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ALTERNATIVE TEST METHODOLOGY FOR BALLISTIC PERFORMANCE RANKING OF ARMOR CERAMICS

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ABSTRACT

A laboratory test method for ranking the ballistic performance of ceramic materials is under development at the U.S. Army Materials Technology Laboratory (MTL) by the Ballistic Impact Behavior Group and Armor Systems Team. Rankings are based on residual penetration of a tungsten long rod fired at constant velocity through a laterally confined ceramic into a semi-infinite steel backup. By varying the thickness or areal density of ceramic from zero to a value producing no residual penetration, a ballistic performance map for the ceramic is generated. Different materials can be compared on the basis of residual penetration observed for a given areal density.

Ceramics tested to date include aluminum oxide in 90% and high purity forms, titanium diboride, silicon carbide, and boron carbide. Performance rankings observed for these materials are in agreement with the rankings yielded by conventional V_{50} protection ballistic limit (PBL) test methods.

This test method requires fewer shots than V_{50} tests, has sensitivity comparable to present test methods, and avoids the fundamental problem of V_{50} dependence on armor design. As a consequence, it should prove to be valuable for acceptance testing of production materials, comparison testing to rank the performance of new materials, and for parametric analysis of ballistic performance variations resulting from material properties, cell size, confinement, and similar factors.

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INTRODUCTION

Contemporary interest in ceramic materials as components of armor systems intended to defeat KE penetrators had its beginnings in the early sixties. The emergence of titanium diboride, silicon carbide, boron carbide, and various grades of aluminum oxide has provided the military community with relatively high efficiency armor options. The trade of lower cost for lower performance has become less attractive due to the decrease in ceramic material costs, and the increased penetration and lethality of current anti-armor munitions. As a result of this increased interest in ceramic armors, the need for a test to provide adequate evaluation and qualification of these materials becomes imperative.

To date, there has not been a totally satisfactory ballistic test to compare the performance of various types of ceramics or to assess the relative quality of any manufacturer's material. During the late seventies, and throughout the eighties, a large data base of terminal ballistic data emerged from the AMC/DARPA Armor Anti-Armor Program and subsequent Ceramic Composite Armor (CCA) Programs. Under these two programs, ballistic limits were, for the most part, generated for various ceramic armor materials in quarter-scale testing with a long rod penetrator (tungsten or depleted uranium). A majority of this work was performed at MTL, BRL, and the DoE laboratories.

Despite this extensive data base, limitations exist in comparing and interpreting the ballistic results. Although there were slight variations in the armor test configuration, the majority of data are based on an arbitrary "1-4-3" system. This system used a component thickness ratio of 1:4:3, with the most common configuration having a 0.25-inch-thick steel cover plate, a 1.0-inch-thick ceramic component, and a 0.75-inch-thick steel rear plate. It is readily apparent that a problem arises in comparing and interpreting ballistic data based on material thickness rather than areal density. Different armor ceramics have different areal densities for 1.0-inch-thick material (ranging from 13 pounds per square foot (psf) for B_4C to 23 psf for TiB_2); therefore, within the "1-4-3" system, various weight percentages of ceramics occur. Most of the armor systems tested had low ceramic weight percentages in the range of 24% to 36%. Recent studies versus similar threats indicate, however, that the optimum weight percentage of ceramic for ideal armor performance is 50% or greater. The testing conducted under this program did not evaluate the armor ceramics at optimum percentages; thus, low efficiencies would be expected. The problem of testing under conditions of variable ceramic areal density and differing weight percentages is compounded by use of different rear component materials. Data are available for various targets fabricated with rear plate materials including MIL-A-12560 *Rolled Homogeneous Armor,* MIL-A-46100 *High-Hardness Armor,* electroslag remelted 4340 steel, and Ti-6Al-4V. The areal densities and mechanical properties of these materials vary, further complicating comparisons. Finally, variations in test setup resulting from variations in confinement methods used at the different test facilities create difficulties in comparing the ballistic performance of different armor ceramics.

A better method for evaluating or ranking the ceramic material performance is to eliminate the effects of ceramic percentage, areal density, and test setup. This report presents an alternative test method which avoids the problems associated with the previous "1-4-3" system.

This test methodology will construct a performance map for a range of ceramic areal densities and allow comparison of materials to be conducted across this range. The method eliminates backplate component effects by using a very thick RHA plate of standard hardness (HRC 22.7 to 28.7) to approximate a semi-infinite backup for evaluation of the ceramic component. Performance is determined by the depth of residual penetration into the plate by a long rod penetrator after it has passed through the ceramic target. For convenience, this residual penetration value is referred to as "DOP." In addition, this method uses a standard test configuration with maximum simplicity, thus eliminating any effects on the ballistic performance from the test setup.

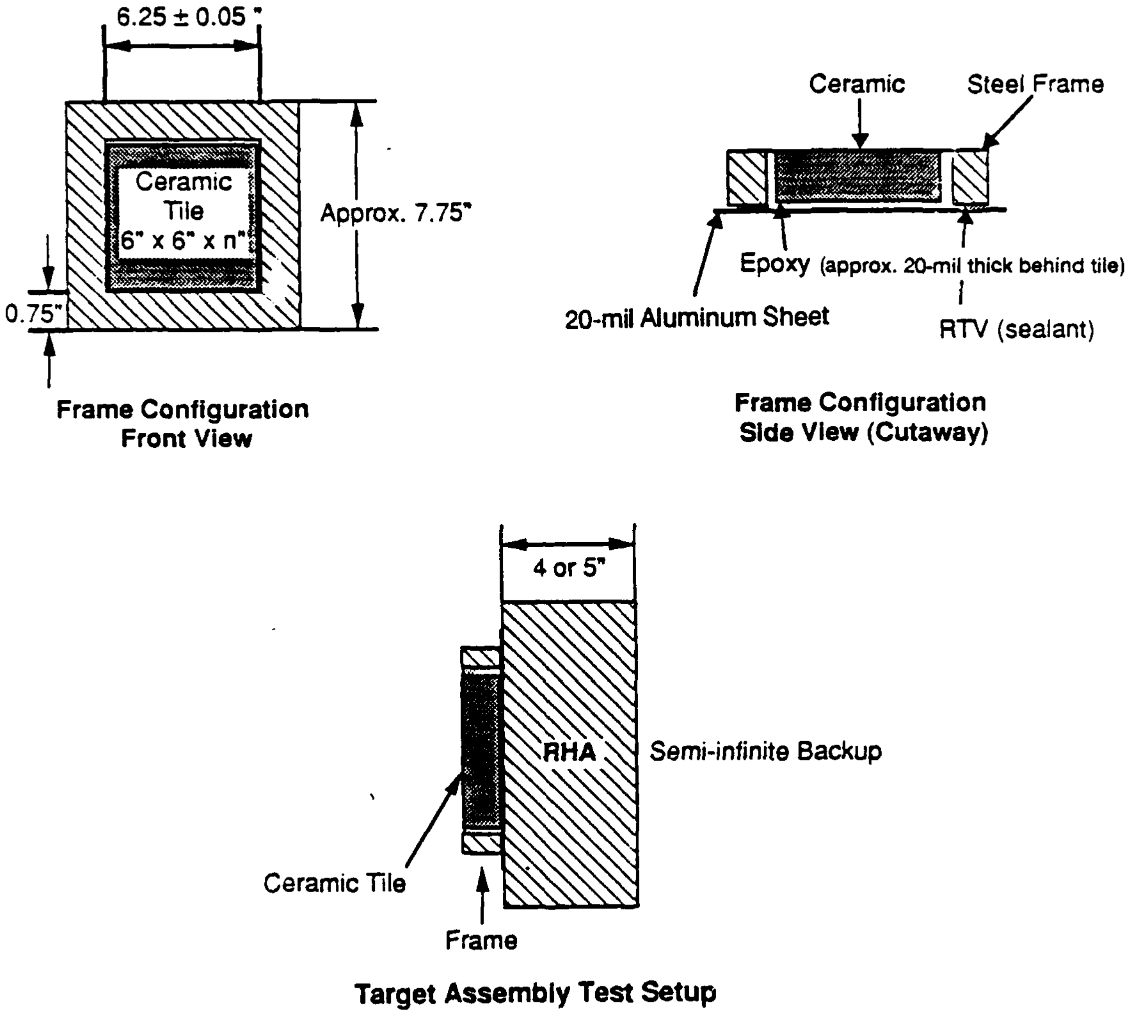
With performance maps and a standardized test configuration in hand, an acceptance test for ceramic materials can be established. Such a test, which is similar to the ballistic tests conducted for military specification steels and aluminums, would be valuable in establishing military specifications for armor ceramics. The advent of standard military specifications could further reduce the cost of ceramic armor materials, and make high efficiency ceramic armor systems more attractive. This method and target assembly technique also provides a means to easily perform parametric analysis of the effects on ballistic performance resulting from differing material properties, and other factors such as cell size, confinement, and penetrator configuration.

EXPERIMENTAL PROCEDURES

The target configuration used for these tests is illustrated in Figure 1. The target consists of a 6" x 6" ceramic tile of a given thickness laterally confined in a steel frame with a 0.75-inch web and a depth equal to or greater than the tile thickness. Ceramic tile thicknesses used for these tests ranged from 0.25 to 2.00 inches. No cover plate was employed. An epoxy resin was used to retain the tile in the frame, in addition to being spread in a thin layer (approximately 0.020 in.) behind the tile to accommodate any slight surface irregularities. A 0.020-inch aluminum sheet was used behind the tile to contain the epoxy within the frame. The backup block employed was RHA steel (MIL-A-12560, class 3) of 4- or 5-inch thickness. (Specification requirements for this steel mandate the same hardness range for these thicknesses.) RHA was chosen as representative of metallic armor which could be employed in a composite armor system; it is also a well-characterized and readily available material. This choice also provides dimensionally feasible target assemblies. An aluminum backup would have to be extremely thick to contain the residual penetration and avoid rear surface effects. Ceramic assemblies were clamped onto the steel backup block for testing and removed after firing.

All tests were run at the U.S. Army Materials Technology Laboratory. The projectile used was a 91% W long rod penetrator with a diameter of 7.87 mm (0.310 in.) and an aspect ratio of 10. Rod weight was 65 grams, and density was 17.45 g/cc. The penetrator was launched in a package consisting of a nylon-6 obturator, a steel pusher, and a two-piece phenolic carrier. The launch tube was a 20-mm smooth-bore of 10-foot length, with the breech end modified for a 30-mm cartridge case and firing action.

The nominal test velocity used for all ceramic shots was 4900 feet per second (fps) (1.5 km/sec), although some shots were made up to 5750 fps (1.75 km/sec) into the steel backup for baseline data collection. This velocity was chosen in order to produce the maximum practical residual penetration while being consistently achievable under operating conditions. Measurement of the projectile yaw and velocity was accomplished by a flash X-ray system, shown in Figure 2. The X-ray equipment used was the Hewlett-Packard 150 kV Flash X-Ray System, Model 43731A. Beam exposure time was 70 nanoseconds. Yaw and velocity of the projectile were measured from two sets of orthogonal X-rays triggered by the passage of the penetrator through two laser break screens. A check velocity was also obtained directly from the laser timing apparatus. Approximately 15 inches before striking the target, the projectile passed through a paper break screen, which triggered a set of three X-ray tubes arranged vertically inside a cluster box tube head that was orthogonal to the target face. The cluster box tubes were fired sequentially at adjustable intervals. This arrangement allowed observation of projectile impact and initial penetration, as well as formation of the debris cloud.



Frame Configuration
Front View

Frame Configuration
Side View (Cutaway)

Target Assembly Test Setup

Figure 1. Ceramic target assembly.

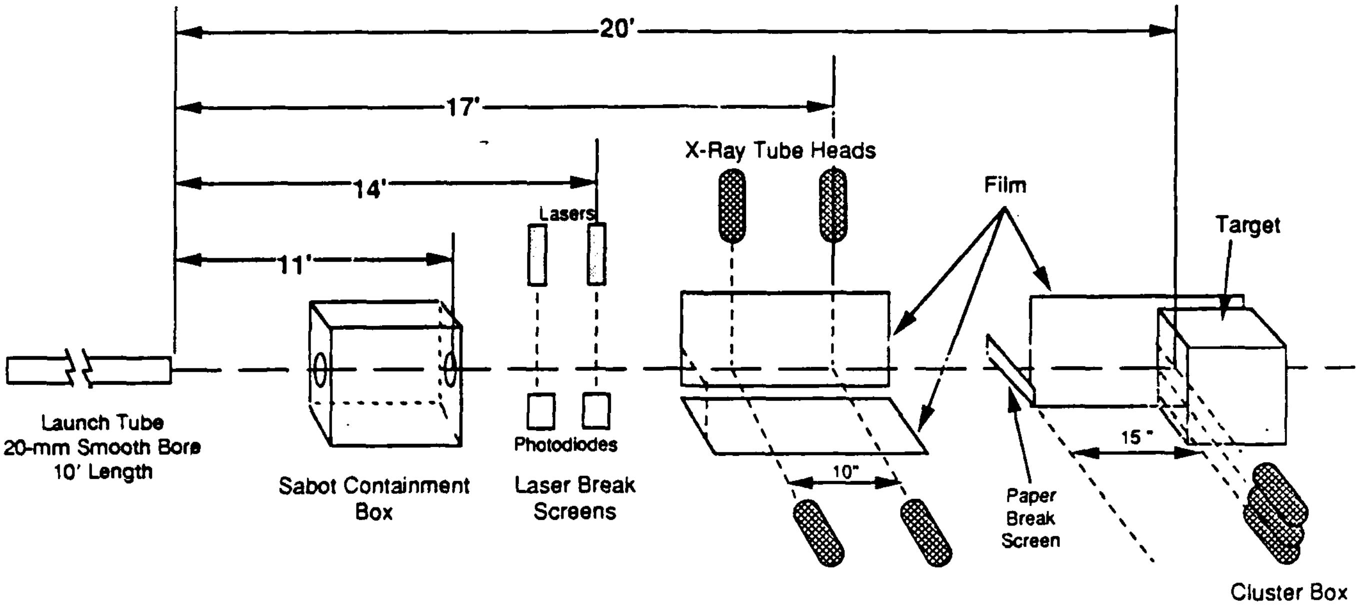
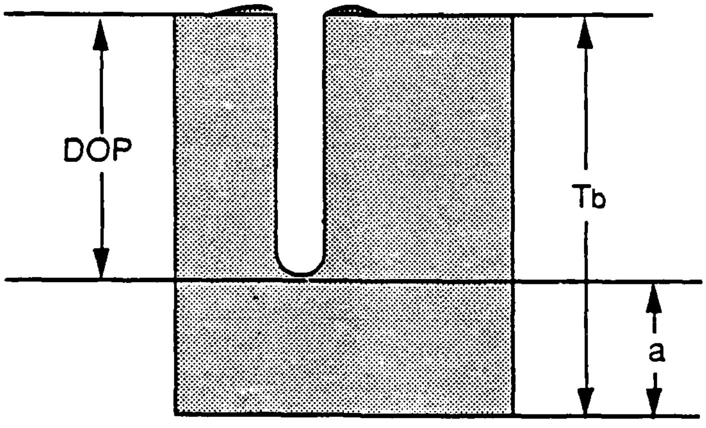


Figure 2. Range diagram.

All residual penetration measurements were taken directly from sections of the RHA block. A bandsaw was used to section all penetration cavities, and measurements were made with vernier calipers on the sections, as indicated in Figure 3. Measurement of the "a" value in this way avoids error which could be caused by deformation of the steel block around the entrance cavity. This method was chosen over measurement of X-ray images of the cavity due to focusing difficulties resulting from the thickness of RHA present in sections containing the penetration cavity, as well as for simplicity in data collection.



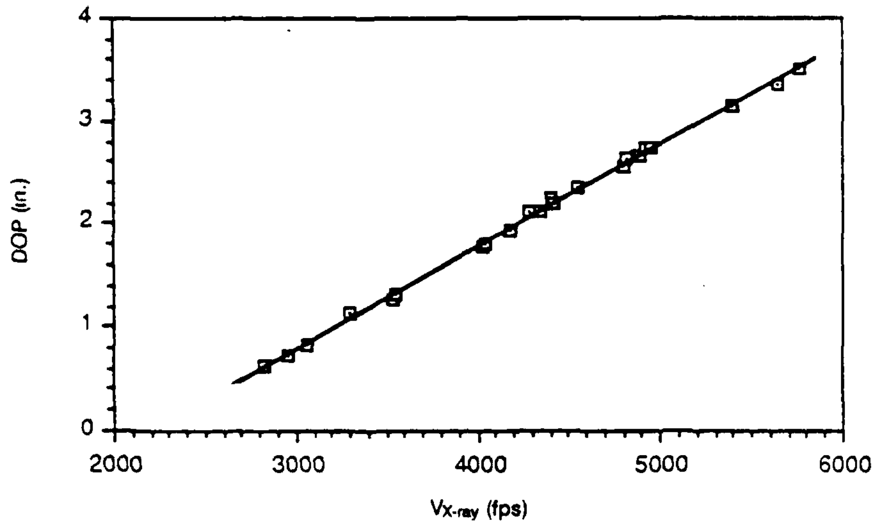
$$DOP = Tb - a$$

Figure 3. Measurement of residual penetration.

RESULTS AND DISCUSSION

Baseline Tests

To provide baseline data for residual penetration into the RHA steel backup, a number of shots were fired over a range of velocities from 2700 fps to 5750 fps (0.80 to 1.75 km/sec). Residual penetration values were then measured and plotted as a function of striking velocity to produce a baseline curve (Figure 4). All data used to produce this plot were from shots with less than 3 degrees total yaw; as previous studies[1] had indicated this as an appropriate cutoff point for ballistic limit tests at zero obliquity. A linear regression on this baseline data produced an empirical equation (Figure 4) which can be used to predict the residual penetration at a given striking velocity. The square of the correlation coefficient for this fit is 0.998, indicating that this fit is a good approximation.



$\text{DOP} = -2.200 + (0.001) \times V_{x\text{-ray}}$ $R^2 = 0.998$

So, Predicted DOP at 4900 fps = 2.700 in.

Figure 4. Baseline data for RHA steel.

A supplemental plot of residual penetration against total projectile yaw at a velocity of 4900 fps was also produced (Figure 5); this indicates a trend similar to published data for yaw effect on the ballistic limit with long rod penetrators.[1] Direct observations of the penetration cavity also show a qualitative tendency toward increased skew and asymmetry as the yaw increases above 3 degrees.

Additional measurements were made to determine the velocity of the rod during the initial stages of penetration into the block using the time-sequenced flash X-rays taken at impact (Figure 6). These data showed that deceleration of the rod end was negligible in this early penetration regime. The impact X-rays do not allow observation of the block interior, so direct observation of the penetration process was not possible. No signs of rod fracture or bulging were observed during impact. It is expected that the penetration process is mainly

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[1] ZUKAS, J. A. et al. *Impact Dynamics.* John Wiley & Sons, New York, 1982.

erosive and quasi-steady state until the initial rod length has been almost completely consumed at the 1.5 km/sec test velocity. The relatively constant diameter of the penetration cavity would seem to bear this out. In many cases, some amount of penetrator material was found in the cavity which had not been ejected as particles, but appeared to have been extruded toward the rear of the rod during penetration. This behavior is also consistent with the suggested mechanism.

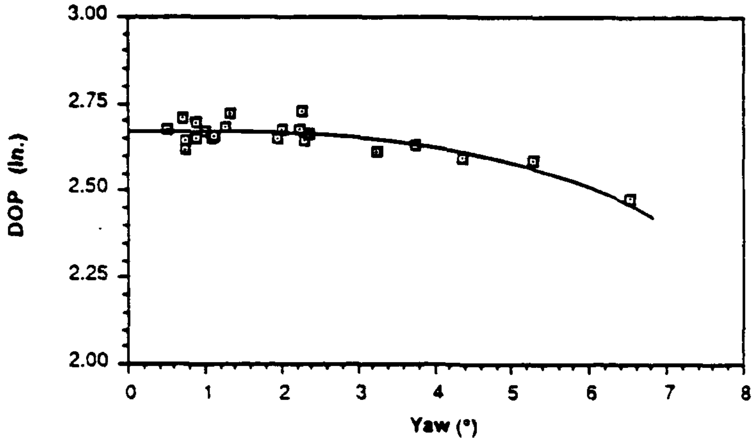

Figure 5. Yaw effect on residual penetration.

Ceramic Tests

A variety of different ceramics, to include the major classes of armor ceramics, were tested to provide a suitable basis for material comparison and to determine the validity to the test procedure. All materials used are commercially available. Ceramics tested included: 90% pure sintered aluminum oxide produced by Coors, Ebon-A hot-pressed 99.8% pure aluminum oxide from CECOM, hot-pressed boron carbide from Eagle-Picher, sintered silicon carbide from Sohio, and hot-pressed titanium diboride from Ceradyne and CECOM.

Ceramic target assemblies, as previously described, were fabricated for all tiles tested. In general, four to five tiles per thickness (or areal density) were tested for each material, unless fewer were available. All data shown were taken from shots with total yaw under 3 degrees. In order to correct for variations in the actual strike velocity, all residual penetration values were normalized to a striking velocity of 4900 fps by means of the empirical fit as shown in Figure 4. The correction is made as follows: Corrected DOP = Measured DOP + $[0.001 \times (4900-V_{X\text{-ray}})]$. This technique should be uniformly valid for different materials provided that a significant amount of the rod reaches the backup plate, and that the rod defeat mechanism has not significantly changed due to the presence of the ceramic. In support of this assumption, observation of early impact stages via flash X-ray techniques show no significant deceleration of the rod or signs of failure. At present, due to the size distribution present in the particle, it is not possible to differentiate between particles from the ceramic, and eroded particles from the tungsten rod and backup block. It should also be mentioned that retained penetrator material, like that described previously, was often found in the backup blocks from the ceramic tests when the degree of residual penetration was sufficiently large. (When penetration occurred mainly in the ceramic, the eroded rod material would have been ejected together with the ceramic fragments.)

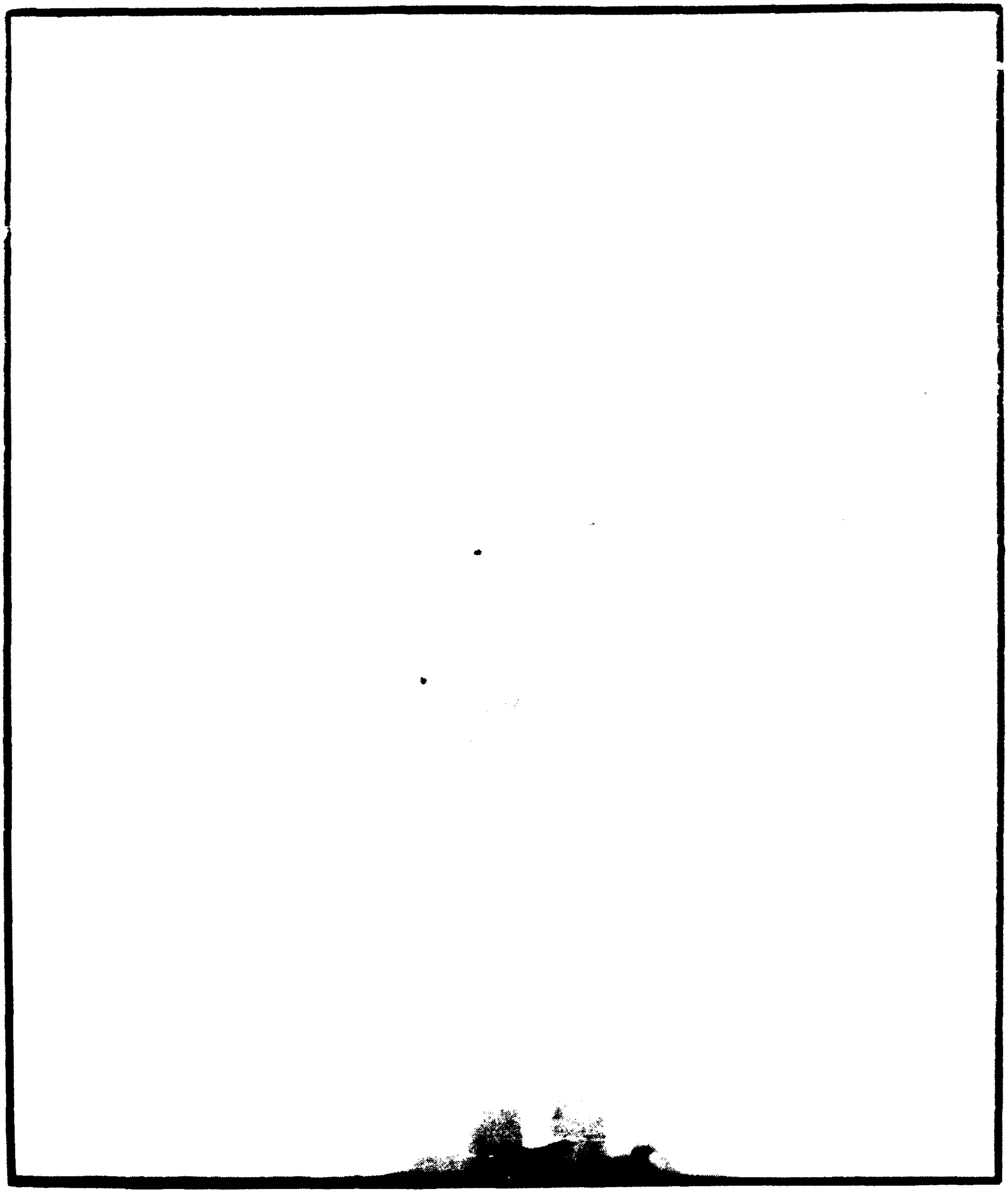

Figure 6. RHA baseline impact X-ray.

Photographs of the impact process exhibit a number of common traits, regardless of the material present. A typical X-ray with exposures made at impact, impact + 100 microseconds, and impact + 200 microseconds is shown in Figure 7. The debris cloud begins to form just after impact and slowly expands. Initial particle sizes tend to be small; particles ejected later have a greater size range. Another feature evident in this picture is the long time over which debris cloud formation occurs.

The failure patterns in the ceramic exhibit several notable features. The first of these is the increase in extent of the fracture zone as the tile thickness increases. Thin tiles (under 1 inch) contain little fractured material away from a region roughly 2 to 2.5 inches in diameter centered on the impact point. As tiles become progressively thicker, the fracture area extends out to encompass the entire tile. This type of behavior holds for all materials tested, and seems to be directly related to thickness rather than areal density. The degree of comminution also varies with distance from the impact point, as would be expected.

The assumption of a semi-infinite backing plate has been checked by observation of the region behind penetration cavities. Bulging of the rear surface, as evidenced by loss of flatness, was only observed in one combination of target and backup (0.25-in. Al2O3 and 4-in. RHA), and was very slight, even for that case. As a result, the initial assumption should be adequate.

Aluminum Oxide

The 90% Al2O3 was tested at thicknesses in the range of 0.5 inch to 1.5 inch; the resultant data are shown in Figure 8. In this range, residual penetration decreases linearly with increased areal density of ceramic. As the fit shows, the linear approximation is very good here.

The Ebon-A high purity aluminum oxide was tested in tile thicknesses of 0.25 inch to 1.0 inch. Unfortunately, a number of shots were lost due to excessive yaw at the higher areal densities so that it is only possible to provide a range for the residual penetration (Figure 9).

Boron Carbide/Silicon Carbide

Data were obtained for both boron carbide and silicon carbide at thicknesses of 1.0, 1.5, and 2.0 inches. The results of these tests are shown in Figure 10 for B4C, and Figure 11 for SiC. These data sets both appear to be linear in the range tested, although the degree of scatter is somewhat higher than that of the 90% Al2O3. One feature noticeable in both plots is that the residual penetration predicted by this linear region for zero areal density is lower than the measured baseline value for zero areal density.

Titanium Diboride

Data for titanium diboride were obtained as shown in Figure 12. Tiles from 0.25 to 2.0 inches thick were tested; at the time of testing, tiles were not available between 0.5 inch and 1.0 inch or 1.0 inch and 1.5 inch so the map is not well defined over these ranges. An interesting feature is the apparent existence of two different regions of performance as the areal density increases. It is also notable that TiB2 is the only material tested for which zero residual penetration was achieved, providing one endpoint on the performance map.

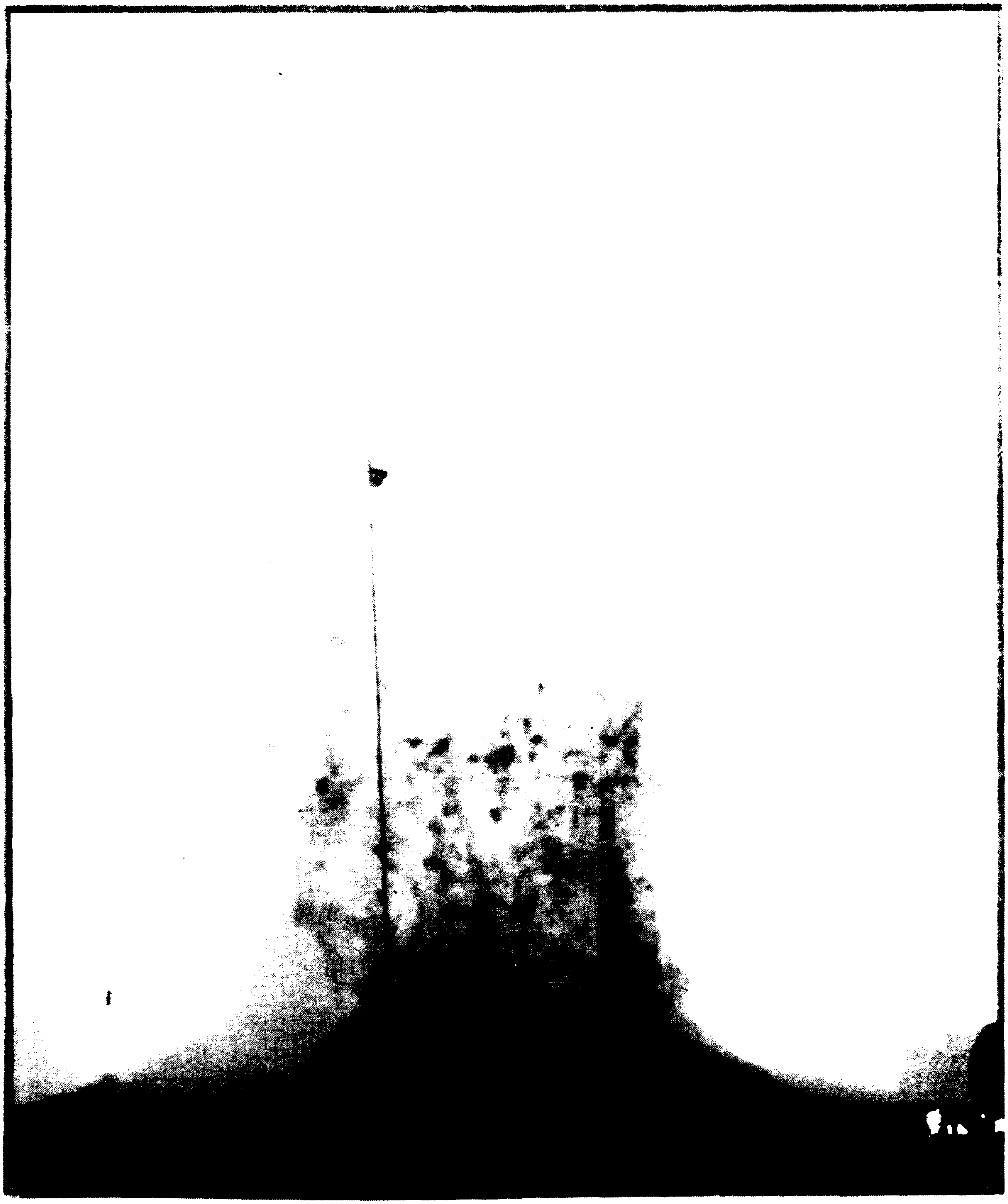

Figure 7. Ceramic impact sequence.

One case of zero DOP was observed at 1.5-inch thickness; the penetrator had apparently just stopped at the tile-backup interface. Both 2-inch tiles tested produced zero DOP values, and also retained some thickness of ceramic in front of the penetrator.

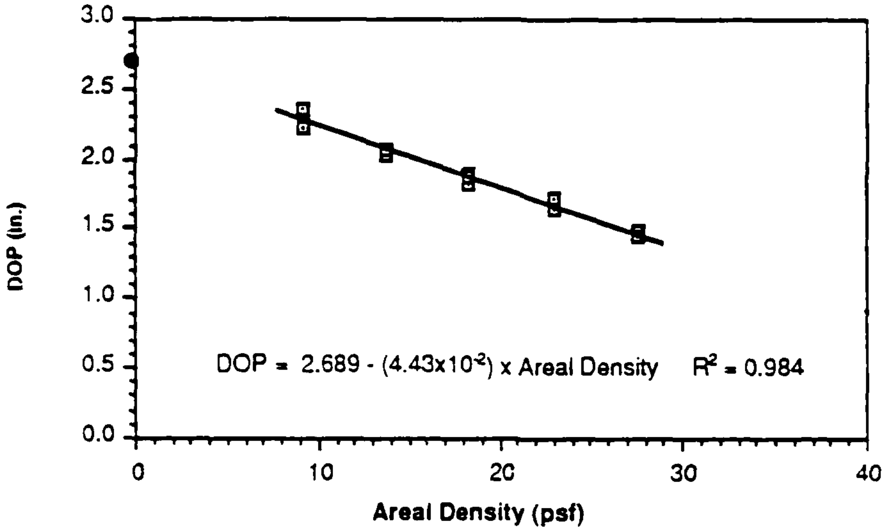

Figure 8. 90% aluminum oxide.

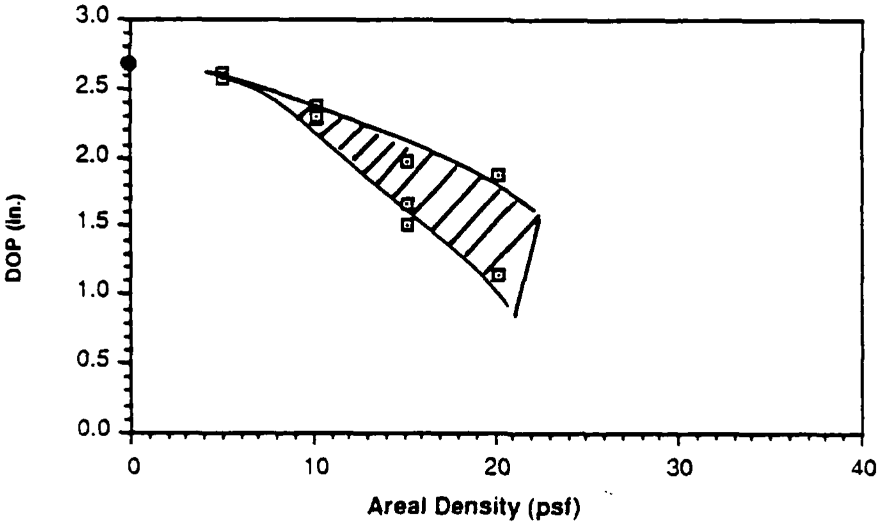

Figure 9. 99.8% aluminum oxide.

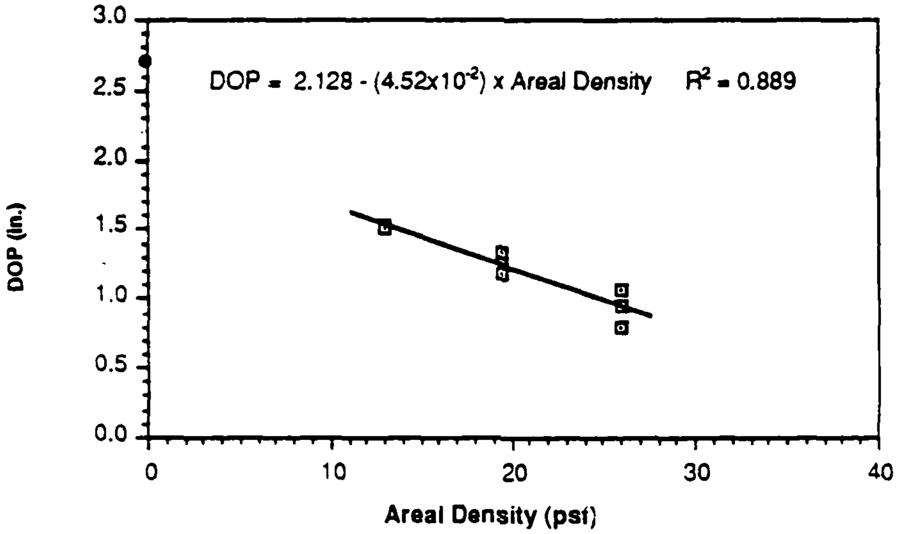

Figure 10. Boron carbide.

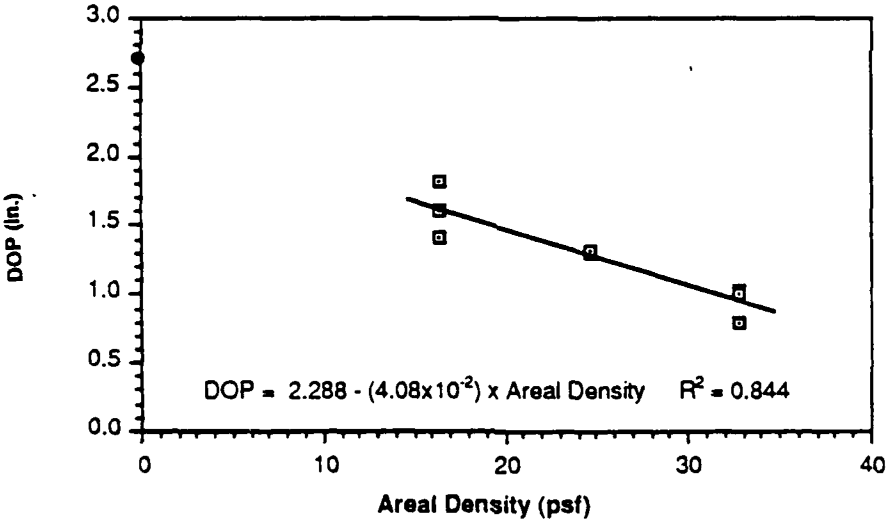

Figure 11. Silicon carbide.

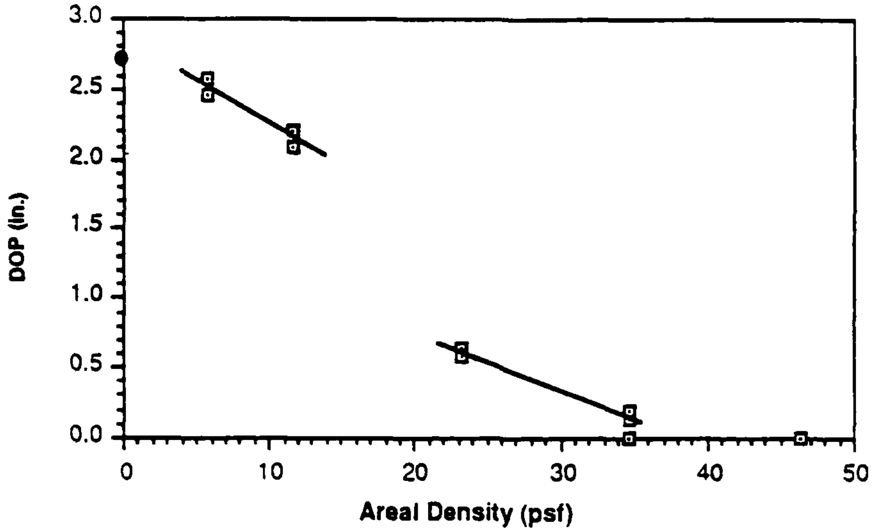

Figure 12. Titanium diboride.

Material Comparison

A direct comparison of the performance maps for all of the tested materials is provided in Figure 13. This plot appears to contain three different areas of interest. A theoretical performance map such as that in Figure 14 would be expected to have a similar form. The *initial region at low areal density* (roughly below 10 psf) for the test data shows a high degree of uniformity between the performance of all tested materials. This should correspond to Region 1 on the theoretical map, where the rod is overmatching the ceramic and the material efficiency is low.

In the central region, from roughly 15 to 30 psf, a clear set of distinct lines for the different materials is evident. A ranking of performance shows TiB_2 as most effective, followed by B_4C, SiC, and the 90% aluminum oxide. This is in reasonable agreement with the performance rankings provided by ballistic limit tests for these materials. Insufficient data were available at these areal densities to provide a distinct map for the Ebon-A. This region corresponds to the second area on the theoretical plot. Further, the data show that material response in this region is definitely linear. It is not yet possible to comment with certainty on the existence of a common slope for these lines, but the present data do not seem to preclude this. This indicates that differentiation between materials is possible based on the results from this test method. Further, this region of performance is the one of greatest interest for ranking materials to be used in armors.

The final region is entered by only the TiB_2 in these tests, and is not fully defined for that material. In this area, the penetrator is being stopped entirely in the ceramic, and there is no residual penetration. Instability in the penetration process due to the small amount of rod remaining may account for the scatter observed at the 1.5-inch thickness for TiB_2. This corresponds to the theoretical case of the rod being overmatched by the target (ceramic tile); penetration no longer occurs in a quasi-steady state, and a change in slope would be expected.

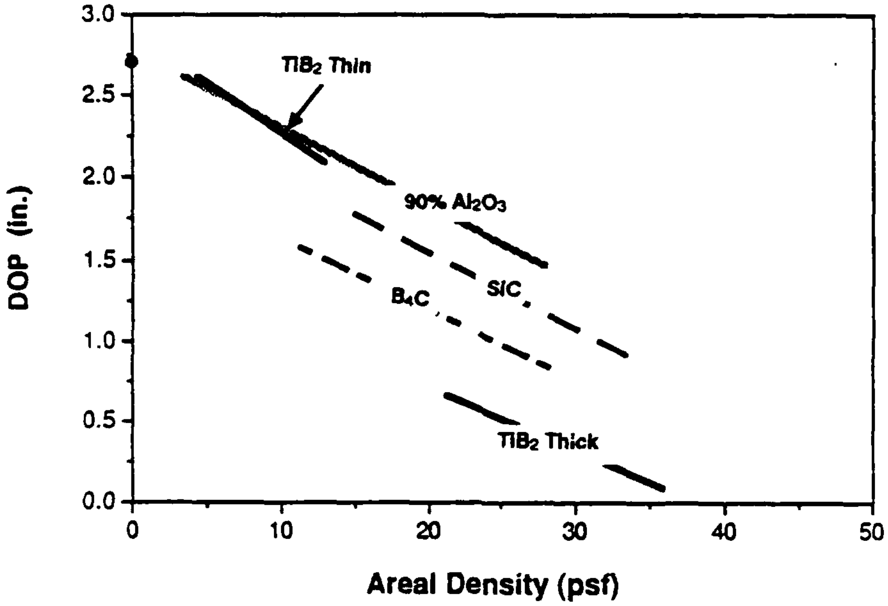

Figure 13. Comparison of ceramic performance maps.

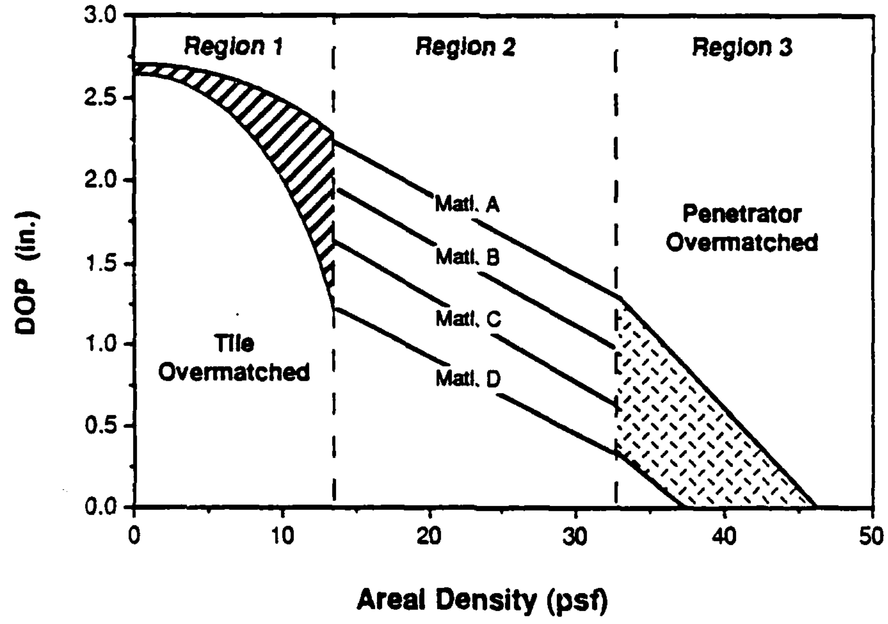

Figure 1 Theorized performance map.

CONCLUSIONS

From the foregoing ballistic data and analysis, several important points arise which demonstrate the promise of this test method for evaluation of armor ceramics:

- Avoids the fundamental problem of V_{50} dependence on armor design; e.g., front-to-back plate ratio and material
- Requires fewer shots than V_{50} tests
- Sensitivity is equivalent to that of existing ballistic test methods
- Comparison test to rank the performance of new materials
- Acceptance test for production materials

Several directions for future work are also apparent:

- Enhance current maps to provide a more extensive view of all performance regions
- Perform parametric analysis of ballistic performance variations resulting from material properties, cell size, confinement, and similar factors.

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A laboratory test method for ranking the ballistic performance of ceramic materials is under development at the U.S. Army Materials Technology Laboratory (MTL) by the Ballistic Impact Behavior Group and Armor Systems Team. Rankings are based on residual penetration of a tungsten long rod fired at constant velocity through a laterally confined ceramic into a semi-infinite steel backup. By varying the thickness or areal density of ceramic from zero to a value producing no residual penetration, a ballistic performance map for the ceramic is generated. Different materials can be compared on the basis of residual penetration observed for a given areal density. Ceramics tested to date include aluminum oxide in 90% and high purity forms, titanium diboride, silicon carbide, and boron carbide. Performance rankings observed for these materials are in agreement with the rankings yielded by conventional V_{50} protection ballistic limit (PBL) test methods. This test method requires fewer shots than V_{50} tests, has sensitivity comparable to present test methods, and avoids the fundamental problem of V_{50} dependence on armor design. As a consequence, it should prove to be valuable for acceptance testing of production materials, comparison testing to rank the performance of new materials, and for parametric analysis of ballistic performance variations resulting from material properties, cell size, confinement, and similar factors.

U.S. Army Materials Technology Laboratory
Watertown, Massachusetts 02172-0001
ALTERNATIVE TEST METHODOLOGY
FOR BALLISTIC PERFORMANCE RANKING
OF ARMOR CERAMICS -
Patrick Woolsey, Stephen A. Mariano, and
David Kokidko

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Key Words

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