrate similar damage tolerance to the S2-glass composites even though the basalt composites have lower peak loads during impact, more impact energy absorption, and increased sample deflections. Like the S2-glass composites, the basalt fiber composites have well contained damage areas per impact that are localized and the result of shear deformation and back face perforation. Localized and contained damage areas directly in the vicinity of the impact are an important indication for good multi-hit performance. From visual inspection of the figures 6–10, the only difference in the damage areas is that the basalt composites have “fringe” damage areas surrounding the main impact. This fringe effect is mostly likely due to delaminations which open during the impact event and partially close enough during the rebound phase to allow through transmission of the ultrasonic signal.

Figure 11. C-scan image showing progression of delamination in a BAS-MTK/SC-15 sample under clamped boundary conditions. (The third impact scan was lost due to file corruption.)

Figure 12 shows the delamination progression per impact as a percentage of exposed sample aperture for the basalt fiber composites and figure 13 shows a direct normalization with the S2-glass composites. From figure 12, the basalt fiber composites like the S2-glass composites experience significant rises in damage area after the first two impacts; by impact three and four, the samples are almost entirely damaged. From figure 13, we can reasonably conclude that the damage progression per impact exhibited by the basalt fiber composites is roughly the same as that of the S2-glass composites within experimental error. Both the Martintek and BGF basalt fiber composites have the same damage progression performance. There is an interesting
difference in the performance with respect to boundary conditions. In figure 12, for both basalt fiber types, the simply supported case displays more overall damage accumulation per impact than the clamped case. Figure 13 also shows this increase with respect to the S2-glass composites. This is a reasonable expectation given that the simply supported boundary condition does not restrict sample bending during the impact event which may allow an increase in delamination and damage propagation in the sample.

Figure 12. Average delamination areas as a percentage of impact table aperture for the basalt fiber composites. SS = simply supported; CLMP = clamped.
3.3 Failure Mechanisms – Visual Inspection

Characteristic images of front-impact locations and back-face perforations and visible impact damage are shown in figures 14–16 for both basalt fiber and S2-glass composites. Both the S2-glass and basalt fiber composites sustain damage with significant front face crushing under the hemispherical impactor and back face perforation. This pattern of damage is mostly associated with localized shear or punching failure due to the impact which results in modest delamination in the vicinity of the impact (see figures 7–11). The notable exception here is that the basalt composites exhibit deeper crushing penetration and increased localized perforation on the back face sometimes resulting in what is essentially a punched-out square of material after the four impacts. This is consistent with the increased energy absorption characteristics of the basalt fiber composites (see figures 4–6).
Figure 14. Front face (a) impact locations and back face (b) damage for a BAS-BGF/SC-15 sample subject to clamped boundary conditions.

Figure 15. Front face (a) impact locations and back face (b) damage for a BAS-MTK/SC-15 sample subject to simply supported boundary conditions.

Figure 16. Front face (a) impact locations and back face (b) damage for S2/SC-15 sample subject to simply supported boundary conditions.
The damage mode for both material types shifted from localized shear failure to widespread delamination during successive impacts. This is most clearly indicated in the S2/SC-15 composite of figure 16b where the first three impacts resulted in localized perforation; however, perforation rarely resulted from the fourth impact. From the damage area c-scan of figure 6 by impact three and four, the sample is completely damaged over the area of the aperture and the impact energy incident on the sample is expected to be dissipated through an increase in the extant interlaminar delamination planes. This same transition of failure mechanism is also observed in the basalt fiber composites (see the third and fourth impact damage of figures 14b and 15b).

With regard to the effect of the boundary conditions on the sample damage pattern, the simply supported basalt panel of figure 15b appears to have slightly more perforation than the clamped basalt panel of figure 14b; however, no overall trend was distinctly observed and clamped and simply supported boundary conditions yielded similar damage patterns. Also, both types of basalt fibers, BGF and Martintek, used in the basalt composites yielded very similar damage patterns even though the Martintek composite samples were slightly thinner at 1.35 cm with a lower volume percent of matrix (46.7%).

3.4 Degradation Rate

In our approach, we assume that the extent of damage within the material is related to the sample stiffness (slope of the force-deflection curve) during impact. For purposes of quantification, we consider the stiffness at 1 cm deflection because the force-deflection curves (see figures 3–5) are still nominally linear up to that point and most of the transient vibration from the initiation of impact has dampened. Figure 17 shows a plot of the average initial stiffness (averaged over four samples of each material) during each impact. The average stiffness values for the basalt fiber composites are plotted in figure 17 for the BGF and Martintek basalt composites subject to different boundary conditions.

From figure 17, we see that the BGF basalt fiber composites retain more sample stiffness across all four impacts regardless of the boundary condition identifying a significant performance difference between the two basalt fiber composites. Also, figure 17 does seem to reveal a slight difference in stiffness between the clamped and simply supported boundary conditions, more so with the BGF basalt fiber, with slightly higher stiffness in the clamped case. A direct comparison of the basalt fiber composites to the corresponding S2-glass composites is given in figure 18 where the average initial stiffness of the basalt fiber composite is normalized with respect to the S2-glass composite with corresponding boundary conditions. Here, the clamped and simply supported case for the BGF basalt fiber composites performs similarly to the S2-glass composites although there is larger reduction in stiffness with impact three and four, especially with the simply supported case. The Martintek basalt composites, however, perform quite poorly against the S2-glass composites exhibiting a 20% to 25% reduction in stiffness especially with...
the final impacts. This finding is consistent with the observation that the basalt fiber composites absorbed more impact energy and displayed more localized damage than their S2-glass composite counterpart. The Martintek composite performs poorly vs. the BGF and S2-glass composites in stiffness retention across multiple impacts. This may be due to the lower matrix volume percentage of SC-15, 2% less than the BGF and 4% less than the S2-glass (see table 2); however, the true reason is not known and will need additional research to identify.

Figure 17. Average initial impact stiffnesses for the basalt fiber composites for both simply supported and clamped boundary conditions. SS = simply supported; CLMP = clamped.
Figure 18. Average initial-impact stiffness for the basalt composites normalized to the average S2/SC-15 composite with matching boundary conditions. SS = simply supported; CLMP = clamped.

3.5 Comparison of Multi-Impact Durability

The present investigation uses an Ashby-type chart to compare the relative durability between different materials for multi-impact Army applications as shown in figures 19 and 20. We define the degradation rate, \( d_s \), as the slope of the linear fit to these initial stiffnesses vs. impact, with units of kN/cm-impact. Degradation rate, \( d_s \), is plotted on the vertical axis and initial sample stiffness normalized by material density is plotted on the horizontal axis (units of kN·cm\(^2\)/g). Such a chart quickly distinguishes the relative durability between different materials. Specifically, materials that appear low and right on the chart are more desirable than materials that plot high and left.
Figure 19. Ashby-type plot showing the relative durability of basalt fiber composites and S2-glass composites subject to the clamped boundary condition.

Figure 20. Ashby-type plot showing the relative durability of basalt fiber composites and S2-glass composites subject to the simply supported boundary condition.
Figures 19 and 20 display the Ashby-type chart developed by Boyd et al. (18) to more easily visualize and assess a particular material’s durability subject to multiply impacts. The plots contain the BGF and Martintek basalt fiber composites and S2-glass composites discussed in this report as well as other S2-glass data collected including an S2-glass panel with a 22 ply [0/90]_{22} lay-up and a three-dimensional weave, 100-oz S2-glass architecture lay-up to five layers. These composites are included for comparison of the basalt fiber composites with all S2-glass composites for which we have multi-impact data at 2.1 kJ. The key result of figures 19 and 20 is that, according to the ranking method developed for multiple-impacts, the basalt fiber composites are slightly outperformed by their S2-glass counterparts under both boundary conditions. The BGF basalt fiber composites have a better relative durability than the Martintek basalt fiber composites regardless of the boundary condition. The Ashby-type chart of figure 20 indicates that the simply supported boundary condition has the least influence on collected impact data and overall effect of impact properties due to the spread of the data.

4. Conclusions

Research was conducted using a newly developed LVI testing protocol to distinguish the multi-impact properties and impact damage tolerance of novel composite materials with both clamped and simply supported boundary conditions. The materials are composites which use the same two-phase toughened epoxy system, SC-15, but different fibers consisting of S2-glass fabric and basalt fabric. The basalt fiber fabrics are sampled from two different manufacturers, BGF and Martintek.

The use of an Ashby-type chart to represent the reduced data from impact testing provides a useful visual comparison of the durability characteristics of different materials. The results indicate that the legacy composite system S2/SC-15 slightly outperforms the basalt composites in impact properties, exhibiting less degradation per impact, superior impact stiffness retention, lower out-plane deflection, less fabric crushing, and more localized shear deformation. However, the basalt composites (especially the BGF-fiber composites) did well overall, exhibiting damage area progression comparable to the S2-glass composites and similar degradation rates. The BGF basalt-fiber composites appeared to slightly outperform the Martintek composites in this study.

The comparisons of impact properties of basalt and S2-glass composites presented in this report are comparable to the mechanical and ballistic properties investigated in the FTAS Program (15). For future research efforts, ARL will be performing similar durability/impact tests on thick-section basalt composites (>1 in) and comparing those results to similar S2-glass thick-section composites. Basalt fibers will continue to be of interest to the Army, especially if foreign suppliers and domestic weavers continue to improve the supply and quality of basalt materials. The Army will continue with similar proposals and research to monitor the progress of basalt.
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Tolerance in Thick-Section Composites. *SAMPE Spring Technical Conference 2011*,
Baltimore, MD, May 2012.

## List of Symbols, Abbreviations, and Acronyms

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARL</td>
<td>U.S. Army Research Laboratory</td>
</tr>
<tr>
<td>PW</td>
<td>Plain weave; applies to reinforcing fiber architecture</td>
</tr>
<tr>
<td>BAS</td>
<td>Basalt fabric reinforcement</td>
</tr>
<tr>
<td>MTK</td>
<td>Martintek USA</td>
</tr>
<tr>
<td>BGF</td>
<td>BGF, Inc.</td>
</tr>
<tr>
<td>SS</td>
<td>Simply supported boundary condition</td>
</tr>
<tr>
<td>CLMP</td>
<td>Clamped boundary condition</td>
</tr>
<tr>
<td>VARTM</td>
<td>Vacuum-assisted resin transfer molding</td>
</tr>
<tr>
<td>DOD</td>
<td>U.S. Department of Defense</td>
</tr>
<tr>
<td>2-D</td>
<td>Two-dimensional</td>
</tr>
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<td>LVI</td>
<td>Low-velocity impact</td>
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<td>Foreign Technology Assessment Support Program</td>
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<td>ASTM</td>
<td>American Society for Testing and Materials International</td>
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<tr>
<td>$V_f$</td>
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<tr>
<td>$V_m$</td>
<td>Matrix volume fraction</td>
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<td>$V_v$</td>
<td>Void volume fraction</td>
</tr>
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<td>$d_s$</td>
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1 DEFENSE TECHNICAL INFORMATION CTR
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   STE 0944
   FORT BELVOIR VA 22060-6218

1 DIRECTOR
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1 DIRECTOR
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<th>ORGANIZATION</th>
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<td>ABERDEEN PROVING GROUND</td>
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| 13 | DIR USARL  
|      | RDRL WMM  
|      | J ZABINSKI  
|      | RDRL WMM A  
|      | J CAIN  
|      | R EMERSON  
|      | J GARDNER  
|      | L HOLMES  
|      | M MAHER  
|      | J SANDS  
|      | D SPAGNUOLO  
|      | J WOLBERT  
|      | RDRL WMM B  
|      | T BOGETTI  
|      | S BOYD  
|      | B LOVE  
|      | M VANLANDINGHAM |
INTENTIONALLY LEFT BLANK.