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Title: **Long-Rod Penetration into Intact and Pre-Damaged SiC Ceramic**

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14. ABSTRACT Penetration experiments with long rods into SiC ceramics are available for two rod materials over a wide range of impact velocities [1-2]. The ceramics used in these experiments were initially intact, without cracks or other induced damage. The penetration response of three types of pre-damaged SiC was also investigated [3]. The pre-damaged targets, which were confined in 7075 aluminum sleeves consisted of 1) thermally shocked (many non-contiguous cracks), 2) thermally shocked with mechanical load/unload cycling (in-situ comminuted), and 3) compacted powder. Further experiments were conducted on intact and thermally shocked (predamaged) SiC-N that overlapped the previous test data, and to extend the data to lower impact velocities. The results of these additional experiments were different than expected; this article describes the experiments and comparisons with previous data.					
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INTRODUCTION

Experiments into silicon carbide (SiC) targets, over a wide range of impact velocities, have been conducted with tungsten [1] and gold [2] long rods. The experiments were conducted in the reverse ballistics mode; the cylindrical SiC “targets” were launched at long rods suspended in the flight path. Flash radiography was used to measure penetration depth versus time after impact. Gold was used in the second set of experiments to minimize the effect of penetrator strength. The penetration-time data are extremely linear; the slope of a linear regression of the penetration-time data gives the penetration velocity.

It has been very difficult to obtain independent laboratory measurements of the constitutive parameters for failed ceramics because they are so strong (e.g., loading platens fail before the confined specimen; confining sleeves yield and limit confining pressures, etc.). It was decided that a series of experiments to measure the penetration performance of a ceramic material with *initially* different strengths [3] would be of value for the study and development of computational ceramic constitutive models. Therefore, to assist in the determination of the strength of failure materials, ballistic experiments were performed on cylindrical SiC targets

with three different grades or degrees of damage, described in the next section. These variously damaged ceramics, contained in an Al-sleeve, were launched in the reverse ballistic mode against stationary gold rods. Impact velocities ranged from 1 to 3 km/s.

This article is focused on the most recent experiments performed to extend the experimental databases in Ref. [3] to lower impact velocities. Some of the impact velocities overlapped with the previous data so that direct comparisons could be made between the new and older data. After a review of the previous results, the new data will be summarized and compared to the older data.

SUMMARY OF PREVIOUS RESULTS

The investigated ceramic was SiC-N ($\rho = 3.2 \text{ g/cm}^3$) from BAE Systems, Advanced Ceramics Division, formerly Cercom, with a diameter of 18 mm and a length of 35 mm, placed inside (slip fit) a 7075-T6 aluminum sleeve of 31.5-mm outer diameter and 45-mm length (Fig. 1). The 7075-T6 base plate was machined with a 45-deg bevel, and then welded to the cylindrical sleeve. After the specimen was prepared/inserted, a 7075-T6 cover plate was press-fit into place using superglue. Three specimen types were prepared. 1) Thermally shocked (TS): pre-damage, in the form of non-contiguous cracks, was induced by 3 cycles of heating the specimen for one hour at 750°C with a subsequent ice water quench; thereafter, placing in the Al-sleeve. Although cracked, the specimens have integrity and strength. 2) Thermally shocked/cyclic loaded (TS/CL): specimens were thermally shocked as above and then subjected to six MTS machine loading/unloading cycles to 1.7 GPa while in the aluminum sleeve. After the cyclic loading, the loading anvils were removed and the cover and base plates were applied. The specimen, if removed from the aluminum sleeve, has interlocked comminuted pieces, and crumbles easily under a very small—"finger-pressure"—applied load. 3) Compacted powder (CP): SiC-N powder was placed into the Al-sleeve through a series of incremental pours and compaction using an MTS machine, achieving 72-73 % of the theoretical density of SiC-N ($\rho_{\text{comp. powder}} \approx 2.35 \text{ g/cm}^3$). (Compacted powder is not a pre-damaged ceramic; it is the raw material from which the intact SiC is fabricated. But for purposes of this article, we will use the word "damage" to describe all three specimen types.)

The rods were made of pure gold (99.99%) and had a diameter of 1.0 mm and a length of 70 mm with the following material properties: density $\rho_p = 19.3 \text{ g/cm}^3$; hardness 65 HV5; UTS 220 MPa and elongation 30%.

The penetration process was observed with five 180 kV flash X-rays. The time measurements for the flash X-ray pictures are very accurate (to better than $\pm 5 \text{ ns}$). Thus, measurement uncertainties lie in the accuracy of the position measurement from the flash X-ray pictures, which is about ± 0.1 to 0.15 mm. Since the gold rod erodes and generates a mushroom head, the foremost front of the gold deposit in the ceramic was used as the penetration depth. Additional details on the experiments can be found in Ref. [3].

The position-time and rod length-time data are quite linear for most experiments. The thermally shocked targets were launched at high velocities ($> 2.2 \text{ km/s}$); all of these had steady-state penetration. Steady-state penetration was

observed for impact velocities above 1.8 km/s for the *in-situ* comminuted (TS/CL) ceramic, and above 1.5 km/s for the compacted powder specimens. The slope of the penetration-time regression gives the penetration velocity, u . The penetration velocities versus impact velocities for the previous experiments are shown in Fig. 2. Open symbols denote results where the penetration-time response was nonlinear over some or most of the penetration event. The penetration velocities of only the early or linear portion of penetration are plotted for these open symbols. Also included in the figure are the data for intact (bare) SiC-N specimens from Ref. [2]. The data for the intact SiC extends to impact velocities of ~ 6 km/s; only the three lowest velocity data points are shown here.

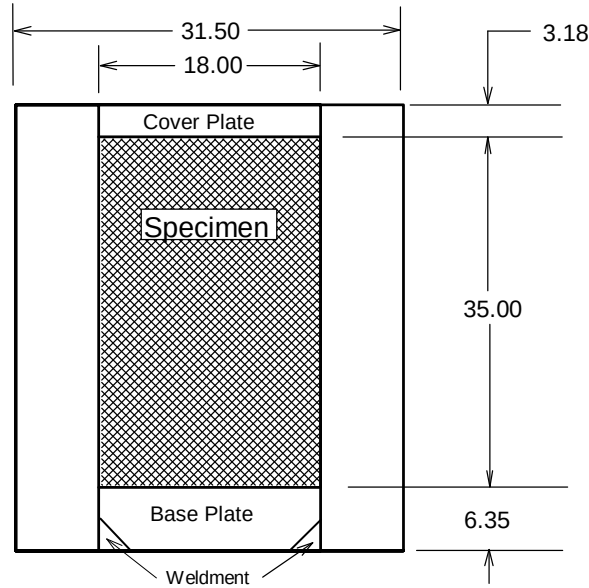


Figure 1. Test specimen with aluminum sleeve and cover plates (dimensions in mm).

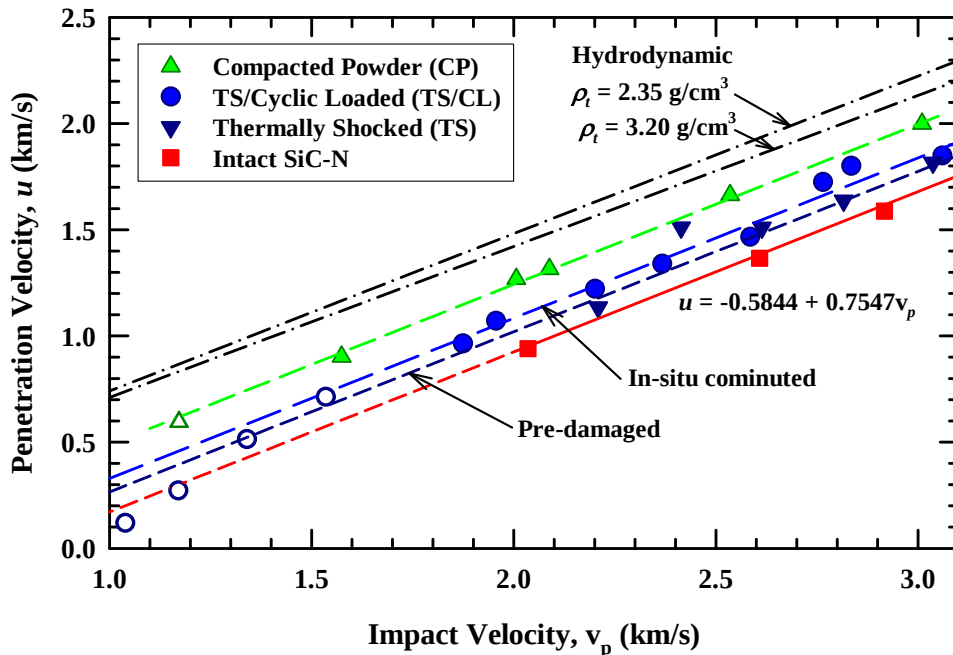


Figure 2. Penetration velocity u vs. impact velocity v_p for different types of SiC-N specimens.

The test series with intact SiC-N in [2] provided a linear relationship between penetration velocity u of the gold rod in the ceramic and impact velocity v_p : $u = -0.5844 + 0.7547v_p$. This regression line for the intact SiC has been extrapolated in Fig. 2 to lower impact velocities, as indicated by the dashed line. We know that the u versus v_p response of intact SiC-N cannot be linearly extrapolated to the very low impact velocities shown in Fig. 2, because at some impact velocity the projectile begins to dwell at the target interface (for example, see [4-5]), but the linear extrapolation serves as a “trend” line.

The evaluations of u for the TS-, TS/CL- and CP-SiC ceramic specimens show a very similar behavior. Linear regression analyses were performed on the experimental data shown in Fig. 2, with the result that the slopes for TS, TS/CL, and CP were very similar to that for the intact SiC. Therefore, linear regression analyses were conducted to determine the intercepts for the TS, TS/CL, and the CP data, *with the slope constrained to be 0.7547*, the value determined for the intact SiC data [3]. These are the regression lines shown in Fig. 2. For the regression to the TS data, the data point at $v_p = 2.4$ km/s was omitted since it deviates more than 6.5 standard deviations from a regression fitted without the point. Examining Fig. 2, it is observed that $u_{\text{intact}} < u_{\text{pre-damaged}} < u_{\text{in-situ comminuted}} < u_{\text{powder}} < u_{\text{hydrodynamic}}$, corresponding to reductions in strength or resistance to penetration in the same order.

NEW EXPERIMENTAL RESULTS

A new experimental test series was developed with several objectives. First, we wanted to verify that for the TS datum point at 2.4 km/s was really an outlier. Then, we wanted to extend the TS data to lower impact velocities. Six TS SiC-N targets (denoted as TS-2) were prepared as described above. They were placed in the aluminum sleeve and launched in the reverse ballistics mode at the suspended long, Au rod. In all aspects, the target specimens and experimental procedures were the same, including the construction of the aluminum sleeve. Impact velocities were varied between 1.248 and 2.543 km/s. The results are shown as the inverted open triangles in Fig. 3. Several observations can readily be made. The original TS datum point at 2.4 km/s does, indeed, have a higher penetration velocity than the new data. However, no longer do all the TS data lay consistently below the *in-situ* comminuted (the circles). In fact, within data scatter, there appears to be no difference in the penetration response of the two types of damaged (TS and TS/CL) SiC-N. At impact velocities less than ~1.5 km/s, some portion or all of penetration is nonlinear in time. For the new TS data, only the linear or early time data were used to estimate the penetration velocity, similar to what was done previously for the lower velocity TS/CL results (open circles). At the lower impact velocities, the new TS-2 data are also indistinguishable from the TS/CL results with respect to penetration response.

Next, six intact SiC-N specimens, 18-mm in diameter and 35-mm long, were prepared and inserted into the aluminum sleeve, Fig. 1. These experiments differed from the original intact series, which were done with 20-mm diameter and 35-mm long, bare (no sleeve or cover plate) SiC-N cylinders. The objective for these new experiments was to investigate if the aluminum confinement influenced penetration results. One other difference is that the original intact experiments [2] were

conducted with 0.75-mm diameter, 50-mm-long Au rods; whereas, all the more recent experiments were conducted with 1.00-mm diameter, 70-mm long Au rods. (The larger diameter rod was adopted to facilitate handling and positioning of the Au rods in the target chamber.)

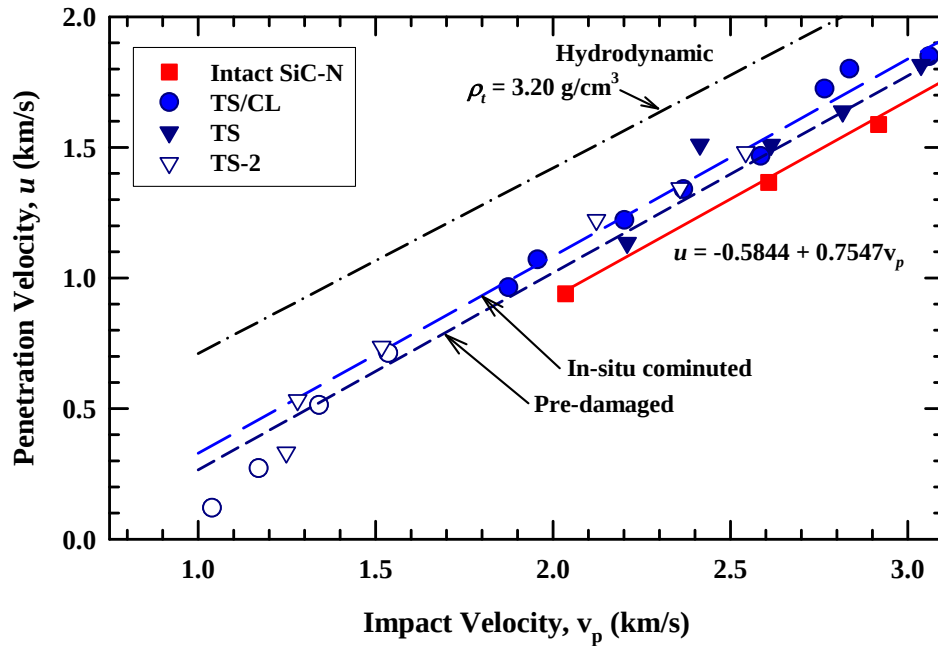


Figure 3. New pre-damaged (TS-2) experimental results.

Previous work had demonstrated that the diameter of the target should have no effect at higher impact velocities [6]; however, numerical simulations indicate that penetration velocity increases at lower impact velocities, e.g., $\sim 1.2 - 1.5$ km/s. Therefore, the test series was designed to obtain data over a velocity range of approximately 1.2 to 3.0 km/s. The results are shown in Fig. 4 as the solid hexagons. It was expected that the presence of the cover plate would affect the lowest velocity experiment by allowing dwell [5], and the lowest impact velocity of 1.234 km/s showed dwell-like behavior and very little penetration. However, the results at the higher impact velocities were clearly surprising. *The penetration response of these intact (but confined within the aluminum cylinder) SiC-N cylinders cannot be distinguished from the penetration response of the two pre-damaged SiC-N specimens (circles and inverted triangles).* The SiC-N specimens for these new experiments come from a different production lot than the older experiments (two purchase orders separated by several years). However, each lot had standard characterization tests conducted and reported (density, longitudinal and shear sound velocities, Poisson's ratio, Young's modulus, shear modulus, and Knoop hardness), and the results for the two lots agree within the measurement accuracies. Further, our experience is that the processing and fabrication of SiC-N specimens by BAE Systems Advanced Ceramics, Inc., is highly controlled. Thus, we do not believe the difference in the penetration response between the new and old intact experiments is likely the result of differences in the SiC-N.

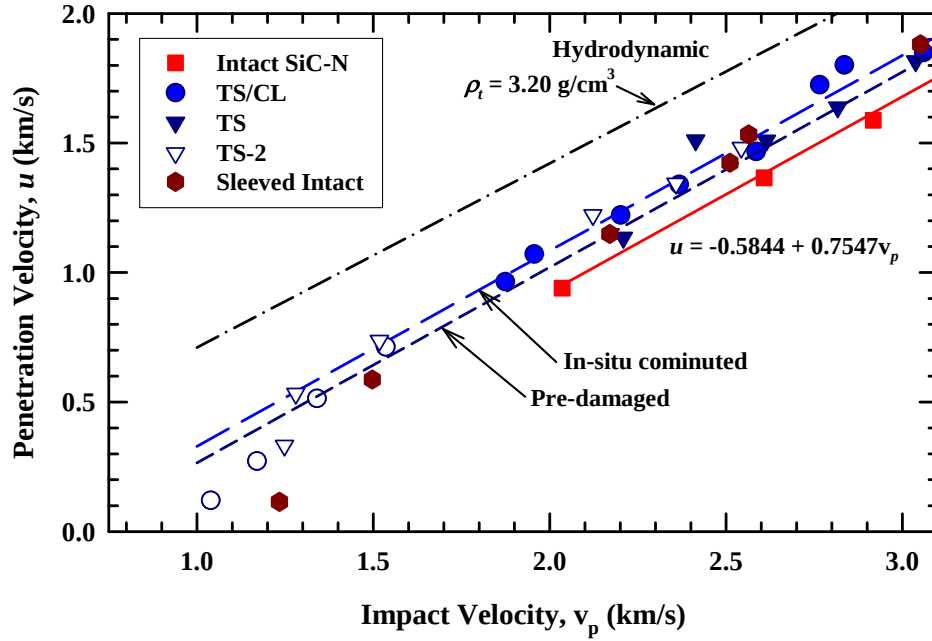


Figure 4. Sleeved, intact SiC-N experimental results.

INTERFACE DEFEAT EXPERIMENTS

A test series was also designed to investigate interface defeat and the transition from dwell to penetration [7]. There were eight experiments for bare, 20-mm-diameter SiC-N targets (no aluminum sleeve was used for these experiments). The Au rods were all 1.00-mm in diameter. Because the interest was in dwell and interface defeat, the impact velocities were relatively low, all below ~ 1.6 km/s. The open squares in Fig. 5 denote the penetration velocities as a function of impact velocity. Interface defeat on a bare ceramic was seen at an impact velocity of 0.776 km/s. Otherwise, the penetration response is similar to the other 1.00-mm-diameter Au rod data. As these experiments did not have the aluminum sleeve or cover plate, and since there is no difference in the penetration response of the intact and pre-damaged targets, it does not appear likely that the disagreement between the original intact data [2] and these newer data can be explained by differences in confinement.

Eight experiments were conducted with a copper buffer or copper plate on otherwise unconfined ceramic (the copper buffer/plate diminishes the effect of the impact shock, and provides ramp loading to the underlying ceramic) [7]. With this buffer, complete interface defeat was observed at an impact velocity of 1.382 km/s. At slightly higher impact velocities, the projectile dwells, and then transitions to penetration. It has been seen experimentally, by comparing the results of Lundberg, *et al.* [8] to those of Orphal and Franzen [1], that the penetration velocity after dwell is very similar as if dwell had not occurred. This has also been seen computationally [5]. We see that the solid triangles in Fig. 6, which denote the dwell-to-penetration experimental results with the copper buffer, lie within the scatter of all the other data. (The “pre-damaged” dashed line plotted in the previous figures has been deleted from Fig. 6.)

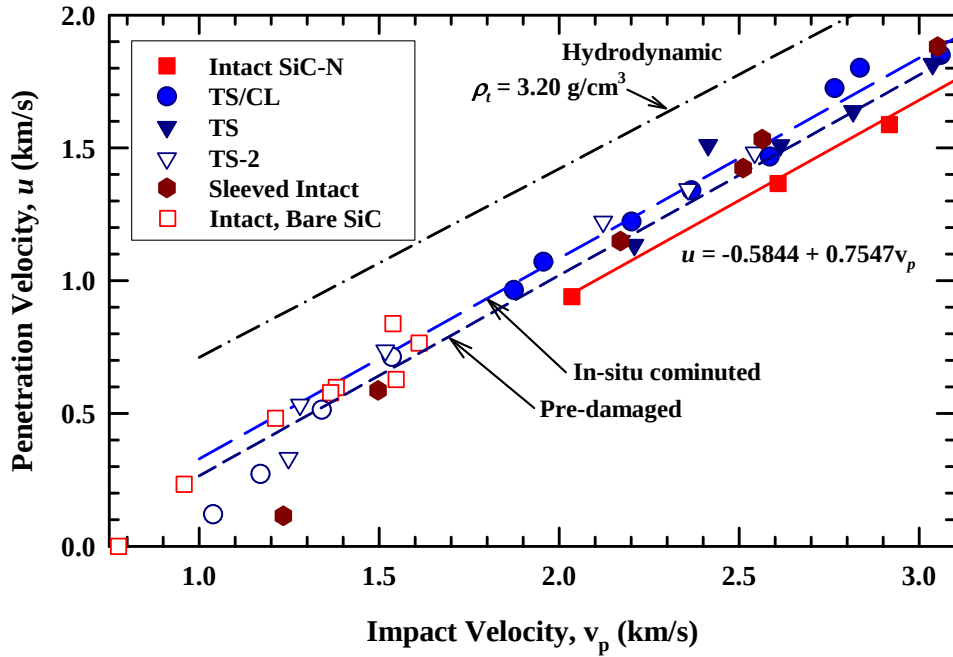


Figure 5. Intact, bare, low-velocity SiC-N results

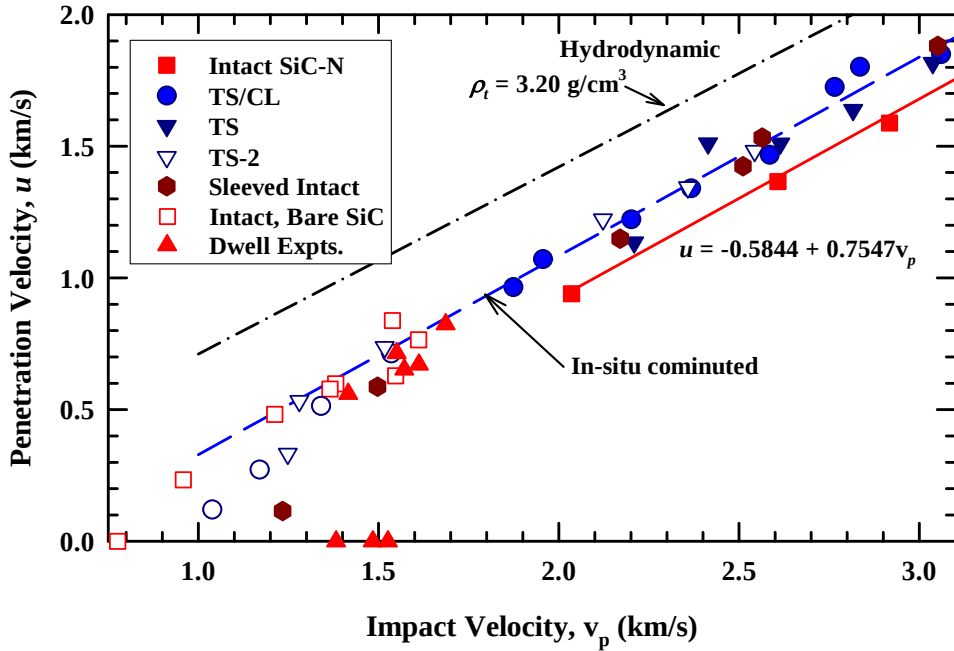


Figure 6. Results of dwell experiments after transition from dwell to penetration.

We make one last observation. It appears that the penetration response, as measured by u , of pre-damaged ceramic and that of intact ceramic at low impact velocities, has more variability than that of intact ceramic at higher impact velocities. In particular, note the scatter in the data represented by the open squares and solid triangles (not including sustained dwell) between 1.5 and 1.6 km/s; although the highest u (open square) had one of the worst off-centered impacts combined with high yaw. The caution, then, is that one could be misled by examining only one datum point. Rather, it is an average penetration response—

with “average” denoting a range of impact velocities—that needs to be considered in evaluating the penetration resistance of a ceramic.

SUMMARY AND CONCLUSIONS

The new experimental data lead to two surprising results: 1) the ballistic resistance of the intact targets from Ref. [2] is larger (slower penetration velocity) than for the intact targets presented here; and 2) the new data indicate that there is no difference in the penetration response of intact versus pre-damaged (thermally shocked or *in-situ* comminuted, i.e., TS, TS-2, and TS/CL) ceramic, which is different than the results from Ref. [3] (which showed the intact targets to have more resistance than the pre-damaged targets).

The results for the intact targets in Ref. [3] are from Ref. [2]. A difference between the intact experiments of Ref. [2] and the intact experiments reported here is the diameter of the Au rod: 0.75 mm for the Ref. [2] experiments, and 1.0 mm for the ones reported here. Therefore, to provide insight into these surprising results, additional experiments are planned using 20-mm-diameter SiC-N cylinders (from the same production lot). No aluminum confinement will be used. The cylinders will be launched at suspended Au rods 0.75 mm and 1.0 mm in diameter, over a velocity range of 2.2 to 3.0 km/s. Recently, Andersson, *et al.* [9], suggested a projectile size effect for the dwell transition velocity, but made no predictions concerning the penetration velocity. The results of the planned experiments seem sure to be informative.

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