Testing of Body Armor Materials for Use by the U.S. Army--Phase II: Letter Report

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Committee to Review the Testing of Body Armor Materials for Use by the U.S. Army--Phase II

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Division on Engineering and Physical Sciences
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Mailing Address:
500 Fifth Street, NW
Washington, DC 20001
www.nationalacademies.org

April 22, 2010

J. Michael Gilmore
Director, Operational Test and Evaluation
Department of Defense
1700 Defense Pentagon
Washington, DC 20301-1700

RE: Phase II Report on Review of the Testing of Body Armor Materials for Use by the U.S. Army

Dear Dr. Gilmore:

At your request, the National Research Council (NRC) of the National Academies established the Committee to Review the Testing of Body Armor Materials for Use by the U.S. Army to assess the methodologies used for body armor testing. The committee provided its Phase I report to you on January 4, 2010. What follows is the evaluation developed in satisfaction of the Phase II component of the statement of task (see Attachment A):

> In Phase II, the committee will consider in greater detail [than in Phase I] the validity of using the column drop performance test described by the Army for assessing the part-to-part consistency of a clay body within the level of precision that is identified by the Army test procedures.
>
> The committee will prepare a letter report documenting the findings from its Phase II considerations.

This Phase II report is focused on the behavior of ballistic clay and on other issues relating to the test process that were raised in Phase I of the study. More detailed evaluations of the array of issues surrounding body armor testing, both present and future, will be presented in the final Phase III report.

The recommendations in this letter report are based on the information that the committee received from the Army and on discussions and observations during a single 4-day meeting that included a site visit to the Aberdeen Test Center (ATC) at the Aberdeen Proving Ground, Maryland. At this meeting, the committee received briefings on specific issues raised in Phase I and by the Phase II statement of task that were of interest to the sponsor. The committee reviewed documentation on the Army's body armor testing program in general and on its tasks for Phase II in particular.

During the site visit, the committee members observed how ATC tests body armor using consistent methodologies for the handling and calibration of the clay (the column drop performance test) and for the measurement of the backface deformation, including procedures for assessing the part-to-part consistency of the clay. In addition, the committee reviewed the statistical basis for the testing and analyzed proposed revisions to the statistical protocols used.

The Phase II Committee was greatly appreciative of the dedication, qualifications, and openness of the ATC staff. Clearly they seek to achieve the highest standards possible for armor testing and are pursuing refinements in established techniques and advances in technology to provide the very best armor performance for our soldiers. As described in the pages that follow, adequate resources are required to achieve such a goal. The committee's analysis of the Phase II issues resulted in the development of 19 recommendations that are summarized in Box S-1 on page 3. These actions are urgently needed to achieve greater part-to-part consistency in the ballistic clay, to analyze BFD dynamics, to determine possible replacements for modeling clay, to achieve a national clay standard for testing body armor, and to implement statistically based protocols. The overarching recommendation is as follows:

Overarching Recommendation: The committee applauds DOT&E for assuming a national-level leadership role in bringing the body armor test community together. The committee recommends that the DOT&E (1) work with Congress, DoD, the military services, and other organizations to find the resources necessary to implement the recommendations described in this report and summarized in Box 1 and (2) oversee, review, track, and assist the designated action organizations with implementing these recommendations. This approach should result in more consistent test results that will provide equally survivable but lighter-weight body armor to our military service members and civilian police forces.

Sincerely,

MG (ret.) Larry G. Lehowicz, *Chair*
Committee to Review the Testing of
Body Armor Materials for Use by
the U.S. Army

Attachments
A Statement of Task
B Committee to Review the Testing of Body Armor Materials for Use by the U.S. Army – Phase II
C Acknowledgment of Reviewers
D Acronyms

Phase II Report on Review of the Testing of Body Armor Materials for Use by the U.S. Army

The committee's analysis of the Phase II issues resulted in the development of 19 recommendations that are summarized in Box S-1 and discussed in detail in the following sections of the report.

Box S-1
Phase II Recommendations to Improve Body Armor Testing

Achieving Greater Part-to-Part Consistency in Clay

1. Quantify the Medical Results of Blunt Force Trauma on Tissue and Incorporate Results into the BFD Methodology
2. Determine Short-Term Standard Clay Specification
3. Conduct Rheological and Thermogravimetric Measurements
4. Procure and Experiment with a Clay Compounding Machine
5. Examine Technologies for "In Box" Mechanical Clay Working
6. Modify TOP 10-2-210 Procedures to Add a Post-calibration Drop (ATC, 2008)
7. Experiment with Various Clay Box Sizes and Shapes
8. Develop and Experiment with a Gas Gun Calibrator or Equivalent Device

Analyzing Backface Deformation Dynamics

9. Analyze the Signal-to-Noise of Flash X-Ray Cineradiography
10. Experiment with Microscopic Temperature and Displacement Sensors in Clay
11. Experiment with the High-Speed Photographic Analysis of BFD Creation in Ballistic Gelatin

Determining Possible Replacements for Modeling Clay

12. Study Ballistic Gelatin as a Mid-Term Alternative to Modeling Clay
13. Study Microcrystalline Waxes as a Long-Term Alternative to Modeling Clay or Ballistic Gelatin.

Achieving a Single National Clay Standard for Body Armor Testing

14. Empower and Resource the Ad Hoc Clay Working Group
15. Convene a Nationally Recognized Group to Establish a Single National Standard for Handling and Validating Clay

Implementing Statistically Based Protocols

16. Compare the Proposed Statistically Based Protocol with the Existing USSOCOM Protocol
17. Quantify the Variation in the Body Armor Test Process and Incorporate in the Protocol
18. Develop a Statistically Based LAT Protocol
19. Conduct Due Diligence Before Implementing and Formally Adopting a Set of Statistically Based Protocols

INTRODUCTION

This section describes the expertise of the Phase II Committee membership, the ceramic armor plates being tested, the testing process, the layout of the testing range, and relationships between medical studies and use of modeling clay in body armor testing.

Phase II Committee Expertise

At the conclusion of Phase I, the Phase I Committee felt that greater consistency in the oil-based modeling clay could reduce variability in the body armor test and give more consistent and precise results. More precise results, in turn, could allow certifying with a high degree of confidence lighter weight armor plates that achieve the same survivability for a soldier. As a consequence, the membership of the Phase II Committee included additional experts on clay, who could address the statement of task requirement to "assess the part-to-part consistency of clay" in more detail.

The sponsor appreciated the Phase I Committee's support for the development of a statistically based protocol to determine test sample sizes and other aspects of testing. The Phase II Committee was asked to continue that work in Phase II, and an additional statistician was appointed to the Phase II Committee.

Ceramic Armor

Ceramic materials have been used successfully in personal armor systems to defeat small-arms threats. They are preferred for personal armor systems because they are lighter than more traditional armor made of metallic alloys. Properties that contribute to the performance of ceramic armor include superior hardness, low density, favorable elastic constants, and high compressive strength. However, as stand-alone items, ceramics would not be particularly good because of their low tensile strength, brittle response, and sensitivity to small mechanical defects such as pores and cracks. Hence, ceramics are used in combination with other materials, such as polymers and metals, to form laminar composites that provide excellent properties for body protection. A typical insert (also referred to as a "plate") of body armor consists of a layer of dense boron carbide or silicon carbide backed by a layer of metal or polymer composite; The entire plate is wrapped in tightly woven ballistic fabric. The ceramic layer breaks up an incoming projectile and dissipates its kinetic energy. The layer of polymer composite and/or metallic alloy provides ductility and structural integrity and spreads the forces resulting from the impact of a projectile over a larger area.

All hard body armor systems currently add a significant burden of weight on the soldier. Armor testing therefore has implicit goals of ensuring that body armor meets survivability standards while allowing sufficient soldier mobility and flexibility. To provide soldiers with more weight than necessary to defeat a specified threat can lead to unintended consequences such as premature exhaustion and restricted ability to rapidly move and react in life threatening situations.

Current Army Body Armor Testing Process

As described in the Phase I report (NRC, 2009), the Army's procedures for testing hard body armor using a clay backing for the measurement of deformations in the clay from ballistic impacts are documented in "Test Operations Procedure (TOP) 10-2-210: Ballistic Testing of Hard Body Armor Using Clay Backing," dated October 1, 2008 (ATC, 2008). The approach may be summarized in four paragraphs:

- A clay box[1] and clay chest plate appliqué[2] (Figure 1) are assembled, appropriately calibrated for part-to-part consistency using the column-drop performance test, and placed upright in the test holder. Independently, a "shoot pack" is prepared. To create a shoot pack, the armor plate is placed in a fabric envelope together with multiple layers of Kevlar to replicate the vest worn by the soldier. The dimensions of the armor plate depend on the size of the vest and can range from 18 cm × 29 cm to 28 cm × 36 cm, with a thickness of approximately 2 cm. The vest has a significant nonconstant radius of curvature.
- Once assembled, the shoot pack is pressed firmly into the surface of the appliqué to ensure conformance. The shoot pack is then removed and the laser scanning system scans the surface of the appliqué to provide a reference surface relative to which subsequent deformations caused by the firing of the projectiles can be compared. The laser scanning system is moved out of the way, the shoot pack is repositioned onto the surface of the clay, with care taken not to disturb the reference surface, and the shoot pack is secured.
- The projectile being tested is then fired into the shoot pack, after which the shoot pack is removed from the clay and inspected for penetration. The displacement or indent in the clay made by the deformation of the armor is thereby exposed. The velocity of the projectile was measured using Oehler Model 57 Ballistic Screens to verify that it was within the desired range.

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[1] A plywood-backed aluminum frame (~61 cm × 61cm × 14 cm) filled with modeling clay is subsequently referred to in this report as a "clay box" or as a "part" when discussing part-to-part variations.

[2] The appliqué is an additional layer of clay that has been molded to the shape of the specific armor plate to be tested.

FIGURE 1 The clay appliqué applied to the clay box. SOURCE: Richard Sayre, Deputy Director, and Tracy Sheppard, Executive Officer and Staff Specialist, Office of the Secretary of Defense, Director of Operational Test and Evaluation (OSD DOT&E) Live Fire Test and Evaluation, "DoD in brief to the National Research Council study team," Presentation to the committee, on November 30, 2009.

- The deformation is measured with the laser scanning system. The data are collected and used to compute the profile (depth distribution) indent. The deformation is analyzed and serves as an indication of the survivability of a soldier subjected to a similar shot and protected by a similar plate in a protective vest.[3]
    - A representative deformation is shown in Figure 2. The nominal design specification is that the maximum depth in the clay relative to the original surface be less than 43 mm. That is, a backface deformation (BFD) with a maximum depth of less than 43 mm is considered to indicate acceptable performance of body armor in service. Experimental data collected by the Army indicate that under nominally identical conditions the standard

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[3] As shown in the Prather et al. (1977) study, there is a correlation between the depths of penetration as a function of time into various media, including the modeling clay Roma Plastilina #1, and the probability of lethality when the same penetrator enters a human surrogate (goat) (Prather et al., 1977). (The study did not address volume of the indentation.)

deviation for the maximum depth of the BFD (hard armor) is in the range of 2.5 to 4 mm.[4] The BFD measurements in combination with the penetration data are used to evaluate the armor.

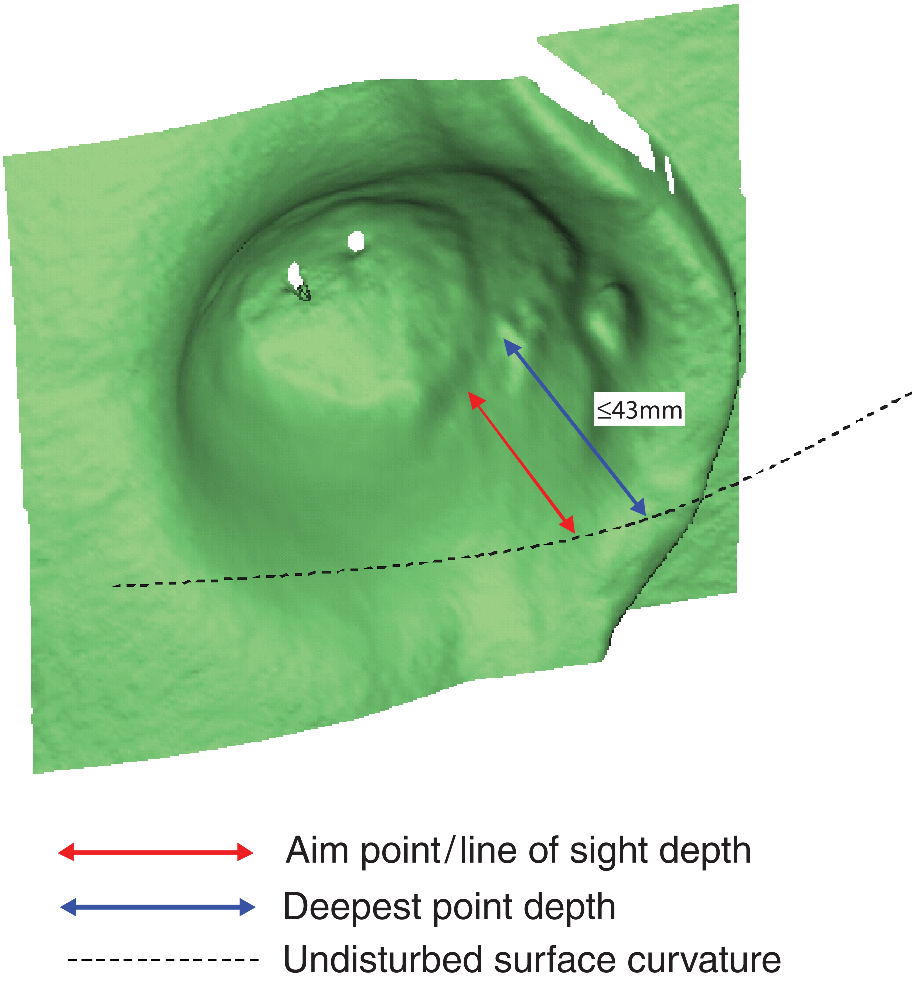

FIGURE 2 Surface of the BFD as measured by a laser scanning system. SOURCE: Richard Sayre, Deputy Director and Tracy Sheppard, Executive Officer and Staff Specialist, Office of the Secretary of Defense, Director of Operational Test and Evaluation (OSD DOT&E) Live Fire Test and Evaluation, "DoD in brief to the National Research Council study team," Presentation to the committee, on November 30, 2009.

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[4] James Zheng, Chief Scientist, Program Executive Office–Soldier, "Ballistic protection for warfighters," Presentation to the committee, on November 30, 2009.

Body Armor Testing Range

A typical firing range used to test body armor consists of: a rifle-like device to fire a projectile; an instrument to measure the velocity of the projectile; the armor plate being tested, which is affixed to an oil-based clay backing of modeling (clay this backing becomes indicated in response to the kinetic forces created on the plate); and a laser system to measure the geometry of the indentation in the clay. A photograph of an indoor range set up for testing body armor at the Aberdeen Test Center (ATC) is shown in Figure 3.

FIGURE 3 The body armor test range at ATC. SOURCE: John Wallace, Technical Director, ATC, “Body armor test capabilities,” Presentation to the committee, on March 10, 2010.

The highest priority of the Phase I report was to examine the validity of the laser profilometry system to determine the contours of the indentation in the oil-based modeling clay, the BFD, at the level of precision established by Army procedures. The committee found the Army’s laser system[5] used in accordance with its ATC Internal Operating Procedure No. 001 provides a valid approach for measuring the BFD indentation at the appropriate level of precision.

The Phase I report also asked the committee to address the oil-based modeling clay medium in which the BFD is formed. Specifically, the committee was asked to provide interim observations on the Army’s column-drop performance test used to

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[5] Faro® Quantum Laser Scan Arm and Geomagic® Qualify® for Hard and Soft Body Armor.

determine that the clay-filled boxes in the test are consistent from box to box. This is referred to as "part-to-part consistency." The committee's Phase I report found that the column-drop performance test (including testing protocols, facilities, and digital caliper instrumentation) is a valid method for assessing the part-to-part consistency of the clay boxes used for testing body armor.

Medical Study Basis for Use of Modeling Clay in Testing Body Armor

The use of clay as a recording medium for body armor testing dates from a 1977 study that correlated the depth that a 200-g, 80-mm hemispherical missile, impacting at approximately 55 m per second (Prather et al., 1977), penetrated live animal tissue and other media. The goal of the study was to develop a simple, readily available backing material for characterizing both the penetration and deformation effects of ballistic impacts on body armor materials and to relate this information to the injury potential of nonpenetrating ballistic impacts. The depth of penetration into various media as a function of time was compared to the probability of lethality for the same penetrator entered into a live animal model (in this study goats were used as models) (Clare et al., 1975).

The study observed strong correlations between lethality probability and penetration into ballistic gelatin[6] and also into modeling clay Roma Plastilina #1. The ballistic gel required the use of high-speed photography to record BFDs, because the gel was elastic and returned to its original shape after the projectile firing. To avoid the necessity of using expensive high-speed photography, an alternative material was sought that would retain its deformation The first conclusion of the Prather et al. (1977) report had a profound effect on testing over the next 30 years. It reads as follows (Prather et al., 1977, p. 11):

> A readily available, easy-to-use backing material, Roma Plastilina 1, has been found which can be correlated to tissue response for use in characterizing both the penetration and deformation effects of ballistic impacts on soft body armor materials.

Roma Plastilina #1 has since been adopted as a recording medium to assess the likelihood of injury or death from ballistics, and its use has been extended from assessing soft armor such as Kevlar vests to assessing hard armor plates, knife wounds, industrial injuries to a drop-forge operator, and nonlethal projectiles (Lyon, 1997; Chadwick et al., 1999; O'Callaghan et al., 2001; Vaughan, 2001; and Karahan, 2008). Roma Plastilina #1 appears to have become an industry standard despite being an imperfect simulant of the human body.

The procedures for the use of this clay have evolved with time. In part, this is because the behavior of the material has changed over time. The manufacturer confirmed

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[6] Ballistic gelatin is a clear or yellowish gelatin that is the standard medium for seeing and evaluating what happens to bullets on impact with soft tissue.

that the formulation sold as Roma Plastilina #1 has changed as the sources of raw material have changed and in response to the needs of artists.

Modeling clay provides an approximation of the actual BFD. It does not record maximum displacement since the clay may exhibit some elastic recovery, nor does it record the rate of deformation. Both of these dynamic events may be important in predicting the magnitude of injury to a person. To address these issues DoD conducted a medical research program, the Body Armor Blunt Trauma Assessment (BABTA) Project, from 2002 to 2006.[7]

The BABTA project developed an anthropomorphic test module (ATM) onto which body armor plates could be placed and firing tests performed. The ATM was equipped with sensors that directly measured the spatial and temporal distribution of the forces and motions caused by a bullet impacting armor. The pressure sensors in the ATM are on the backside of an approximately 25 mm thick layer of Dragon Skin, a high-performance silicone polymer that simulates the mechanical properties of the body. The layer of Dragon Skin is necessary to avoid damaging the sensors during the test. The spatial and temporal distribution of the forces at the surface was inferred using a finite-element calculation. Based on this, a blunt projectile was developed that when fired from an air-gun impactor at the ATM without an armor plate resulted in a distribution of forces and motions believed to accurately simulate those produced by the bullet impacting armor, assuming that the armor was not completely penetrated. The blunt projectile was a ~60 mm hemisphere mounted on the end of a smaller cylinder. Using this blunt projectile impactor, the project team experimented with highly instrumented and anesthetized human surrogates (in this case, pigs). From the response of the human surrogates, including in some cases postmortem analysis, a large database was generated that related the temporal and spatial distribution of forces to the injury. The BABTA project and numerous others indicate that depth of indentation alone is an inadequate indicator of injury probability (Cannon, 2001; Bass et al., 2006).

The BABTA study suggests that a means of easily and economically measuring the temporal and spatial distribution of the forces during the BFD would enable a more accurate assessment of armor efficacy and could lead to lighter armor that provides equal protection. The BABTA project established the need to develop testing methodologies that determine not just the BFD but also the dynamic forces that result from the impact of the projectile on body armor.

During presentations to the committee on March 9, 2010, Dr. Prather and Dr. Legierri agreed that the initial conclusions on BFD in the 1977 Prather study are very conservative. That is, humans may be capable of more easily surviving forces that correspond to those that make a BFD larger than the 43 mm BFD that is currently accepted by the body armor community. The committee applauds the efforts of the medical and testing communities to better quantify and correlate laboratory-generated mechanical impacts with the blunt force trauma caused in surrogate human beings. During Phase III the committee hopes to be able to further investigate (1) the relationships between temporal and spatial forces that cause blunt force trauma in the laboratory and injuries experienced by soldiers on the battlefield and (2) ways to more

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[7] Michael Leggieri, Director, DoD Blast Injury Research Program Coordinating Office, U.S. Army Medical Research and Materiel Command, “DoD medical research perspective on the clay-based body armor performance testing methodology,” Presentation to the committee, on March 9, 2010.

accurately correlate blunt force trauma impacts experienced by soldiers with the signatures that similar forces cause in body armor media that are not restricted to oil-based modeling clay or similar approaches.

Recommendation 1: The Army's medical and testing communities should be adequately funded to expedite the research necessary both to quantify the medical results of blunt force trauma on tissue and to use those results as the updated mathematical underpinnings of the back face deformation (BFD) body armor testing methodology.

Regardless of the current imperfect correlation between existing medical data and the BFD approach, the committee believes that the current methodology for testing body armor should be continued, mainly because this approach has allowed the Army to send body armor with adequate survivability characteristics to soldiers in combat. Importantly, the committee was informed earlier by the Program Executive Office–Soldier that no soldier deaths are known to be attributable to a failure of the issued ceramic body armor.[8,9,10] The committee agrees with a number of briefers that additional study in these areas could lead to insights that that current body armor, which provides an adequate level of survivability, may be unnecessarily heavy for a given threat.

CLAY PROPERTIES AND TESTING METHODOLOGY

This section provides brief descriptions of clay properties and behavior, clay in testing methodology, and short-term development of a standard clay formulation. It also discusses the procedures for preparing and working clay, calibrating clay, and analyzing BFD dynamics. It concludes with recommendations on possible mid-term and long-term replacements for modeling clay in the testing of body armor.

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[8] Question-and-answer session between Debi Dawson, Director, Strategic Communications, Program Executive Office–Soldier, and the Body Armor Phase I committee, December 1, 2009.

[9] Personal communication between LTC Jon Rickey, Product Manager (PM), Personnel Survivability Equipment, Program Executive Office–Soldier, and Larry G. Lehowicz, Chair, December 21, 2009.

[10] Personal communication between James Zheng, Chief Scientist, Program Executive Office–Soldier, and Larry Lehowicz, Chair, December 29, 2009. According to LTC Rickey and Dr. Zheng, in no case has it been determined that an issued enhanced small arms protective insert (ESAPI) or enhanced side ballistic insert (ESBI) armor plate failed to prevent an armor piercing (AP) by small arms projectiles of 7.62 mm × 63 mm or less. However, in some instances a casualty may become separated from issued body armor. In these situations it may not be possible to track the armor back to the original casualty. As a result the Army chose the word "known" to qualify the statement "no known deaths." For a nonmilitary, nonexpert audience it is noted that soldiers wearing body armor may suffer casualties when their ceramic armor is defeated by rounds of caliber larger than 7.62 mm × 63 mm when projectiles or shrapnel strike a portion of the body not protected by body armor, when the blast comes from improvised explosive devices (IEDs) or other explosives, and so forth.

Clay Properties and Behavior

"Clay" is a common word with different definitions. To a mineralogist, clay is a well-defined chemical composition having the crystal structure of a hydrous aluminosilicate. The same word is also commonly used for a geological formation of minerals that occur in nature. In practice, the term "clay body," which contains multiple constituents formulated in industry, is often shortened to "clay." Roma Plastilina #1 is an oil-based modeling clay that is not designed to be fired, such as is often done by artists to produce a densified ceramic part. This prescription allows the manufacturer to formulate the clay to obtain a given set of rheological (or flow) characteristics–modeling clay, for instance, is made to offer a given feel or particular consistency. Some materials, such as "polymer clay" and "precious metal clay," do not contain any clay minerals but are called clays because of their consistency based on the fact that they offer the user similar flow properties. Accordingly, it is important to be specific when "clay" is used to convey a technical meaning.

Typically, an artist who uses clay desires a particular "feel"—that is, he or she can shape the clay by handling it in a certain way. When clay is used for technical purposes, its flow behavior must be quantified. That is, the rheological parameters that describe its response to applied stress must be determined under the relevant conditions. Typical parameters include yield strength, viscosity, and elastic modulus.

A clay's flow characteristics are determined by the details of its formulation, the ambient conditions (temperature and pressure), and the shear history of the mass. To understand why this is so, it is helpful to consider the role of the constituents in an oil-based modeling clay. According to the manufacturer, "the main ingredients [of Plastilina] are wax, oil, and clay flour…"[11] Although the details of the formulation are proprietary, this description of ingredients more or less matches open-source formulations for plasticine, a formerly trademarked term for oil-based modeling clay that has moved into common use. A typical open-source formulation for plasticine contains microcrystalline wax, grease, oil, and clay. While proportions vary, a wax:grease:oil:clay ratio of roughly 25:7:8:60 by weight or 38:14:16:32 by volume is reasonable.

Microcrystalline wax is a food-grade additive obtained from de-oiling petrolatum. Microcrystalline waxes can be alloyed with oils to alter the flow properties (i.e., soften the material) and will remain homogeneous (i.e., it will not separate) over time after the initial mixing.

The distinction between oil and grease is that the former is a fluid at room temperature and the latter a solid,. And the distinction depends on molecular weight. Commercial greases and oils often contain multiple components and include additives designed to stabilize viscosity or inhibit oxidation, among other things.

What is important for a modeling clay of microcrystalline wax, oil, and grease is its homogeneity and the strong dependence of its rheological properties on temperature and the relative proportions of each constituent (Pena et al., 1994). The rheology also will depend on the shear history of the clay, since clay is thixotropic.

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[11] For additional information, see www.sculpturehouse.com/plastilina_info.aspx.

Thixotropy[12] occurs when a three-dimensional structure develops over a long time in a material. The rheological response changes with time when the system is disturbed such that the structure is broken down (i.e., it becomes more flowable) or when it is allowed to rest and the structure reforms (i.e., it becomes less flowable). The distinguishing characteristic of thixotropy is that the changes occur only with the passage of time.

Such behavior is common in clay-containing systems as three-dimensional networks of clay particles develop. Such assemblages of particles can often be broken down by the application of shear forces to the body. However, clay particles are not necessary for thixotropy to be observed. In particular, the above-referenced article on model ointments demonstrates that significant thixotropy is observed in a mixture of microcrystalline wax, grease (white petrolatum), and oil (mineral oil) in the absence of clay (Pena et al., 1994). This is due to the formation of a structural network involving both the amorphous and crystalline fractions of the microstructure.

The above discussion focuses on the four main constituents of modeling clay. However, Isaac Peng of Chavant, the current manufacturer of Roma Plastilina #1, mentioned that there are typically about 10 constituents in a commercial material.[13] These include pigments or colorants, antioxidants, and other minor materials as well as an intentional blending of multiple sources of, for example, the microcrystalline wax to dampen out lot-to-lot variations from individual suppliers.

It is perhaps useful to point out that minor constituents can affect the behavior of modeling clay in the context of armor testing in other indirect ways. One example is the particulate sulfur that is present to make the smoother, more homogeneous texture required by professional artists.[14]

One complication of the presence of particulate sulfur in Roma Plastilina #1 is that it loses weight during storage due to the sublimation of sulfur. Sulfur is observed to condense in the storage ovens around the door where the ambient temperatures are low. For obvious reasons, it is undesirable for the clay to have volatile constituents when its expected service life can be up to a year.

In summary, the medium used to record the BFD of a ceramic armor system being tested for ballistic impact is a multicomponent, oil-based modeling clay body. Knowing the behavior of the individual constituents that make up the modeling clay makes it possible to develop an expectation about how the consistency will be influenced by thermal history and shear history.

Clay in Testing Methodology

As described in the introduction, the clay backing material used in armor testing has two important purposes. The first is "to simulate [some aspects of] the tissue response appropriately beneath the point of impact so that the ballistic data generated in laboratory

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[12] Thixotropy is the property of certain gels or fluids that are thick (viscous) under normal conditions but that flow (become thin, less viscous) over time when shaken, agitated, or otherwise stressed.

[13] Isaac Peng, Chauvant, "Testing of body armor materials," Presentation to the committee, on March 9, 2010.

[14] For additional information, see www.sculpturehouse.com/plastilina_info.aspx.

tests can be correlated to the effects seen on the human body" (Prather et al., 1977, p. 7). The second purpose of the backing material is to mark the extent of BFD during ballistic testing. Multiple materials are available to simulate a body; in fact, at the time it was introduced, modeling clay was recognized to only approximate tissue response, and empirical correlations were needed to develop a probability for lethality or injury. The chief advantage of modeling clay over other materials available at the time was that it better served the function of recording BFDs; that is, when impacted, modeling clay deforms plastically and a permanent cavity (also termed indent, impression, or crater) is developed under the point of impact. Correlations were developed between the geometry of the cavity and the probability of lethal injury.

Short-Term Development of a Standard Clay Formulation for Ballistic Testing

The Army's protocol for ballistic testing of soft and hard body armor specifies Roma Plastilina #1 as the backing material (DoD, 2008). Since the initial validation studies (Prather et al., 1977), the formulation of Roma Plastilina #1 has changed, and this has changed its properties.[15] Whereas historically calibration and testing could be performed at room temperature, the current formulation of Roma Plastilina #1 must be above 100°F to pass the column-drop performance test (described in the section on Calibrating Clay). The committee was informed that the thermal conditioning temperature has increased of about 1°F every year.[16] In response to these known deficiencies of the current backing material, the director, of DOT&E established an ad hoc clay working group whose members are technical clay experts from the Department of Defense (DoD), the National Institute of Standards and Technology (NIST), the National Institute of Justice (NIJ), certified private laboratories testing body armor, for and others. Their purpose is to pursue short-term improvements in clay formulation, the processing of clay, and short and long-term alternatives to clay.[17] A short-term goal is to develop a replacement for Roma Plastilina #1 in less than 1 year.

Based on their experience, members of the clay working group have developed the following list of the desirable characteristics of clays for ballistic testing:[18]

1. Known, controlled, and consistent change in properties as temperature is changed.
2. A long useful life for repeated testing at room temperature.
3. Known, controlled, and consistent change in properties due to cold working (thixotropic effect).
4. Excellent dimensional stability.
5. Minimum "stickiness" to the target (i.e., the clay must not peel away when the target is removed) but high "stickiness" of clay to clay.

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[15] Isaac Peng, Chauvant, "Testing of body armor materials," Presentation to the committee, on March 9, 2010.

[16] James Zheng, Chief Scientist, Program Executive Office–Soldier, "Clay and NIJ history," Presentation to the committee, on March 9, 2010.

[17] Shane Esola, ATC, "ATC perspective on clay used for body armor testing: NRC Phase II Vandiver Inn brief," Presentation to the committee, March 9, 2010.

[18] Scott Walton and Shane Esola, ATC, "ATC perspective on clay used for body armor testing," Presentation to the Body Armor Phase I committee, on December 1, 2009.

6. Easy moldability, so that clay blocks can be formed with no voids, air bubbles, or gaps.
7. Long shelf life (1 year or more??)
8. Nontoxic, minimum odor, and reasonable price
9. Specifiable and controllable mechanical properties: density, seismic velocity, elastic modulus, shear modulus, grain size, hardness, etc.

Because its properties depend on shear history, time, and temperature, Roma Plastilina #1 appears to meet only some of these criteria. For example, it is typically heated to over 100°F to meet the calibration specification, which limits its useful life for testing in a room-temperature test range to less than 45 minutes. As a result of its properties, the current formulation requires a complex preparation and packing procedure to produce boxes with uniform, reproducible properties that are capable of passing the calibration test described in MIL-STD-3027 (DoD, 2008). The goal of the clay working group is to develop a short-term replacement that can meet the calibration specification at ambient temperature and minimize the sensitivity of the properties of the clay in the box to cold working.

In addition to the criteria developed by the clay working group, two additional considerations could facilitate development of the short-term clay replacement. First, the formulation could be simplified by minimizing the number of ingredients. For example, as previously noted, Roma Plastilina #1 contains sulfur, which has an unknown effect on performance in ballistic testing. Minimizing the number of ingredients should reduce variability in performance over time and simplify attempts to characterize and model performance. Second, the current Roma Plastilina #1 formulation of microcrystalline wax, oil, and grease includes clay as an inorganic filler. The inherent anisotropic (i.e., platy) nature of the clay particles may complicate the behavior of Roma Plastilina #1. Eliminating the clay particles or replacing them with an inorganic filler that has an equiaxed particle morphology may provide properties that are less dependent on work history and time.

Two approaches are possible for the procurement of a standard ballistic clay from an industrial supplier. One approach would be to develop a material specification that uses a precise composition formulated with particular raw materials that are called out in the specification. This approach would guarantee a consistent product as long as the raw materials do not change but would not allow the supplier to adjust the formula in the event that properties change because raw materials are no longer available, properties of the raw materials change over time, or other such factors. This approach could cause the properties of the standard ballistic clay to evolve, as happened with Roma Plastilina #1. The second approach would be to develop a performance specification. This approach would allow the supplier to continually evaluate and adjust the composition to produce a consistent product. This would put the burden on the Army to specify the properties that are most important to the application but would seem to be the best approach to meet the Army's need for a consistent backing material.

Recommendation 2: The Army should develop ballistic testing performance specifications and properties that will lead to a short-term, standard replacement for the current Roma Plastilina #1 oil-based modeling clay.

Preparing and Working Clay

The clay is cut into small pieces and worked with a mallet and by hand into pliant flat sheets that are placed sequentially in overlapping layers to fill the test box, with attention to filling the corners (ATC, 2008). This is a new practice, intended to maintain spatial uniformity in the box. As discussed in the Phase I report, holes formed during column-drop test calibration are filled with worked clay and manually smoothed. The box surface is scraped before calibration and testing to create a flat surface of precisely known elevation, introducing some final mechanical deformation to the immediate surface region.

The Roma Plastilina #1 clay composition currently in use is proprietary but is known to include a multicomponent organic phases(s), a kaolinite filler, and two other inorganics, sulfur and zinc stearate. Multiphase suspensions are often yield-stress materials that exhibit thixotropy— that is, the material does not flow until it experiences a stress that exceeds a critical value (the yield stress)—and the material properties following the initiation of flow depend on time (thixotropy). Before they yield, the materials appear to respond as viscoelastic solids. The probable cause of shear sensitivity and thixotropy is shear-induced modification of the microstructure, which changes the modulus, yield stress, and viscosity, among other things Accordingly, these materials can exhibit aging, shear conditioning, and even “avalanche” (runaway) behavior. The current understanding of thixotropic yield-stress materials has been reviewed in Bonn and Denn 2009). Rheological modeling of the time-dependent mechanical response of these materials is a topic of current research, and the simulation of complex flows is beginning to be studied.

The way of preparing and working the clay reflects the thixotropic nature of the clay composition, as well as the temperature dependence of the material properties of the organic phase. Hand kneading produces a consistency that permits the clay to be shaped and formed into the sheets that are placed in the test box, probably by effecting changes in the microstructure. Temperature control changes the consistency, probably in large measure by changing the viscosity of the organic phase and, at sufficiently high temperatures, possibly causing a phase change of one or more microstructural elements; the temperature must be maintained within a fixed interval for the clay to exhibit acceptable mechanical properties. Temperature drift with time appears to have a measurable effect on drop-test penetration, for example. Thus, both the shear history and the operating temperature affect the deformation properties of the clay, and either (1) kneading at fixed temperature or (2) varying the temperature without mechanical processing can be used to change the consistency. These effects have not been quantified in conventional rheological tests for the Roma Plastilina #1 clay, but both mechanical and thermal conditioning are employed in the testing practice.

It is accepted practice, for example, that either mechanical working of the clay in the box or changing the temperature will bring a clay into an acceptable penetration range for column-drop calibration test; the former probably changes the structure, while the latter probably has a small effect on structure. The committee was told of a test intended to determine the effect of thermal changes versus mechanical conditioning to obtain acceptable performance in calibration in which a statistically significant difference in mean BFD performance was observed between the clays conditioned by the two methods. The single-point measurement (of the column-drop test penetration) for such a complex material as clay in this case may reflect the different macroscopic responses in three-dimensional deformations of the clay's constituent materials as well as the thermo-mechanical histories of each material. These observations are consistent with a 1994 NIST report on the rheological properties in torsional shear of an earlier formulation of Roma Plastilina #1, which found that the material was highly nonlinear and time dependent, and that the shear properties of kneaded and "melted" (i.e., raised to a temperature of 90^{o}C) clay at a fixed test temperature were different (NIST, 1994). The NIST study also reported that the clay was viscoelastic, in which case the material would be expected to recover a fraction of the imposed deformation upon removal of the load. (This observation is consistent with the unsupported observation in the Aerospace Report ATR-75(7906)-1—namely, that elastic springback of the clay backing material would require correction factors) (Aerospace Corporation, 1974). Low-rate indentation experiment on plasticine indicates recovery would be expected at high rates (Huang et al., 2002; Ji et al., 2009).

Fundamental thermomechanical information about the clay formulation appears to be lacking. Plasticine rheology has been widely studied over the decades due to its technical importance as a model material in a number of scientific and technical fields. It is a complex material with a response that has been shown to depend on strain, strain rate, and thermal and mechanical history. The committee is, however, unaware of any linear viscoelastic measurements at either low or high frequency for either worked or unworked Roma Plastilina #1 to determine the relative recoverable (elastic) and dissipative (viscous) fractions of the response; linear viscoelastic measurement, even at frequencies well below the operational timescales, can be sensitive indicators of structural change. Nor have there been shear measurements at a range of temperatures to determine the viscoelastic solid response prior to yielding, the equilibrium yield stress, aging, the thixotropic response, or the apparent equilibrium viscosity and shear modulus as a function of shear rate. These are properties that are likely to affect (hence correlate with) clay response during calibration and testing. Such measurements are standard practice in other industries that use similar materials, including oil well drilling, personal products, etc. These properties are also required for any simulation intended to relate indirect measurements to the mechanics of body armor deformation. In particular, any viscoelastic recovery may give a measured BFD that is less than the maximum experienced dynamically during the test. A priori calculation of temperature change and straightforward calculation of temperature variations within the box as a function of time require knowledge of the thermal diffusivity of the clay, which has also not been measured for the materials in use. Thermogravimetric measurements to measure weight loss and components that may be eluted over time at a fixed temperature have likewise not been carried out.

The committee notes that rheological measurement is planned by the clay working group, but the particular measurements to be carried out have not been specified. The experiments enumerated above should be part of this program.

Recommendation 3: Rheological and thermogravimetric measurements should be carried out to better understand the properties and behaviors of clay as it is being prepared and worked.

During a briefing to the committee, the ATC Protective Equipment Division science officer stated that in his opinion perhaps some of the most significant variation in the testing process could result from the hand processing that goes into filling the clay boxes and subsequently working it before and after test firing.[19] Standardized thermo-mechanical working of the clay prior to filling the box would provide more uniform mixture of the clay and improve part-to-part consistency in clay. This might be accomplished by using a mechanical compounding machine, which might also permit reuse of the clay. ATC personnel indicated that such equipment has been under consideration.

Recommendation 4: If it is demonstrated to achieve improved part-to-part consistency of the clay compared to hand preparation procedures, a mechanical compounding machine for clay preparation should be acquired, experimented with, and used by the Aberdeen Test Center.

Thermal conditioning of the box to obtain a calibration within the acceptable range would make it likely that the clay structure is the same from test to test on the same sample. However, this introduces several complications. First, the test ranges must have appropriate ovens. This imposes a capital cost, dedicated space, and maintenance. Second, the use of high temperature may degrade the modeling clay. This includes oxidation of the waxes and oils as well as the loss of volatile species (such as sulfur). Third, if the modeling clay is equilibrated at a temperature significantly higher than the ambient room temperature (as is current practice), then the cooling that takes place over the time necessary to conduct the test can change the modeling clay response.

An alternative approach would be to develop an automated process that could be used to mechanically condition the clay without removal from the box. There are at least two established processes that embody the desired elements of such a device–friction stir welding and insitu soil mixing. “Friction stir welding” was developed in the early 1990s at the Welding Institute in the U.K. The Welding Institute’s Web site[20] provides the following description:

> [I]n friction stir welding a cylindrical, shouldered tool with a profiled probe is rotated and slowly plunged into the joint line between two pieces of sheet or plate material, which are butted together. The parts have to be clamped onto a backing bar in a manner that prevents the abutting joint faces from being forced apart. Frictional heat is generated between the wear resistant welding tool and the material of the work pieces. This heat causes the latter to soften without reaching the melting point and allows traversing of the tool along the weld line. The plasticised material is transferred from the leading edge of the tool to the trailing edge of the tool probe and is forged by the intimate contact of the tool shoulder and the pin profile. It leaves a solid phase bond between the

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[19] Question-and-answer session between Shane Esola, ATC, and the committee, March 11, 2010.

[20] Available at http://www.twi.co.uk/content/fswintro.html.

two pieces. In an experimental study using oil-based modeling clay as a simulant of a metal, friction stir welding was shown to be feasible (Leichty and Webb, 2007).

It seems plausible that this could be extended to a raster pattern that would allow an entire box to be worked in place. Insitu soil mixing, or auger mixing, appears to be primarily used to admix a material such as cement to soil for purposes of creating foundations or to immobilize soil contaminants. In the field, soil mixing works on a length scale of several feet, but there are laboratory-scale mixers used to study auger designs, etc., that would be amenable to the length scale associated with a clay box (Al-Tabbaa and Evans, 2003). In this case as well, an extension to clay box mechanical treatment would require a system to permit x-y translation of the auger.

Recommendation 5: In-box mechanical conditioning might obviate the need for precise temperature control and reduce the need for hand working of the clay. Mechanical working methods should be tested.

In briefing the committee, the clay working group subchair**,** who is responsible for addressing clay working techniques, stated that he was not authorized by his organization to discuss plans in these areas.[21,22] Therefore, some aspects of the above recommendations may already be in motion.

Calibrating Clay

Calibration is conducted to determine that the clay-filled boxes meet a specified level of consistency before and after a body armor test.

Column-Drop Performance Test

The column-drop performance test was described in detail in the Phase I report.[23] It is the standard used throughout the body armor testing community and the process for calibrating the clay for use in ballistic testing of armor. Several versions of the drop test are in use. All versions are based on the penetration of indenters of well-defined weight and geometry that have been allowed to fall and impact the surface of a box filled with the modeling clay. One recognized difference between the calibration test and the experience of the system in the ballistic test is that the penetrator speed is calculated to be slightly in excess of 6 m/s at the point of impact, whereas the speed of the backface during ballistic testing is markedly (approximately 10 times) faster.

Details of the procedures are documented in standards by the NIJ and the Army. Three standards are relevant: NIJ Standard–0101.03; NIJ Standard–0101.06; and MIL-

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[21] Shane Esola, ATC, “ATC perspective on clay used for body armor testing: NRC Phase II Vandiver Inn Brief,” Presentation to the committee, on March 9, 2010.

[22] Mike Riley and Amanda Forster, NIST, “Handling and validation of clay for NIJ–0101.06 tests, current practice and limitations,” Presentation to the committee, on March 9, 2010.

[23] NRC, 2009, pp. 14-17.

STD-3027 (NIJ, 1987; NIJ, 2008; DoD, 2008). Also of relevance is the U.S. Army TOP 10-2-210 (ATC, 2008).

As these standards have evolved, drop tests to ensure that the modeling clay has a well-defined consistency have been introduced. It was related by Army personnel that the drop test was introduced specifically to account for the complexity of conditions leading to a given consistency. That is, whereas heating to between 105°F and 110°F was necessary to achieve a drop test penetration in the desired range for undisturbed modeling clay, the same result was achieved at a significantly lower temperature when the clay had been "recently worked." This indicates an understanding that both thermal history and shear history affect consistency. It assumes that the observed correlations from the 1977 Prather study are preserved no matter which process pathway is used to obtain a drop test within the standard given by TOP 10-2-210 (Prather et al., 1977; ATC, 2008).

To take the above considerations into account, the test-preparation assembly (i.e., attachment of the modeling clay appliqué used to fill the space between the armor pack and the clay box), the column-drop calibration test, and the actual testing of the body armor plate must be completed within 45 minutes.

Personnel who repair and recondition clay boxes follow procedures that are consistent with standard practice by artists and others to fill space without entrapping air. That is, small additions are sequentially made and each is heavily sheared by hand to express any entrapped air. This represents good practice. Army personnel related that periodic x-ray of clay boxes only rarely indicates the presence of entrapped air. The same rebuilding procedure appears to be used both in rebuilding indentations produced during calibration and after an armor test to restore the box.

Boxes are used for as many as 200 shots for a year. Appliqués are prepared for each individual armor plate to be tested. After boxes have been used for their individual service life, the modeling clay is discarded.

One feature of the Army TOP calls for comment. The column-drop calibration test requires the result of each indentor drop to yield a cavity with a maximum depth of 25±3 mm. Data given to the committee (see Figure 4) indicate that as the clay box cools during the time interval associated with completing the test (up to 45 minutes), the clay hardens to the degree that a drop test cavity will be up to 4.5 mm shallower than would have been the case when the box was first removed from the oven. Given that the full range of the acceptability is only 6 mm (i.e., + 3 mm to – 3 mm), it must be the case that any box that displayed indents shallower than 26.5 mm would necessarily be expected to yield a drop test result that would not be acceptable if a post-test calibration drop were conducted. Thus, as currently written, the TOP allows tests to be conducted on clay that would not pass the initial drop test, thereby introducing additional variation into the testing process and probably into the BFD measurements.

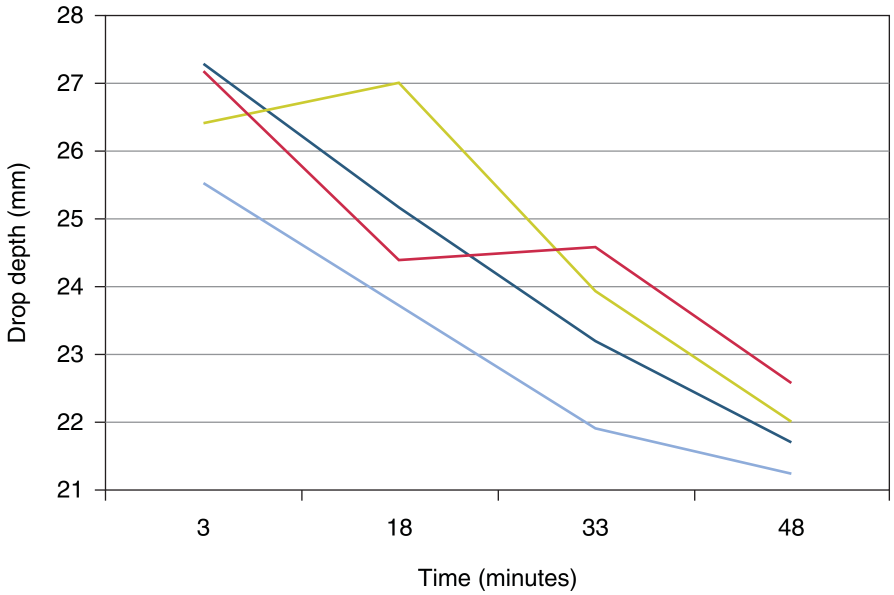

FIGURE 4 Depths resulting from column-drop calibration tests conducted in a standard clay box after undergoing four different environmental conditioning scenarios. As a result of cooling temperatures in the clay box, the depth of penetration decreases systematically over time. The penetration depths were demonstrated to decrease in linear fashion at approximately the same rates of change regardless of conditioning. The observed range spans virtually the entire range ., (+ 3 mm to – 3 mm) of accepted variance associated with the test. SOURCE: Scott Walton and Shane Esola, ATC, "ATC perspective on clay used for body armor testing," Presentation to the committee, on March 10, 2010.

Recommendation 6: Since oil-based modeling clay is time and temperature sensitive, a post-drop calibration test is needed to validate that the clay remains within specification at the end of a body armor test. The Army should add this requirement for a post-drop calibration test of the clay to its Test Operating Procedure (TOP 10-2-210).

In addition to the observed systematic changes, experimental data collected at the ATC and presented to the committee show spatial variation in the plane parallel to the surface of the clay box (the x-y plane) and through the thickness (z-direction).

The variation in the x-y plane of the box is complicated by the presence of the walls and floor of the box because they constrain the plastic flow of the clay. This fact is recognized, and TOP 10-2-210 stipulates the allowable spacing between drops and proximity to the edges (ATC, 2008). However, it was not demonstrated that either an analysis or an experimental program has been conducted that permits the effect of placement in the x-y plane to be separated from clay property variation. Furthermore, the mixed nature of the results does not permit one to determine the degree to which the test might be improved by redesigning the box in the form of a circle or other.

With respect to variation in the z-direction, the reported data include the results of an experiment in which calibration drops into the top surface of the box were compared to an equivalent set of drops onto what had been the bottom of the clay mass. (The plywood backing was removed from the bottom of the box, moved and fastened to the top, the box inverted, and the drop test conducted.) Whereas the drop test results for the normal top surface yielded a narrow variation and were all in within specification, the drop test results for the surface that had been at the bottom of the box were on average more than 4 mm shallower, were out of specification, and had a much higher variance.

These results demonstrate that the response of the modeling clay differs by location in all three dimensions and that the differences are large enough to affect the outcome of the test.

Recommendation 7: The spatial variation of modeling clay is significant and three-dimensional. The response of the clay appears to depend on temperature, shear history, and proximity to the edge. Given the confounding effect of box geometry, the Aberdeen Test Center should perform a systematic set of column-drop performance tests as experiments to assess the consequence of variation due to the shape and size of the frame that defines the clay box. These tests should determine if a circular box of approximately the same area as the current box reduces the spatial variation that affects ballistic testing, or if a larger box area eliminates the clay edge effects that affect ballistic testing.

Alternatives to the Column-Drop Performance Test

Clearly the conditions of the column-drop performance test are different from those experienced by the modeling clay during the actual ballistic test of the armor. For example, the velocity of the indenter is much less than the velocity of the penetration of the back of the body armor that forms the BFD. Also, the typical depth of penetration of the indenter, 25 mm, is only half the distance of a "pass" BFD, 43 mm. There are several alternatives to the current column-drop performance tests that appear to offer advantages.

At the time of impact, the velocity of the indenter used in the current calibration test is just over 6 m/s. However, estimates provided to the committee by ATC personnel (W. Scott Walton and Shane A. Esola) are that the backface of the armor moves at a velocity >50 m/s after impact with current threat projectiles. That is, the current calibration occurs under significantly lower strain rates than expected in the armor test. The Army is developing a gas gun capable of directing a penetrator onto the surface of a clay box at velocities were like those of the BFD. Although it is recognized that the gas gun is only one approach to achieving high velocities, and there are others, it will be used in the following discussion for illustrative purposes. The first advantage of employing high speeds is that impactors will penetrate to depths comparable to the BFD in ballistic tests.

In addition, a gas gun will in principle be able to deliver penetrators ranging from spheres to other specialty shapes. The existence of such a device offers a number of opportunities. One is that it allows choosing steel spheres to reproduce a cavity in the clay that approximates the dimensions associated with the BFD in a ballistic test. A second is to reproduce the impactor of the original Prather et al. study, which will permit direct comparison to the original work with modern clay formulations and conditions. Thirdly, it allows using shaped impactors are designed to reproduce that the force distributions expected when a blunt trauma occurs as a projectile strikes hard armor. Shaped impactors are commonly used in injury simulation to induce specific and reproducible forces over a well-defined area. This option is particularly appealing as work progresses to measure the force distribution associated with armor testing (Raftenberg, 2006).

An additional appealing possibility is using small diameter spheres (as in the study by Weber, because this allows a high-density matrix of small impacts that may permit direct measurement of clay homogeneity (Weber, 2000).

It is important to stress there are two different functions of an improved calibration test. The first is to characterize the variability of clay within a given box at a given time in a manner that is directly relatable to the BFD. The second, equally important role is to use such a system to estimate the variation of BFD measurements both within a given box and between boxes, under realistic testing conditions using existing test protocols. The latter will help to provide information of use in the statistical analysis of armor testing results.

Specifically, statistical analyses of the test protocols require quantification of how much of the observed variation in BFD is due to the clay medium (and the test protocol in general) and how much is due to variation in the plates themselves. Using actual plates cannot answer this question because of the destructive nature of the tests (confounding the results of the individual plates with the testing). Thus, a surrogate must be used. However, unless the degree to which the surrogate mimics actual plates is high and well determined, a different type of confounding may be introduced.

Recommendation 8: As an alternative to the current column-drop performance test the Army should quickly develop and experiment with a gas gun calibrator, or equivalent device, that delivers impactors to the surface of clay boxes and that determines local variation within a clay box at speeds and depths corresponding to those involved in the generation of the backface deformation. These experiments should be used to estimate as accurately as possible the variation of backface deformation measurements both within a given box and between boxes, under realistic testing conditions using existing test protocols.

Analyzing BFD Dynamics

Description of the Problem

As described earlier, the medical analysis by the BABTA project indicated that in order to predict blunt trauma injury resulting from BFD of the armor plate, information on both the shape and the rate of formation of the deformation is needed. This is because the rate at which BFD occurs was found to be the primary determinant of the probability of injury and the nature of the injury. This conclusion of BABTA is supported by numerous independent studies of damage to animals and cadavers caused by blunt trauma (Cannon, 2001; Bass et al., 2006). Thus, both the shape of the BFD and the rate at which it occurs are needed to make reliable predictions of injury. Expressed another way, for two identical BFDs, the one that occurs faster is highly likely to produce greater injury, so measuring the dynamics of BFD in clay is of significant interest.

Measuring BFD Dynamics

When clay is used as the backing of an armor plate being tested, its optical opacity necessitates a nonoptical method to determine the rate and shape of BFD. A flash x-ray source available at ATC has been proposed for studying BFD dynamics as the plate deforms into modeling clay. Calculations by the committee indicate that during a single flash of the proposed flash x-ray cineradiography system, the number of x-rays that will penetrate the clay box and impinge on a resolution element (i.e., a pixel) of the scintillator screen, where they can be detected, may be too small to provide the desired information. That is, the images expected from the x-ray cineradiography may be too blurry to determine BFD shape and rate with the desired spatial and temporal resolution.

Recommendation 9: While the committee applauds the Aberdeen Test Center efforts to understand and attempt to measure the dynamics associated with the creation of a backface deformation, the signal-to-noise ratio of the flash x-ray cineradiography approach should be thoroughly analyzed to determine if the desired spatial and temporal resolution can be achieved.

It would be helpful to have means other than the flash x-ray of measuring the forces that create the BFD. One alternative is to borrow from the technologies that are used in the auto industry to study the impact of automobile crash forces on the human being. These studies typically use dummies that are instrumented with sensors. The instrumented dummies are subjected to experimental accidents and the sensor data are analyzed to obtain insights into the impact of a similar accident on a person. Similarly, experiments based on the placement of microscopic temperature and displacement sensors in the clay near the site of the BFD could provide insight into the forces that create the BFD. It is possible that experimentation could determine the depth below the clay surface of the appliqué where the sensors survive the impact of the round striking the plate and provide meaningful data. However, the sensors (and other approaches to seeding the clay box with various markers) are likely to affect the behavior of the clay. These changes in the behavior of the clay would have to be carefully analyzed to determine the impact of sensors and markers in accurately measuring the forces that create a BFD.

Recommendation 10: To better understand and measure the forces that create the backface deformation the Army should experiment with inserting microscopic temperature and displacement sensors into the clay near the site of the backface deformation.

Ballistic gelatin may be a suitable alternative to understanding and measuring the forces behind the BFD since it is optically transparent and its mechanical properties are well understood. Optical transparency permits the use of high-speed photographic equipment to record the dynamics of BFD. Several high-speed photographic systems are available commercially and have come down in price considerably since the original work of Prather, which led to the use of Roma Plastilina #1 for BFD measurement. Appendix 1 presents calculations that illustrate the requirements for photographic BFD dynamic analysis in ballistic gelatin; it shows that photographic equipment capable of such analysis is readily available.

Recommendation 11: The Army should consider experimenting with high-speed photographic analysis of backface deformation in ballistic gelatin as an alternative for providing needed information on the forces that shape the backface deformation.

Mid-Term and Long-Term Replacements for Modeling Clay

As stated previously, Roma Plastilina #1 is used as a backing material in current ballistic testing of body armor based in part on the Prather study that compared it to a standardized gelatin composition (DoD, 2008). Also, as discussed earlier, the Army is looking at short-term modeling clay formulations alternative to Roma Plastilina #1 that have better thermal and other properties for body armor testing. However, ballistic gelatin and microcystalline waxes are possible mid- and long-term replacements for modeling clay.

Ballistic Gelatin

Ballistic gelatin may offer advantages as a mid-term backing material for body armor testing that is an alternative to clay. Gelatin has been deemed a suitable simulant for the penetration of the human body during a ballistic event (Metker et al., 1975). As previously discussed in this report, gelatin differs from clay in that it exhibits complete elastic recovery after the ballistic event.

Gelatin offers several attractive characteristics that overcome the shortcomings of the current backing material, including these: (1) gelatin offers consistent, reproducible properties; (2) it is widely used in the ballistic community; and (3) as previously described, it is transparent (Nicholas and Welsch, 2004). The last characteristic allows for optical characterization of BFD in real time, which can be used to evaluate quantities such as local acceleration that are suitable for input in damage models for blunt force trauma. In addition to its other attributes, gelatin can be reused and recycled if it is properly stored and handled. Along with its advantages, gelatin also brings possible concerns, including consistent/repeatable processing, storage conditions, potential spoilage, and recyclability, that will also need to be considered.

The Prather study concluded that the standard gelatin and Roma Plastilina #1 (as it was formulated in 1977) had similar responses (Figure 5). The disadvantage of gelatin at the time was the cost of the high-speed photography needed to record the deformation response during ballistic testing. The relatively low cost of technology for capturing digital images and for computer storage media has reduced price as a consideration and would likely bring the cost of testing with gelatin down to or below that associated with clay. The main technical impediment to implementation of gelatin is the need for a modern study to compare the response of gelatin to Roma Plastilina #1 (as it is now formulated) as a backing material. Unlike the Prather study, which focused solely on soft armor applications, the modern study should validate gelatin or another replacement material for testing of both soft and hard body armors. Other possible considerations in the use of ballistic gelatin are the need to modify standard test procedures to include gelatin and to modify acquisition contracts to allow the Army to purchase armor that has been tested with standard ballistic gelatin.

Recommendation 12: The Army should conduct rheology and other studies on ballistic gelatin as a mid-term alternative to modeling clay due to its properties, which include the ability to directly record BFD using high-speed photography and the elimination of the effects of shear history, time, and temperature on the response of the backing material. However, correlation studies and tests are needed to better understand the differences in the extent of deformation and dynamics among gelatin and alternative clay formulations.

Microcrystalline Wax Mixtures

Microcystalline wax mixtures may offer some of the attractive features of gelatin (its reproducibility) with the flexibility to control temperature-dependent behavior. The proportions of microcrystalline wax, petroleum jelly, and oils can be varied to control properties such as melting temperature, viscosity, and temperature-dependent response (Pena et al., 1994). The mixtures have a number of potentially desirable attributes. First, they are the organic constituents of Roma Plastilina #1, so it may be possible to replicate not only the properties of the current formulations of Roma Plastilina #1 but also the historic response of previous generations of Roma Plastilina #1 by changing the proportions of the constituents. The composition of the mixture could be adjusted to allow for use at ambient temperature, eliminating the need for thermal conditioning and the time limitations on testing. Second, the mixtures are plastic, which would allow BFD during ballistic tests to be captured directly, as they are with the current material. The waxes may also eliminate concerns related to cold working and temperature history. These compositions could be formed by melting the ingredients or remelting a previously used batch at a moderate temperature (i.e., 150°C), pouring the liquid into the test box, and then allowing the liquid to cool to room temperature. The melt casting process should produce a consistent, reproducible test material that would not require cold working or temperature conditioning prior to use. Finally, the wax mixtures may allow for optical characterization of BFD such as optical time domain reflectometry. Because these mixtures are used by the cosmetics industry and are similar in composition to the current backing material, the technical risk of developing a new, simpler material for ballistic testing is low. However, the response during ballistic testing is unknown and requires investigation.

Recommendation 13: The Army should perform rheology and other evaluations on microcrystalline wax mixtures as a possible long-term replacement for Roma Plastilina #1 as a backing material for ballistic testing. Studies are needed to optimize the composition of the mixtures to produce the desired properties. In addition, correlation studies are needed to compare the response of the microcrystalline wax mixtures to the current material and/or ballistic gelatin.

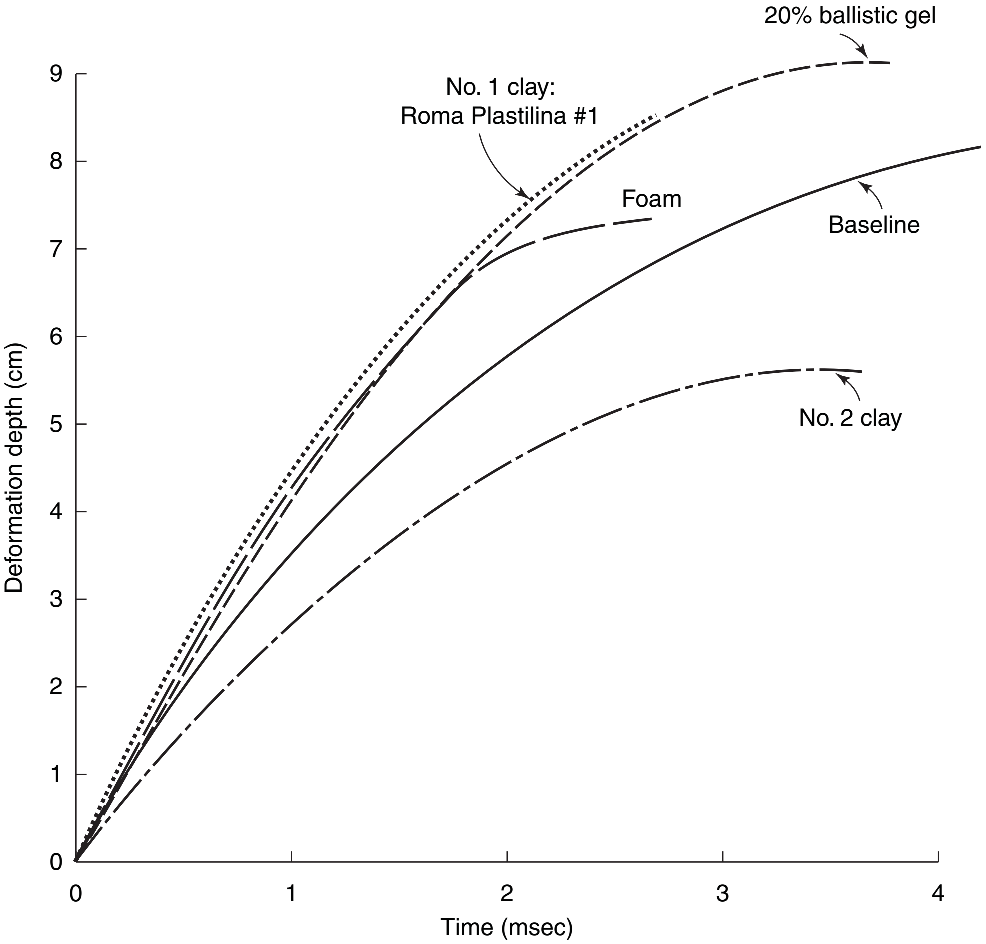

FIGURE 5 Comparison of the deformation depth as a function of time for various materials including Roma Plastilina #1 and ballistic-grade gelatin. SOURCE: Prather et al., 1977.

ACHIEVING A COMMON NATIONAL TESTING STANDARD FOR HANDLING AND VALIDATING CLAY

The NIJ, with assistance from the NIST, has developed technical standards for clay handling and validation for body armor testing. These standards are used by DoD testing organizations to guide clay procedures and processes that in turn determine if various body armors are adequate for military applications. Other non-DoD and private testing laboratories also use NIJ standards to guide their procedures and processes to test body armor that is used by police forces and other organizations. Over time the NIJ has developed several different standards. Different standards have been adopted by different testing organizations at different times in their organizational histories. As a result, it is possible at this time that identical body armor plates could be tested by different organizations, using different standards, and that they could achieve dissimilar and not easily comparable results. In the extreme case, one plate could be deemed acceptable at one testing facility and another identical plate could be deemed unacceptable at another testing facility due to standard differences.

The committee was presented with briefings on the two main NIJ testing standards.[24,25] NIJ Standard 0101.03 and NIJ Standard 0101.06, which includes elements of 0101.03 and earlier standards 0101.04a and 0101.4, or slight variations are used by the U.S. Army , the U.S. Marine Corps, the U.S. Special Operations Command, the NIJ certified private laboratories, and others. Table 1 was presented to the committee as an overview of some of the differences in testing procedures that have resulted from major testing organizations adopting different NIJ standards.

TABLE 1 Major Differences in Clay Calibration Techniques

Point of Comparison	Army (TOP 10-2-210)	NIJ (0101.06)	U.S. Special Operations Command
Origin	Revisions as necessary Adaptation from NIJ 0101.03	NIJ 0101.04a NIJ 0101.04 NIJ 0101.03	
Drop weight	Cylinder 1-kg, 44.5-mm diameter cylinder with a hemispherical striking end Cylinder may have some yaw, but it impacts to a deeper depth	Sphere 1043-g, 63.5-mm sphere Sphere eliminates yaw, but does not go deep enough	Cylinder Varies, but historically the 1-kg, 44.5-mm diameter cylinder with hemispherical striking end
Pass/fail criteria:	Individual	Arithmetic mean	Individual
Individual drop depth vs. arithmetic mean	Three drop indentations are scored individually. If any one drop is out of the 25 mm ± 3 mm range, the clay fails calibration.	The arithmetic average of five drop indentations scored against a 19 mm ± 2 mm passing range	Historically, drop indentations scored individually
Drop pattern	No pattern No specified drop pattern. Ideally want to test near the projected test area but avoid shot lines. Random location sampling is best way to determine bulk clay block properties	Specified pattern Specified five-location, symmetrical drop pattern	No pattern Follows NIJ 0101.03; no pattern specified

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[24] Shane Esola, ATC, “ATC perspective on clay used for body armor testing: NRC Phase II Vandiver Inn brief,” Presentation to the committee, on March 9, 2010.

[25] Mike Riley and Amanda Forster, NIST, “Handling and validation of clay for NIJ–0101.06 tests, current practice and limitations,” Presentation to the committee, on March 9, 2010.

Point of Comparison	Army (TOP 10-2-210)	NIJ (0101.06)	U.S. Special Operations Command
Pretest vs. post test calibration	Pretest calibration only Imposes 45-min limit on the useful life of the clay block	Pre- and post-test calibration	Pre- and post test calibration Five pretest drops (chest mold and clay block) Three post test drops (just clay block)
Calibration of the chest mold and built-up areas	Does not drop on chest mold	Does not drop on chest mold	Drops on chest mold
Reconditioning and retesting of failed clay blocks	Allows for reconditioning and retesting Maximum of two attempts to pass calibration Working on establishing rules to govern reconditioning and retesting	Allows for reconditioning and retesting Unlimited attempts to retest failed clay blocks	Allows for reconditioning and retesting
Conditioning time	Minimum of 3 hours	Not specified (changed over the years)	?
Other	Fixture construction: metal with 0.75 in. wood or plywood backing Clay conditioning temperature requirements have changed over the years	Fixture construction: Wood or metal with 0.75 in. wood or plywood backing “Actual conditioning temperature and recovery time between uses will be determined by the results of the validation drop test.”	Processes may vary; techniques are adjusted according to the range capability of the facility at which testing is performed and the customer

SOURCE: Shane Esola, ATC, “Major clay calibration technique differences,” Presentation to the committee, on March 10, 2010.

The committee agrees that it could be helpful if there were one national standard for all body armor testing. Such a standard could lead to more consistent procedures and more consistent results across the testing community. The committee appreciates that the different commands and laboratories have different missions, customers, resources and organizational cultures and that eventual adoption of a single national standard would require detailed analysis of key issues such as the various threats that are being tested and the rationale for variation in testing processes being used. Ideally, the development of consensus across all organizations involved in body armor testing will likely be more effective than mandating a single national standard. As an important step in this process, the committee agrees that the ad hoc clay working group approach that was started by and is currently chaired by DOT&E provides a way ahead. The clay working group consists of four sub-groups: clay properties, clay calibration, clay working techniques, and future efforts. The working group and its subgroups consist of testing experts that represent the expertise of various organizations involved with body armor testing. The committee received several briefings from members of the working group. The committee was impressed that all briefers conveyed the impression of willingness to exchange information, learn from each other, and work toward achieving more consistent testing procedures. The committee applauds this approach and believes that the effort should be continued and emphasized by DOT&E and the other participating organizations. Some continuing and future actions should be emphasized and resourced for the clay working group that could help lead to a single national body armor testing standard:

- Continue to improve existing body armor testing procedures by collaborating and investigating clay properties, formulation, calibration and working techniques.
- Continue to collaborate on alternatives to the procedures and standards.
- Continue to gather detailed information that defines and explains the reasons for different testing procedures that are used by various organizations.
  - Determine areas where synchronization of processes among organizations makes sense.
  - Determine areas where different missions, customer requirements, resources, and other organizational considerations provide a reasonable rationale for different testing procedures to be retained, at least in the short term.
  - Determine areas that need more detailed data and analysis before procedure and process synchronization recommendations can be made. In these cases, it would be useful to design experiments, gather data, and perform analysis that could lead to informed recommendations to the chains of commands of the participating organizations.

Recommendation 14: The ad hoc clay working group should be empowered and adequately resourced to gather information, influence research, and develop working-level consensus across body armor testing organizations for the uniform application of National Institute of Justice standards across participating test organizations.

After the clay working group has generated reasonable consensus, DOT&E and NIJ should convene a nationally recognized group to achieve a single national standard for body armor testing.

Recommendation 15: The Department of Defense Director of Operational Test & Evaluation (DOT&E) and the National Institute of Justice (NIJ), in collaboration with the military services, unified commands, other governmental organizations, NIJ-certified laboratories, and appropriate nongovernmental and commercial organizations should convene a nationally recognized group to review all appropriate considerations and develop recommendations that could lead to a single national body armor testing standard to achieve more uniform testing results.

STATISTICALLY BASED TEST PROCEDURES

In this section of the report, the committee presents its findings on statistical aspects of the plate test procedures, beginning with a general discussion of how uncertainty and variation can influence plate overdesign and overmanufacture. It then describes the existing test protocols and discusses the proposed new first article testing (FAT) protocol. The report continues with recommendations on statistically based lot acceptance testing (LAT) standards. It concludes with recommendations on involving stakeholders and performing due diligence before formally adopting a set of statistically based protocols.

Uncertainty and Variation Drive Overdesign

Larger and/or thicker body armor insert plates provide additional survivability but at the cost of more weight. Heavier body armor can contribute to fatigue, may inhibit mobility and effectiveness, and, at its worst, may result in personnel choosing not to wear the body armor, completely defeating its purpose (OTA, 1992).

Body armor is designed to protect against a particular level of threat. To the extent that the armor exceeds this level, it can be thought of as overdesigned or overmanufactured, in the sense that lighter plates could have been produced to achieve the desired level of protection. Uncertainty and variation in the manufacture, testing, and employment of body armor, as well as the natural concern for protecting personnel, tend to result in conservative decision making, which in turn can result in body armor overdesign and/or overmanufacture. For example,

- Variation in body armor manufacturing processes can drive suppliers to produce plates that are generally heavier than required to lower the risk of producing nonconforming plates.
- Variation in FAT and LAT can further drive suppliers to produce heavier-than-necessary body armor to ensure their product successfully meets the FAT and LAT test standards.
- Uncertainty about the particular threat that personnel may face can result in specifications and/or testing to a higher possible threat and sometimes to threats beyond what personnel would actually see in order to ensure that the likely threats are clearly met.

Furthermore, variation in both the manufacturing and testing processes requires testing greater quantities of body armor to achieve a given level of certainty about performance. To the extent that variation in the manufacturing and testing processes are reduced, higher certainty about body armor performance can be achieved within a given testing protocol or, alternatively, fewer tests can be conducted, with attendant savings in cost and effort, to achieve an equivalent level of certainty.

Simply put, uncertainty and variation at each step of design, manufacture, and test is frequently accounted for with safety margins, the cumulative effect of which can be overdesign. To the extent that uncertainty and variation in manufacturing and testing are minimized, body armor with the desired level of performance may be achieved with greater certainty and perhaps at lower weight.

Statistically based protocols are designed to quantify variation. Explicitly identifying sources of variation and their relative sizes can allow explicit trade offs of risk and resource investment for reducing variation.

Background and Historical First Article Testing

FAT is used to ensure that body armor conforms to all contract requirements for acceptance, including specific inspections and tests as well as drawings or other specifications. As described in the DoD Inspector General (IG) report *DoD Testing Requirements for Body Armor*, the U.S. Army and the U.S. Special Operations Command (USSOCOM) currently conduct FATs using similar measures but to separate standards (DoD, 2009).

Both the Army and USSOCOM assess ballistic performance using plate penetration and BFD under various threats and environmental conditions. They both assess $V_{50,}$ the highest velocity of a threat at which the probability of complete penetration is 50 percent, by measuring plate penetration over a range of velocities. In addition, USSOCOM tests plate shatter gap, which occurs when a bullet penetrates body armor at a lower velocity than the body armor was designed to defeat (DoD, 2009).

As described in the DoD IG report, the Army uses a non-statistically based protocol for enhanced small arms protective inserts (ESAPI) that requires testing:

- One plate against defined adversary threats “A,” “B,” and “C” in ambient conditions,
- Three plates against defined adversary threat “D” in ambient conditions, and
- One plate for each of nine environmental conditions.

In addition, the Army uses 12 plates for V_{50} testing, so that in total 26 plates are tested (Dunn, 2010). Successful completion of FAT is based on a scoring system that assigns points to various combinations of first- or second-shot penetration and depth of BFD. These requirements differ somewhat in the current Ceradyne ESAPI/ X Small Arms Protective Inserts (XSAPI) procurement contract, but they are similar in magnitude and intent (RDECOM, 2009).

USSOCOM uses a statistically based protocol with sample sizes that can vary from a minimum of 146 plates tested to a maximum of 480 plates tested. At the minimum, USSOCOM requires the following:

- Sixteen plates each against threats “A,” “B,” “C,” and “D” in ambient conditions, and
- Six plates for each of eight environmental conditions.

In addition, USSOCOM uses 6 plates for V_{50} testing and another 28 for shatter gap testing. Should a plate fail in any of the above categories, the USSOCOM protocol requires additional testing in that category. Successful completion of FAT is based on achieving the following:

- A 90 percent probability the plate will stop the first shot and not exceed BFD requirements, with 80 percent confidence for all four threats,
- A 90 percent probability the plate will stop the second shot with 80 percent confidence for threats "A," "B," and "C," and
- A 60 percent probability the plate will stop the second shot for threat "D," with 80 percent confidence for threat "D" (USSCOM, 2010).

In its report, the DoD IG analyzed Army and USSOCOM sampling plans using first- shot data under threat "D" and ambient conditions and found that "…the USSOCOM sampling plan provided a 27 percent better chance that defective plates are detected during first article testing…" (DoD, 2009, pp. 30-31).

Proposed Standard for Hard Body Armor Ballistic Testing

In *DoD Testing Requirements for Body Armor* (DoD, 2009), the IG recommended that "the Director, Operational Test and Evaluation (DOT&E) develop a test operations procedure for body armor ballistic inserts and involve the Services and USSOCOM to verify the procedure is implemented DoD-wide" (DoD, 2009, p. *i*). It also stated that "standardization of body armor testing and acceptance will ensure that Service members receive body armor that has been rigorously tested and will provide uniform protection in the battlefield" and proposed that "the test procedure should include, at a minimum, requirements for sample size, shot pattern, types of testing, and acceptance criteria to verify the rigor of testing." (DoD, 2009, p. 32)

On the same page, the report went on to say that "…body armor testing should provide a certain level of confidence that the manufacturing process is capable of producing an armor product that will meet the established requirements." (DoD, 2009, p. 32). In response, the DOT&E stated its goal to develop a statistically based FAT protocol that requires a 90 percent lower confidence limit on reliability of 90 percent that material under test passes the requirement. Subsequently, Army and DOT&E statisticians and U.S. Army Test and Evaluation Command (ATEC) test personnel collaborated to develop a statistically based protocol, the proposed Standard for Hard Body Armor Ballistic Testing, which DOT&E disseminated for review and comment.

The proposed standard would establish a statistically based protocol that sets minimum requirements for tests that will result in a decision to qualify a design for full-rate production and FAT. It does not address the LAT. The proposed standard establishes "standard testing references, protocols, procedures, and analytical processes for hard body armor testing." In the following, the committee discusses issues related to the 60-plate design matrix and the assessment requirements as described in the proposed standard.[26] The design matrix and the assessment requirements are hereinafter defined as the "proposed statistically based protocol."

The 60-plate design matrix is given in Table 2. This design matrix is replicated for each threat. The proposed standard does not specify the specific threats for testing. An important consideration when evaluating this design matrix is to recall that it is intended to support technical testing as opposed to operational testing. A technical test is intended to evaluate the hard body armor against requirements—in this case, against a requirement for the probability of penetration and BFD under a variety of environmental conditions. An operational test would be intended to assess performance under realistic operational conditions and might lead to different choices about the allocation of tests. For example, an operational test might allocate additional plates to ambient conditions, if those were judged to be the most likely environments that service members would be expected to face in a war zone.

TABLE 2 Sixty-Plate Design Matrix

Environment	First Shot Edge/Second Shot Crown	First Shot Crown/ Second Shot Edge
Ambient (unconditioned)	2 extra small plates 1 medium plate	1 small plate 1 large plate 1 extra large plate
Temperature cycling	1 extra small plate 2 extra large plates	1 small plate 1 medium plate 1 large plate
JP-8 soak	1 extra small plate 1 small plate 1 large plate	2 medium plates 1 extra large plate
Oil soak	2 small plates 1 medium plate	1 extra small plate 1 large plate 1 extra large plate
Salt water	1 small plate 1 large plate 1 extra large plate	2 extra small plates 1 medium plate
Weathered	1 medium plate 2 large plates	1 extra small plate 1 small plate 1 extra large plate
High temperature	1 small plate 1 medium plate	1 extra small plate 2 extra large plates

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[26] Formal staffing document for review and comment of the DOT&E proposed Standard for Hard Body Armor Ballistic Testing.

Environment	First Shot Edge/Second Shot Crown	First Shot Crown/ Second Shot Edge
	1 large plate	
Low temperature	2 medium plates 1 extra large plate	1 extra small plate 1 small plate 1 large plate
Altitude	1 extra small plate 1 large plate 1 extra large plate	2 small plates 1 medium plate
Impacted	1 extra small plate 1 small plate 1 extra large plate	1 medium plate 2 large plates
Total plates	30	30

SOURCE: Staffing document for review and comment on the DOT&E-proposed Standard for Hard Body Armor Ballistic Testing.

The assessment requirements from the proposed standard are given in Table 3. To pass the test, the following must be achieved:

- For the first shot, the one-sided 90 percent lower confidence bound for the probability of complete system penetration is greater than 0.9.
- For the second shot, the one-sided 90 percent lower confidence bound for the probability of complete system penetration is greater than 0.8.
- For the first shot, the one-sided 90 percent upper tolerance limit with 90percent confidence for BFD must be less than 44.0 mm.
- For the second shot, the one-sided 80 percent upper tolerance limit with 90percent confidence for BFD must be less than 44.0 mm.

TABLE 3 Statistical Analysis Requirements

	First Shot	Second Shot
	Resistance to penetration	
Analysis required	90 percent no penetration with 90 percent confidence	80 percent no penetration with 90 percent confidence
	Backface deformation	
Analysis required	90 percent upper tolerance limit with 90 percent confidence	80 percent upper tolerance limit with 90 percent confidence

SOURCE: Staffing document for review and comment of the DOT&E-proposed Standard for Hard Body Armor Ballistic Testing.

The design assumes the following:

- Ballistic performance measured using penetration and BFD;
- A 44.0-mm BFD requirement; and
- Current clay preparation, handling, and calibration techniques.

The committee notes that the design is reasonably balanced, with every size plate appearing in each environment and an equal number of tests for the two shot orders. Based on analytical results of past test data conducted by Army statisticians, the committee believes it is important to include the effect of shot order (first shot edge/second shot crown vs. second shot crown/second shot edge) in the 60-plate design matrix. The proposed standard establishes fair-hit/no-hit criteria, where data from any shot with a velocity that too high is excluded from analysis regardless of outcome, while data from shots with velocities that are too low are included only if they completely penetrate (both plate and system) or have a BFD of greater than 44.0 mm. This biases the test results toward soldier safety, as would be expected, but it also biases toward overdesign of the hard armor. This trade-off should be explicitly recognized. The committee commends the Army and DOT&E statisticians and ATEC testing personnel for their constructive collaboration in defining the new statistically based protocol.

Just as body armor design requires making an explicit trade-off between weight and protection, test-sampling design requires making trade-offs between the precision of the estimates and the number of items tested. At issue is that not every plate produced can be tested, particularly in destructive testing, where each item tested is destroyed in the testing process. Thus, the goal is to estimate the quality of the production process as accurately as possible based on a limited sample. Yet, because only a sample of plates can be tested, the resulting test conclusion is subject to error and unavoidable risk both for the DoD and the manufacturer.

The committee would like to illustrate how the risks of the proposed test protocol can be understood and where the testing uncertainties that arise from using clay as a backing material impact the 60-shot protocol. Let us consider the first-shot complete penetration requirement.

Table 4 shows how the risks vary for various sample sizes, true probabilities of no penetration, and requirements. The “true probability of no penetration” [True P (No Penetration)] is the probability that a particular design is not penetrated by a particular threat—this is the unknown characteristic of the hard body armor that DoD and the Army are trying to learn from the experimentation. The “Government Risk” is a risk the DoD assumes; it is the probability of allowing a set of armor plates that just meets the “no penetration” requirement to pass the test. The Manufacturer Risk is the probability that a set of armor plates that meets or exceeds the “no penetration” requirement will fail. These risks are a function of the sample size required in the sampling plan and the level of the manufacturer's quality.

For example, the fourth line in Table 4 is interpreted as follows. A test requirement that the 90 percent lower confidence limit must exceed 90 percent means that a successful test of 60 plates can have no more than two failures. Under these conditions, a manufacturer's plates each of which has a probability of passing the test (i.e., of no penetration) of 0.98 stands an 11.9 percent chance that at least three or more of the 60 plates will fail the test, so that manufacturer will fail the test. Conversely, under these test conditions, the government has a 5 percent chance that a manufacturer's marginally-performing plates that have a probability of no penetration of 0.90 will pass the test.

As the table shows, for a sample size of 60, a manufacturer must produce hard body armor that has a true probability of no penetration substantially higher than 0.9 to have a reasonable chance of passing the test. From a soldier-safety perspective, this is appropriate. This kind of analysis can be helpful for ensuring that the test design does not lead to overdesign.

The first three lines of the Table 4 demonstrate that reducing the sample size from 60 shifts the risk to the manufacturer. For a sample size of 15 it is not possible to pass the test because the sample size is too small to demonstrate a 90 percent requirement with high (90 percent) confidence.

The last two lines of Table 4 show the sharp increases in required sample size when the requirement is increased beyond 0.9 and the risks are held roughly constant.

TABLE 4 Risk Comparisons for Probability of Complete Penetration

Sample Size	Allowable Failures	True P (No Penetration)	Requirement	Government Risk	Manufacturer Risk
15	0	0.98	0.86	0.206	0.261
22	0	0.98	0.90	0.098	0.359
40	1	0.98	0.90	0.080	0.190
60	2	0.98	0.90	0.053	0.119
60	2	0.99	0.90	0.053	0.022
60	2	0.92	0.90	0.053	0.868
300	9	0.98	0.95	0.000	0.082
6,000	134	0.98	0.975	0.000	0.092

Recommendation 16: Before adopting the proposed statistically based protocol, the Department of Defense Director, Operational Test & Evaluation, (DOT&E) should explicitly compare the risks of the proposed protocol and those of the existing Army and U.S. Special Operations Command (USSOCOM) protocols, in order to establish which test plan increases soldier safety while balancing the manufacturer's risk and incentives to overdesign. The committee notes that the USSOCOM first article test protocol may not be intended as a comprehensive technical test, and clarifying this issue would also help in the comparison of the protocols.

Because of the issues discussed in earlier sections of this report, it is difficult to tell if the observed variation in BFD for hard body armor is attributable mainly to the variation in plates, to the variation in the test process, or to both. As a result, all observed variation is being attributed to the plates. While this is clearly incorrect, without a better understanding of the specific sources of variation, it is impossible to do otherwise. This probably results in overdesign and/or overmanufacture of the plate to ensure a high probability of passing FAT and LAT.

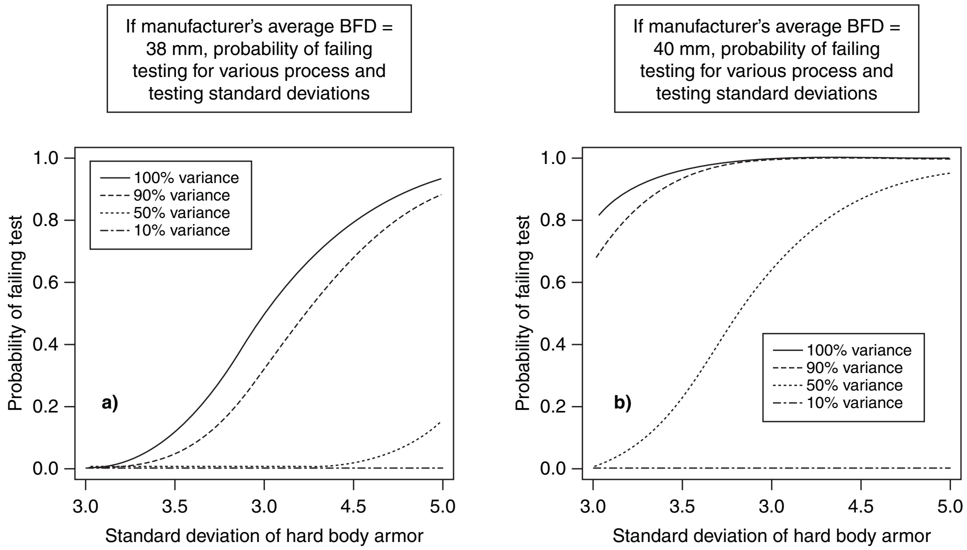

FIGURE 6 Risk comparisons for BFD assume that the manufacturer's true mean BFD is (a) 38 mm and (b) is 40 mm. The associated fraction of variation is shown on the x-axis. The plots show that decreasing variability in BFD, by means of a more consistent manufacturing process or more repeatable testing measures, reduces the manufacturer's chance of failing testing (given that the manufacturer's plates do meet standards and holding everything else constant).

Figure 6 illustrates the potential impact on manufacturers by simulating the effects of the BFD test on the probability of a manufacturer failing FAT under various conditions. In Figure 6 (a), the assumption is that the plates resulting from a manufacturer's process have a mean BFD of 38 mm. The solid line (100% variance) shows the results when all observed variation is attributed to the plates. The amount of variation is shown on the x-axis in terms of standard deviations, and the probability of failing to meet the BFD criterion is shown on the y-axis. The plot shows that the probability of failure ranges from zero for standard deviations just above 3 to nearly 1 for standard deviations just less than 5. The dashed curves show the impact of attributing less of the observed variation to the plates. Notice that the percentage attributed to the plates decreases as the probability of passing the test increases. Figure 6(b) shows a similar result for a mean BFD of 40 mm.

The plots show that decreasing variability in BFD, by means of a more consistent manufacturing processes or as a result of more repeatable testing measures, lowers the manufacturer's chance of failing testing (given that the manufacturer's plates do meet standards and that all other factors are constant). At issue is the current impossibility of estimating what fraction of the variation in BFD is attributable to variation in the plates and what fraction is attributable to the testing methods. As the experimentation recommended in the Clay section of this report (Recommendations 2-8) is completed, a better estimate of the test process variation may become apparent. As discussed in earlier sections, there are known but not well quantified issues that relate to variations in the thermal and stress properties of the clay medium itself, variations caused by different individuals hand working the clay as it is prepared for testing, variations in calibration, and other variation causes. Information on how the existing process performs will facilitate improving the process (minimizing excess variation, should it exist.) Importantly, this information may require refining the proposed standard.

Recommendation 17: The committee recommends that testers and statisticians continue to work together as a team (1) to quantify in a statistically rigorous manner the amount of variation in backface deformation attributable to the testing process and that attributable to the plates, and (2) to ensure these results are appropriately reflected in an updated protocol. In particular, the statisticians involved with developing and implementing the statistically based protocol should be involved with the experimentation recommended in Recommendations 2-8. It would be helpful for statisticians to be part of the process of understanding and quantifying test system variation.

Lot Acceptance Testing

Once a manufacturer has passed FAT and begins production, LAT is used to ensure that body armor continues to conform to contract requirements. LAT samples are typically smaller than FAT samples and often vary by the size of the lot. For example, the current ESAPI/XSAPI Army contract specifies a sample of 3 for lots of 26-150 plates, of 5 for lots of 151-1,200 plates, of 8 for lots of 1,201-3,200, and of 13 for lots of 3,200 plates or more. As with the FAT, a penalty point system is used to determine acceptance, rejection, or additional testing of the lot.

However, as described in MIL-STD-1916, “sampling inspection alone does not control or improve quality” (DoD, 1996, p. 8). Owing to the critical nature of safety when it comes to body armor, continued LAT testing is both desirable and necessary, but the committee also recognizes that modern quality control calls for manufacturing processes to be improved to eliminate as much variation as possible. As the committee has previously shown, elimination of variation can provide a number of benefits, including the reduction of risks to both the manufacturer and the DoD. In addition, to the extent that such reductions in variation lead to more predictability in plate performance and testing outcomes, these reductions might lead to innovations in plate design that allow reductions in plate weight while maintaining ballistic protection.

The committee also notes that MIL-STD-1916 describes “switching procedures” by which the quantity of items inspected during LAT can vary depending on how the manufacturer has performed on previous LATs (DoD, 1996). For example, a manufacturer that has demonstrated consistently good LAT performance can have the number of items tested in future LATs reduced. Conversely, a manufacturer that has demonstrated poor past performance can have the number of items tested in future LATs increased for tighter scrutiny.

Recommendation 18: The Department of Defense should develop standard statistically based body armor Lot Acceptance Testing (LAT) protocols that incorporate aspects of MIL-STD-1916, particularly those related to quality control and improvement and switching procedures. Adopting and incorporating modern statistical process control methods into the manufacturing processes is specifically recommended so that plate quality can be managed and assessed prior to lot acceptance testing. This could potentially reduce testing effort and costs. Note that while MIL-STD-1916 states that the "sampling plans and procedures of this standard are not intended for use with destructive tests," these aspects of the military standard are relevant to body armor LAT testing.

Using a statistically based approach that quantifies the risks inherent in test design enables decision makers to explicitly address the trade-offs and is both commendable and desirable. While further research and coordination are necessary to finalize the design and continuing review will be needed as test and manufacturing conditions change over time, a statistically sound protocol will ensure the quality of the body armor that is so critical to our soldiers.

Conducting Due Diligence Before Formally Adopting the Statistically Based Protocol

The DoD IG report *DoD Testing Requirements for Body Armor* recommended that DOT&E use "quantitative methods to develop a test sample size for testing that limits the number of possible failures" (DoD, 2009, p. 34). A statistically based test protocol is critical because it is the only way to quantitatively characterize body armor performance under a variety of threat conditions and operating environments to better inform DoD decisions. Because there is variation in manufactured body armor, testing alone cannot ensure that body armor is 100 percent effective. One can, however, develop higher confidence in the effectiveness of the body armor by using a statistically rigorous assessment with sufficient sample size. The committee feels that DOT&E is making a good faith effort to follow the DoD IG guidance in its development of the proposed statistically based protocol.

Many thousands of body armor plates have been produced and sent to soldiers on the battlefield. No soldiers are known to have been killed from projectiles that the plates were designed to defeat. The acquisition process that has successfully fielded body armor with superior ballistic protection sets a high threshold when making changes to armor design, manufacture, and testing, but at the same time it should not hinder the development of even better body armor for fielding to soldiers. For example, current test procedures induce an unknown amount of variation into the measurement of BFD, adding risk for the manufacturer and perhaps resulting in heavier-than-necessary plates. Thus, any and all changes in design, manufacturing, or testing processes should be made with deliberate caution to ensure that plate performance is maintained while also ensuring that the best science and engineering are brought to bear on testing and improving body armor.

The DoD has a responsibility to set performance requirements and to establish the protocols that verify that they are met. Any test protocol involves some risk that bad body armor will pass the test and good body armor will fail. The DoD has a responsibility to be explicit about these risks and to design a test protocol that balances cost, performance, ability to execute, fairness to the manufacturer, and risk to the soldier. Trade-offs can be made to result in protocols that are both statistically rigorous and practical in application. This conceptual approach is supported by the development of the current DOT&E

proposed protocol. The committee believes DoD should address these issues with all stakeholders, DoD (military service Program Executive Officers, testers, users, and others) and non-DoD (NIJ, NIST, certified private testing laboratories, manufacturers, and others).

The committee also believes that DOT&E should use the input from discussions with stakeholders to reconsider (and possibly revise) the proposed statistically based FAT protocol, and it believes that the following three considerations should be explicitly addressed.

First, issues in the proposed statistically based protocol that add to the manufacturer's risk and to the armor's weight must be openly discussed. It is important to reach consensus on what constitutes a BFD failure and how such failure relates to soldier injury or death. Dr. Prather said that his 1977 study was very conservative, and he felt it was highly likely that a human could survive a blunt trauma force resulting from a BFD somewhat in excess of 47 mm. However,

- The Army's body armor testing Test Operations Procedure (TOP) states that 43 mm constitutes BFD failure while also allowing a sliding BFD point scale between 44 and 47 mm.
- The proposed statistically based protocol changes the BFD upper limit for failure to 44 mm and requires that this limit be demonstrated with 90 per cent confidence for 90 per cent of the population of the plates.
- NIJ Standard 0101.06 states that "the armor model shall be deemed to meet these requirements [that is, to constitute a failure] if no BFD depth measurement due to a fair hit exceeds 50 mm (1.97 in.)" (NIJ, 2008, p. 49).

Thus, at the outset of the report, Recommendation 1 highlights the need to conduct the research to quantify the medical results of blunt force trauma on tissue and to use those results to underpin a BFD standard.

Second, the committee wishes to avoid the misperception that the proposed statistically based protocol accepts a higher death rate for soldiers wearing body armor. In particular, there must be no inadvertent public misperception that U.S. body armor is less survivable under the proposed protocol. For example, Table 3 of this report shows that the proposed requirement for a first-shot resistance to penetration is "90 percent no penetration with 90 percent confidence." Taken out of context, a nontechnical, nonstatistical audience with no understanding of statistics could interpret this requirement to mean that the DoD will accept some penetration of the plates and some deaths on the battlefield. Adding to the confusion is the wording in NIJ Standard 0101.06, which is used extensively by testers for civilian law enforcement organizations: "Each panel must withstand the appropriate number of fair hits and may not experience any perforations" (NIJ, 2008, p. 49). One unintended consequence of the proposed protocol is that nontechnical audiences could incorrectly conclude that soldiers are knowingly being placed at greater risk than is currently the case in combat or in civilian law enforcement. It is possible that DoD could develop zero-failure FAT protocols that would achieve the appropriate levels of risk and that would eliminate such misperceptions.

Third, it is important that the proposed statistically based protocol be seen not just as another in a long line of standards but as an improvement that incorporates input from all of the stakeholders and that embodies the best science. Recommendation 15 calls for the DOT&E and NIJ to take the lead in developing a single national body armor standard. It is particularly important to develop broad-based support for a future statistically based protocol and ensure that its adoption will not undo many years of successful engineering, or significantly increase manufacturer costs, or take too much time. For example, vendors of body armor plates are likely to view a new protocol more favorably if the protocol is founded on: (1) discussions on the basis and application of statistically based protocols; (2) feedback and debriefings from statistical experiments; (3) the post-test availability of armor for inspection and further technical analysis; and (4) shared knowledge on how armor standards and test protocols influence armor development.

The committee unequivocally supports the concept of a statistically based test protocol that explicitly and scientifically acknowledges and addresses the testing risks described in this report. However, it also appreciates that due diligence and deliberate caution are warranted to ensure that the change in test protocol does not result in unintended effects on body armor manufacture or performance. If these considerations are addressed in a straight forward and transparent manner with the body-armor stakeholders, the proposed statistically based protocol is likely to be well accepted.

Recommendation 19: The Department of Defense (DoD) Director, Operational Test & Evaluation (DOT&E) should provide briefings to and receive feedback from all stakeholders in DoD (military service Program Executive Officers, testers, users) and non-DoD organizations (National Institute of Justice, National Institute of Standards and Technology, certified private testing laboratories, vendors) concerning the statistically based protocol. This feedback, as well as the results of the experiments and analyses proposed in this report, should be used as due diligence to carefully and completely assess the effects, large and small, of the proposed statistically based protocol before it is formally adopted across the body armor testing community. DOT&E should act on feedback from the community to improve the proposed protocol as necessary, to ensure that testing terms and concepts make sense to a nontechnical audience, and it should promote the use of statistically based protocols in future national standards for body armor testing, as appropriate.

OVERARCHING RECOMMENDATION FOR PHASE II

Over the course of both the Phase I and Phase II studies, committee members were impressed with the ongoing work at ATC but were dismayed by the lack of standardization in body armor test criteria exhibited by DoD and other organizations concerned with body-armor testing. They considered their recommendations for action to be fully justified by the urgency and criticality of body armor on the battlefield.

Each of the 19 recommendations in the Phase II study contains an express or implied action to achieve greater part-to-part consistency in ballistic clay, analyze BFD dynamics, determine possible replacements for modeling clay, achieve a national clay standard for body-armor testing, or implement a statistically based protocol. The importance of body armor testing, as well as the life-or-death nature of body armor itself, require that such a large number of recommendations be acted on in a concerted fashion.

Both DOT&E and the Army will recognize the issues addressed by the recommendations and have initiated or proposed several projects that move in the same or similar directions toward essential improvements. Many, if not most, of these projects are unfunded and will require the resources of DoD, the military services, specific service laboratories and testing organizations, as well as non-DoD agencies, such as NIJ, NIST or a Federally Funded Research and Development Center/University Affiliated Research Center, to implement.

Overarching Recommendation: The committee applauds DOT&E for assuming a national-level leadership role in bringing the body armor test community together. The committee recommends that the DOT&E (1) work with Congress, DoD, the military services, and other organizations to find the resources necessary to implement the recommendations described in this report and summarized in Box 1 and (2) oversee, review, track, and assist designated action organizations with implementing these recommendations. This approach should result in more consistent test results that will provide equally survivable but lighter-weight body armor to our military service members and civilian police forces.

Box 1
Phase II Recommendations to Improve Body Armor Testing

Achieving Greater Part-to-Part Consistency in Clay

1. Quantify the Medical Results of Blunt Force Trauma on Tissue and Incorporate Results into the BFD Methodology
2. Determine Short-Term Standard Clay Specification
3. Conduct Rheological and Thermogravimetric Measurements
4. Procure and Experiment with a Clay Compounding Machine
5. Examine Technologies for "In Box" Mechanical Clay Working
6. Modify TOP 10-2-210 Procedures to Add a Post-calibration Drop (ATC, 2008)
7. Experiment with Various Clay Box Sizes and Shapes
8. Develop and Experiment with a Gas Gun Calibrator or Equivalent Device

Analyzing Backface Deformation Dynamics

9. Analyze the Signal-to-Noise of Flash X-Ray Cineradiography
10. Experiment with Microscopic Temperature and Displacement Sensors in Clay
11. Experiment with the High-Speed Photographic Analysis of BFD Creation in Ballistic Gelatin

Determining Possible Replacements for Modeling Clay

12. Study Ballistic Gelatin as a Mid-Term Alternative to Modeling Clay
13. Study Microcrystalline Waxes as a Long-Term Alternative to Modeling Clay or Ballistic Gelatin.

Achieving a Single National Clay Standard for Body Armor Testing

14. Empower and Resource the Ad Hoc Clay Working Group
15. Convene a Nationally Recognized Group to Establish a Single National Standard for Handling and Validating Clay

Implementing Statistically Based Protocols

16. Compare the Proposed Statistically Based Protocol with the Existing USSOCOM Protocol
17. Quantify the Variation in the Body Armor Test Process and Incorporate in the Protocol
18. Develop a Statistically-Based LAT Protocol
19. Conduct Due Diligence Before Implementing and Formally Adopting a Set of Statistically Based Protocols

REFERENCES

Aerospace Corporation. 1974. Equipment Systems Improvement Program–Protective Armor Development Program–Final Report, v 3. ATR-75(7906)-1. El Segundo, Calif.: Aerospace Corporation.

Al-Tabbaa, A., and C. Evans. 2003. Deep soil mixing in the UK: Geoenvironmental research and recent applications. Land Contamination & Reclamation 11(1): 1-14.

ATC (U.S. Army Aberdeen Test Center). 2008. Test Operations Procedure (TOP) 10-2-210 Ballistic Testing of Hard Body Armor Using Clay Backing. Aberdeen Proving Ground, Md.: Aberdeen Test Center.

Bass, C., R. Salzar, S. Lucas, M. Davis, L. Donnellan, B. Folk, E. Sanderson, and S. Waclawik. 2006. Injury risk in behind armor blunt thoracic trauma. International Journal of Occupational Safety and Ergonomics 12(4):429-442.

Bonn, D., and M. Denn. 2009. Yield stress fluids slowly yield to analysis. Science 324(5933): 1401-1402.

Cannon, L. 2001. Behind armour blunt trauma—An emerging problem. Journal of the Royal Army Medical Corps 147: 87-96.

Chadwick, E., A. Nicol, J. Lane, and T. Gray. 1999. Biomechanics of knife stab attacks. Forensic Science International 105(1): 35-44.

Clare, V., J. Lewis, A. Mickiewicz, and L. Sturdivan. 1975. Blunt Trauma Data Correlation. EB-TR-75016. Aberdeen Proving Ground, Md.: Edgewood Arsenal.

DoD (U.S. Department of Defense). 1996. DoD Preferred Methods for Acceptance of Product. MIL-STD-1916. Arlington, Va.: Department of Defense.

DoD. 2008. DoD Test Method Standard for Performance Requirements and Testing of Body Armor. MIL-STD-3027. Arlington, Va.: Department of Defense.

DoD (Department of Defense). 2009. DoD Testing Requirements for Body Armor. Report Number D-2009-047. Arlington, Va.: Department of Defense Inspector General.

Dunn, N. 2010. ATEC Proposed Army Protocol and Background for NAS Statisticians. Aberdeen Proving Ground, Md.: Army Testing and Evaluation Center.

Huang, Z., M. Lucas, and M. Adams. 2002. A numerical and experimental study of the indentation mechanics of plasticine. Journal of Strain Analysis for Engineering Design 37(2): 141-150.

Ji, H.., E. Robin, and T. Rouxel. 2009. Compressive creep and indentation behavior of plasticine between 103 and 353 K. Mechanics of Materials 41(3): 199-209.

Karahan, M. 2008. Comparison of ballistic performance and energy absorption capabilities of woven and unidirectional aramid fabrics. Textile Research Journal 78(8): 718-730.

Liechty, B., and B. Webb. 2007. The use of plasticine as an analog to explore material flow in friction stir welding. Journal of Materials Processing Technology 184(1-3): 240-250.

Lyon, D. 1997. Development of a 40-mm Nonlethal Cartridge. ARL-TR-1465. Defense Technology Federal Laboratories Research Journal.

Metker, L., N. Prather, and E. Johnson. 1975. A Method for Determining Backface Signatures of Soft Body Armors. EB-TR-75029. Aberdeen Proving Ground, Md.: U.S. Army Armament Research and Development Command.

Nicholas, N., and J. Welsch. 2004. Ballistic Gelatin. Available online at <http://www.nldt.org/documents/ballistic_gelatin_report.pdf>. Accessed March 19, 2010.

NIJ (National Institute of Justice). 1987. Ballistic Resistance of Police Body Armor. NIJ Standard 0101.03. Washington, D.C.: National Institute of Justice.

NIJ. 2008. Ballistic Resistance of Body Armor. NIJ Standard 0101.06. Washington, D.C.: National Institute of Justice.

NIST (National Institute of Standards and Technology). 1994. Memorandum: Rheology of Clays. December 12, 1994. Gaithersburg, Md.: National Institute for Standards and Technology.

NRC (National Research Council). 2009. Phase I Report on Review of the Testing of Body Armor Materials for Use by the U.S. Army. Washington, D.C.: The National Academies Press.

O'Callaghan, P., M. Jones, D. James, S. Leadbeatter, S. Evans, and L. Nokes. 2001. A biomechanical reconstruction of a wound caused by a glass shard—A case report. Forensic Science International 117(3): 221-231.

Pena, L., B. Lee, and J. Stearns. 1994. Structural rheology of a model ointment. Pharmaceutical Research 11(6): 875-881.

Prather, R., C. Swann, and C. Hawkins. 1977. Backface Signatures of Soft Body Armors and the Associated Trauma Effects. Aberdeen Proving Ground, Md.: Chemical Systems Laboratory.

Raftenberg, M. 2006. Modeling thoracic blunt trauma: Towards a finite-element-based design methodology for body armor. Pp. 219-226 in Selected Topics in Electronics and Systems, Volume 42: Transformational Science and Technology for the Current and Future Force, Proceedings of the 24th US Army Science Conference, Orlando, Fla. J.A. Parmentola, A.M. Rajendran, W. Bryzik, B.J. Walker, J.W. McCauley, J. Reifman, and N.M. Nasrabadi, editors. Hackensack, N.J.: World Scientific Publishing Company, Incorporated.

RDECOM (U.S. Army Research, Development and Engineering Command). 2009. Amendment of Solicitation/Modification of Contract W91CRB-09-D-0001/P00004. Aberdeen Proving Ground, Md.: RDECOM.

Vaughan, N. 2001. Assessment of Aprons for Protection Against Drop Forging Projectiles. Contract Research Report 395/2001. Sheffield, U.K.: Health and Safety Laboratory.

Weber, D. 2000. Measuring Impact Velocities of Non-Lethal Weapons. Available online at <http://www.dtic.mil/ndia/nld4/weber.pdf>. Accessed March 19, 2010.

OTA (Office of Technology Assessment). 1992. Police Body Armor Standards and Testing, Volume II: Appendices, OTA-ISC-535. Washington, D.C.: Office of Technology Assessment.

APPENDIX 1

The high-speed photographic camera used at by R.F. Kinsler at the Army Research Laboratory is frequently operated with a repetition rate of 25 microseconds, a pulse duration of 1 microsecond, and a recording array of 304 by 192 pixels. This would yield a spatial resolution at a moving deformation front of 0.26 mm.[1] For a BFD displacement rate of 100 m/s, the surface will move by only 0.1 mm during the 1 microsecond that the "shutter" is open, producing a small smear of the 0.26 mm spatial resolution.

A BFD of 40 mm would occur over approximately 1 millisecond. A repetition rate of 25 microseconds would therefore enable about 40 discrete contours of deformation to be recorded during a given shot with a spatial resolution of 0.26 mm and a velocity resolution of about 1 m/s.

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[1] Question and answer session between R. Kinsler, ARL, and the committee, March 10, 2010.

ATTACHMENT A

STATEMENT OF TASK

The National Research Council will convene a committee to consider the technical issues relating to the testing of body armor. To do this the committee shall conduct a 3-phase study:

In Phase I the committee

- will comment on the validity of using laser profilometry/laser interferometry techniques to determine the contours of an indent made by a ballistic test in a non-transparent clay material at the level of precision established in the Army's procedures for testing personal body armor. If laser profilometry/laser interferometry is not a valid method, the committee will consider whether a digital caliper can be used instead to collect valid data.
- The committee will also provide interim observations regarding the column-drop performance test described by the Army for assessing the part-to-part consistency of a clay body used in testing body armor.

The committee will prepare a letter report documenting the findings from its Phase I considerations.

In Phase II the committee will

- consider in greater detail the validity of using the column-drop performance test described by the Army for assessing the part-to-part consistency of a clay body within the level of precision that is identified by the Army test procedures.

The committee will prepare a letter report documenting the findings from its Phase II considerations.

In Phase III the committee will

- consider test materials, protocols and standards that should be used for future testing of personal armor by the Army.
- The committee will also consider any other issues associated with body armor testing that the committee considers relevant, including issues raised in the Government Accountability Office Report—Warfighter Support, Independent Expert Assessment of Body Armor Test Results and Procedures Needed Before Fielding (GAO-10-119).

The committee will prepare a final report.

The final report will document the committee's findings pertaining to the following issues that are of particular immediate concern to DOT&E [Director of Testing and Evaluation] including the following:

- The best methods for obtaining consistency of the clay, and of conditioning and calibrating the clay backing used currently to test armor.

- The best instrumentation (e.g., laser scanning system, digital caliper, etc.) and procedures to use to measure the BFD [backface deformation] in the clay.
- The appropriate use of statistical techniques (e.g., rounding numbers, choosing sample sizes, or test designs) in gathering the data.
- The appropriate criteria to apply to determine whether body armor plates can provide needed protection to soldiers; this includes the proper prescription for determining whether a test results in a partial or complete penetration of body armor, including, as appropriate, the soft armor underlying hard armor.

The final report will also document the committee’s findings regarding any other issues regarding body armor testing that the committee found relevant. The study team will have access to all data with respect to body armor testing that the team needs for the conduct of the study.

ATTACHMENT B

COMMITTEE TO REVIEW THE TESTING OF BODY ARMOR MATERIALS FOR USE BY THE U.S. ARMY – PHASE II

LARRY G. LEHOWICZ, MG, U.S. Army (ret.), *Chair*, Quantum Research International, Arlington, Virginia
MORTON M. DENN, NAE,[27] City College of the City University of New York
WILLIAM G. FAHRENHOLTZ, Missouri University of Science and Technology, Rolla
RONALD D. FRICKER, JR., Naval Postgraduate School, Monterey, California
JAMES D. McGUFFIN-CAWLEY, Case Western Reserve University, Cleveland, Ohio
HENRY I. SMITH, NAE, Massachusetts Institute of Technology, Cambridge
KENNETH L. WALKER, NAE, Luna Innovations Incorporated, Danville, Virginia
ALYSON G. WILSON, Iowa State University, Ames

Staff
BRUCE A. BRAUN, Director, Board on Army Science and Technology
ROBERT LOVE, Study Director, Board on Army Science and Technology
HARRISON T. PANNELLA, Senior Program Officer, Board on Army Science and Technology
NIA D. JOHNSON, Senior Research Associate, Board on Army Science and Technology
JAMES C. MYSKA, Senior Research Associate, Board on Army Science and Technology
ALICE WILLIAMS, Senior Program Assistant, Board on Army Science and Technology
CONSTANCE CITRO, Director, Committee on National Statistics
GARY J. FISCHMAN, Director, National Materials Advisory Board
JAMES P. McGEE, Director, Army Research Laboratory Technical Assessment Board
SARAH EDWARDS, Mirzayan Science and Technology Policy Fellow

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[27] NAE, National Academy of Engineering.

ATTACHMENT C

ACKNOWLEDGMENT OF REVIEWERS

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

WILLIAM M. CARTY, Alfred University
JOHN FOSTER, JR. (NAE), Northrop Grumman Space Technology
CHRISTOPHER W. MACOSKO, (NAE), University of Minnesota
PETER MATIC, Naval Research Laboratory
MAX D. MORRIS, Iowa State University
LESLIE J. STRUBLE, University of Illinois
EDWIN L. THOMAS (NAE), Massachusetts Institute of Technology
JAMES C. WYANT (NAE), University of Arizona
WILLIAM YASHCHIN, IBM Thomas J. Watson Research Center
LAURENCE R. YOUNG, (NAE/IOM), Massachusetts Institute of Technology

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Lawrence D. Brown, NAS, Wharton School, University of Pennsylvania, and Arthur H. Heuer, NAE, Case Western Reserve University. Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

ATTACHMENT D

ACRONYMS

ATC	Aberdeen Test Center
ATM	anthropomorphic test module
BABTA	Body Armor Blunt Trauma Assessment
BFD	backface deformation
DoD	Department of Defense
DOT&E	Director of Operational Test & Evaluation
ESAPI	Enhanced Small Arms Protective Insert
FAT	first article testing
IG	Inspector General
LAT	lot acceptance testing
NIJ	National Institute of Justice
NIST	National Institute of Standards and Technology
TOP	Test Operations Procedure
XSAPI	X Small Arms Protective Insert
USSOCOM	United States Special Operations Command