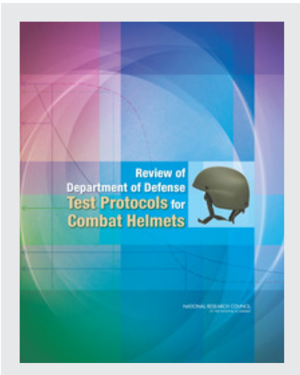

Review of Department of Defense Test Protocols for Combat Helmets

DETAILS

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5

Helmet Performance Measures and Trends in Test Data

5.0 SUMMARY

A helmet's protective capabilities are evaluated on the basis of two primary test measures: resistance to penetration (RTP) and backface deformation (BFD). These are formally defined and their limitations are discussed in this chapter. RTP data available to the committee indicate that the probability of penetration of a helmet shell by a 9-mm bullet, fired under specified conditions, is on the order of 0.005 or less. Available BFD data show that the probability of exceeding the BFD thresholds is around 0.005 or less. The distributions of the BFD data also demonstrate significant differences among helmet sizes and shot locations. Some of the performance differences among helmet sizes may be attributed to the test process, such as headforms and stand-offs. Many others are likely to be due to the differences in the geometry of helmet shells, molds, manufacturing processes, and other factors. In fact, helmets of different sizes are intrinsically different products. Therefore, Recommendation 5-5 proposes changes to DoD's test protocols so that helmets of different sizes are treated separately. This is one of the major recommendations in the report.

5.1 INTRODUCTION

For the purpose of helmet testing, protective capabilities are measured by RTP and BFD. Section 5.2 defines these measures and discusses their limitations. Section 5.3 summarizes results from test data that were made available to the committee. The implications of these results for the Director of Operational Test and Evaluation's (DOT&E's) first article testing (FAT) and lot acceptance testing (LAT) protocols are discussed in Section 5.4.

Another measure, called $V_{50,}$[1] is also used in FAT. However, the estimated value of V_{50} is not used in the decision process. Thus, the committee considers V_{50} estimation and testing to be an aspect of characterization analyses. This topic is discussed in Chapter 8.

5.2 PERFORMANCE MEASURES

Resistance to Penetration

RTP is measured by shooting a given ballistic projectile at a set of helmets and counting the number of complete penetrations. Most ballistic impacts penetrate the helmet to some degree, so the DOT&E FAT and LAT testing protocols distinguish between complete and partial penetrations. A *complete penetration* in RTP testing is defined as:

> Complete perforation of the shell by the projectile or fragment of the projectile as evidenced by the presence of that projectile, projectile fragment, or spall in the clay, or by a hole which passes through the shell. In the case of the fastener test, any evidence of the projectile, fragment of the projectile, or fastener in the clay shall be considered a complete penetration. Non-metallic material[s] such as paint, fibrous materials, edging, or edging adhesion resin that are emitted from the test specimen and rest on the outer surface of the clay impression are not considered a complete penetration.[2]

A *partial penetration* is defined as "any fair impact that is not a complete penetration."[3] In this report, the term *penetration* is used to refer to complete penetration. In DoD documents, the term "perforation" is used synonymously with "complete penetration."

According to personnel from the Army Test Center, there is currently no practical way to determine or measure the degree or depth of penetration, and thus helmet penetration testing is currently attribute-based: on a given (fair) shot, the result is recorded as either a complete penetration or a partial penetration. The intuitive notion is that a projectile

[1]V_{50} refers to "the velocity at which complete penetration and partial penetration are equally likely to occur" (DoD, 1997).

[2]The protocols for FAT and LAT testing are given in Appendix B.

[3]Ibid.

that penetrates the shell is apt to cause more serious head injuries than a projectile that does not, but there is no other linkage between what is measured and head injury.

Finding 5-1. It is not known whether partial penetrations might be reasonably and usefully measured in order to assess the degree to which a non-perforated helmet is penetrated.

V_{50} testing refers to estimating the bullet speed at which there is a 50 percent chance of penetration. This test uses a witness plate mounted inside the headform rather than packing the headform with clay as is done with RTP/BFD testing. (See Appendix D for details.) Because of this difference, the DOT&E FAT protocol defines a V_{50} complete penetration as a shot where

> Impacting projectile or any fragment thereof, or any fragment of the test specimen perforates the witness plate resulting in a crack or hole which permits light passage. A break in the witness plate by the helmet deformation is not scored as a complete penetration.[4]

Finding 5-2. The definition of what constitutes a penetration, and how such penetrations are measured, differs between RTP and V_{50} tests. V_{50} specifies a "hole which permits light passage" whereas RTP does not.

Recommendation 5-1. The Office of the Director, Operational Test and Evaluation, should revise the first article testing protocol for resistance to penetration and V_{50} testing to ensure that the two protocols are consistent.

Backface Deformation

Helmet BFD is measured on the non-perforating ballistic impacts from RTP testing. It is defined as the *maximum depth* in the post-impact clay surface at the intended impact location as measured from the original clay surface. It is measured as follows: After mounting the helmet on the headform and mounting the headform in the test fixture, the helmet is removed from the headform, and the clay surface is scanned with a laser. The helmet is then reattached to the headform and the shot taken. Finally, the helmet is again removed from the headform, inspected for penetration and perforation, and the clay is rescanned with the laser to calculate BFD. A typical BFD laser scan is shown in Figure 5-1.

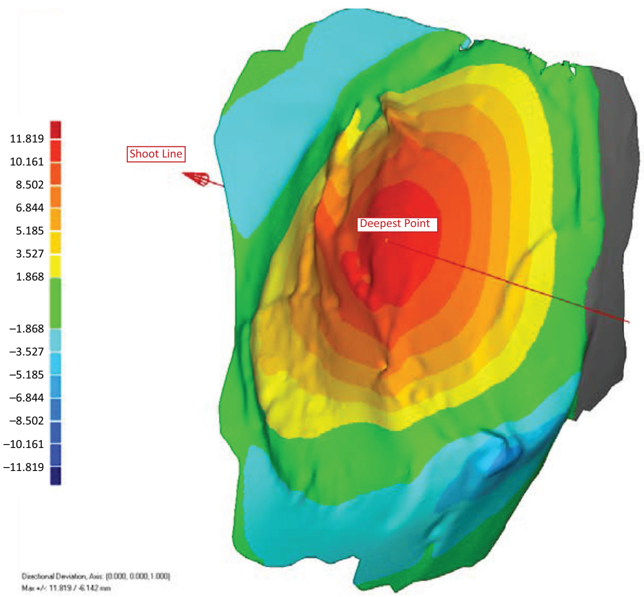

FIGURE 5-1 Illustrative backface deformation laser scan. SOURCE: Courtesy of the Office of the Director of Operational Test and Evaluation.

The definition of BFD as the maximum depth of indentation left in the clay has a number of issues. First, as discussed in the Phase III report (NRC, 2012) report, clay is an imperfect recording medium. As that report said:

> The qualitative assertion that RP #1 exhibits little recovery has been interpreted to mean that the level of elastic recovery is small enough to be safely neglected. This has led to an assumption that the shape of the resultant cavity provides a record of the BFD. Since the relative degree of elastic and plastic deformation will vary as a function of strain rate, the backing material must be characterized under conditions that are relevant to those under which the tests will be performed. The cavity that results from live-fire ballistic testing is indeed related to the deformation on the back face of the armor, but it is not a true record of maximum deflection. It remains unknown how the dimensions of the cavity relate to the true BFD and how such a relationship may depend on the rate at which the cavity is formed (NRC, 2012, p. 5).

Further, whether the appropriate measure is the depth of the BFD rather than BFD area, BFD volume, or some other measure such as total or instantaneous force imparted, is not known. It is also unclear how well BFD from ballistic impact characterizes the effect of blunt-force trauma, which is one of the main types of brain injury that the helmet is intended to protect against.

Finding 5-3. It is unknown whether the current definition of BFD is the most appropriate for assessing how well helmets protect soldiers and marines from the helmet deformation due to ballistic impact and other blunt-force trauma. It may be that some other measurement, such as the area or volume of the BFD, or perhaps some measure of force or acceleration imparted, is more appropriate for assessing the ability of the helmet to protect against brain injury. If such an alternative measurement is found, the protocols and thresholds would have to be changed appropriately.

[4]Ibid.

Recommendation 5-2. The Department of Defense should develop a better understanding of the relationship between backface deformation and brain damage, including the examination of alternative metrics to maximum depth.

In addition to the definition of BFD, the DOT&E protocol specifies BFD thresholds at 25.4 mm for front and back shots and 16 mm for side and crown shots. These appear to be based on historical helmet testing precedent and are not connected to the potential for brain injury. The analysis, however, appears to be based on the presumption that the larger the BFD, the greater the likelihood of serious head injury.

Finding 5-4. The choice of the helmet BFD threshold values—25.4 mm for front and back shots and 16 mm for side and crown shots—does not have a scientific basis. In contrast, the body armor BFD limit was derived from scientific studies.

As a result, the usefulness of the helmet FAT and LAT test data on BFD is limited. The data can be used for assessing helmet performance against the requirements in the purchase description and the DOT&E helmet testing protocol; the results can also be used to compare helmet performance within and between manufacturers and over time. But the data cannot be used to determine the level of protection provided by a new helmet that is designed and manufactured according to a different set of specifications. This becomes critical when assessing the protection offered by new helmets because there are trade-offs between penetration, BFD, and other helmet characteristics, such as weight, form, and fit.

Recommendation 5-3. The Department of Defense should examine the basis for backface deformation thresholds and develop appropriate ones based on scientific studies and data.

Recommendation 5-4. As research progresses, methods, measures, and thresholds should be continuously reviewed to determine whether the new knowledge warrants changes to any of them. The review team should include adequate expertise from a broad range of disciplines, including medical, engineering, and testing professionals**.**

5.3 SUMMARY OF RESULTS FROM AVAILABLE TEST DATA

The DOT&E FAT and LAT protocols, as well as any additional requirements included in service-specific contractual requirements, specify RTP and BFD pass or fail requirements. The particular details of these tests are described in detail in Chapters 6 and 7. This section summarizes how the Advanced Combat Helmet (ACH) performs in terms of these two measures using data made available to the committee.

Resistance to Penetration Data

Table 5-1 provides a summary of RTP test data for ACH helmets, provided to the committee, from FAT and LAT. There were two sources of FAT data: the first with 309 shots and the second one with 816 shots, and there were no penetrations. So, the estimate of the penetration probability from the combined data is 0, and a 90 percent upper confidence bound (UCB) is 0.002. The LAT data were from four different vendors (as shown at the bottom of Table 5-1), and there were only 7 penetrations out of 11,049 shots. This yields an estimated probability of penetration of 7/11,049 = 0.0006. The corresponding 90 percent UCB is 0.001. Hence, we see that a Remington 9-mm full-metal-jacket (FMJ) projectile shot at a randomly selected ACH, under test conditions, is unlikely—with only a 0.1 percent chance—of completely penetrating the helmet.

TABLE 5-1 Summary of Resistance to Penetration Test Data

Test Type	Penetrations	Number of Shots	Penetration Proportion (90% Upper Confidence Bound)
FAT—20-shot, five vendors	0	309	0
FAT—240- or 96-shot, four helmets	0	816	0
FAT—All	0	1,125	0.000 (0.002)
LAT—Four vendors (see below)	7	11,049	0.0006 (0.001)
Total	7	12,174	0.0006 (0.001)
			Penetration Proportion (90% Upper Confidence Bound)
LAT, Vendor A	5	5,422	0.0009 (0.002)
LAT, Vendor B	0	2,872	0.0000 (0.001)
LAT, Vendor C	2	1,285	0.0016 (0.004)
LAT, Vendor D	0	1,470	0.0000 (0.002)

NOTE: FAT, first article testing; LAT, lot acceptance testing.
SOURCE: Office of the Director, Operational Test and Evaluation.

During FAT and LAT, each helmet is subjected to five shots at different locations. So the 11,049 LAT shots correspond to roughly about 2,200 helmets. See Appendix D for additional details. (If a perforation is observed on a helmet, that helmet is not tested further, so the seven observed perforations were all on separate helmets.) One can estimate the probability of helmet failure (rather than penetration at any given location) to be approximately 7/2,200 = 0.003, which is also very low.

Finding 5-5. Available data indicate that there is very low probability of helmet perforation (less than 0.005) from a Remington 9-mm FMJ projectile shot under test conditions.

This level of penetration probability is considerably smaller than the 10 percent "standard" on which the DOT&E protocol is based. The implications of this result are discussed in Chapter 6.

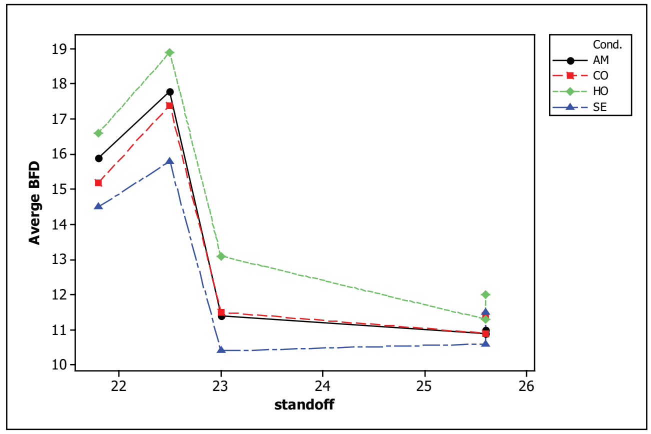

FIGURE 5-3 Average backface deformation (BFD) as a function of stand-off for Data Set 1. Colors represent different environments. NOTE: AM, ambient; CO, cold; HO, hot; SE, sea water.

Backface Deformation Data

This section summarizes relevant results from BFD data that were made available to the committee.

Data Set 1

Data Set 1 is from a test of 48 ACHs (referred to here as Helmet 1). Twelve helmets each are exposed to four different environments (ambient, cold, and hot temperatures and seawater) prior to testing. The test consisted of firing single shots at five locations on the helmet: front, back, left side, right side, and crown, leading to a total of 240 shots. The data are all from a single-sized helmet (size Large), so the effect of helmet size cannot be studied from this data set.

Figure 5-2 shows the BFD measurements by shot locations. DOT&E's tolerance limit analysis is based on pooling the data across environments as well as across helmet sizes and shot locations in the two location groups. Therefore, the committee has also pooled the data across the environments. The horizontal solid lines in the figure are the BFD upper limits of 25.4-mm for back and front shot locations and 16-mm for left, right, and crown shot locations. The BFD measurements are below the thresholds at all locations, and in some cases considerably so. Note also that the distributions for the left, right, and crown locations are quite comparable, while the distribution for the front location is substantially higher than that of the back. This difference was consistent across the four different environments (figures not shown here), and similar effects were seen with other helmet test data as well.

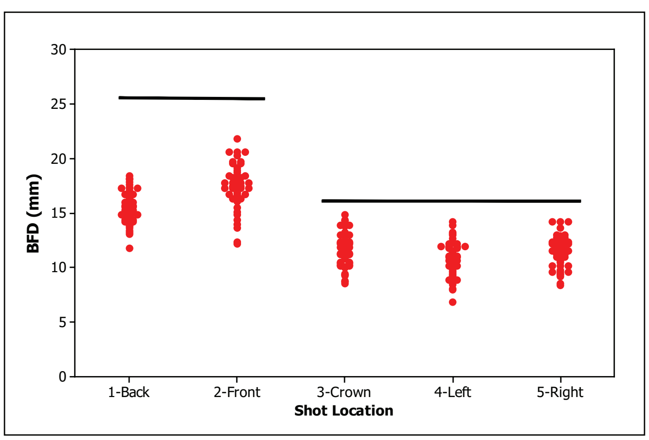

FIGURE 5-2 Backface deformation (BFD) measurements by location for Data Set 1. Specified limits of 25.4 mm and 16.0 mm are indicated by solid lines.

The DOT&E protocol based on BFD is formally described in Chapter 7, and it requires that the upper 90/90 tolerance limit of the BFD distribution not exceed the threshold. Figure 5-2 shows that no BFD values exceeded their limits. Further, for the back/front group of data, the BFD values are considerably below their limit.

One possible reason for the differences in BFD measurements among location is stand-off: the distance between the inside of the helmet shell and the headform (see discussion in Chapter 4). For a large ACH, the stand-offs were as follows: back, 21.8 mm; front, 22.5 mm; crown, 23.0 mm; and left and right, 25.6 mm.[5] Figure 5-3 shows how the average of the BFD measurements differs with stand-off. The colors correspond to different environmental conditions. Note that the data are clearly separated by environment. The average BFDs are clearly different for different values of stand-off, but the relationship is not monotone, and hence not easy to

[5]Frank J. Lozano, Product Manager, Soldier Protective Equipment, "Setting the Specifications for Ballistic Helmets," presentation to the committee on April 25, 2013.

interpret. It may be expected that BFD would decrease as stand-off increases, but the average BFD for front and back have the opposite difference. The average BFDs for the crown, left, and right locations are quite close, even though the crown offset is considerably less than the side stand-offs. Perhaps other geometric aspects of the test and the shape of the helmet contribute to these patterns.

Data Set 2

Data Set 2 was from a test of the Marine helmet (MICH) (Helmet 2). Three helmets each corresponding to four sizes (small [S], medium [M], large [L], and extra large [XL]) were tested at four environmental conditions (ambient, cold, hot, seawater). Again, there were single shots at five locations (front, back, left side, right side, and crown) for a total of 240 shots. This is the suite of shots specified in the DOT&E protocol. Figure 5-4 shows the same sort of location differences for this helmet as for Helmet 1.

There is more spread in the Helmet 2 data than for Helmet 1 because the data are pooled over four helmet sizes as well as four environments. The BFD distributions for L and XL helmets were different, with the measurements for XL being generally smaller than those for L. Perhaps this is due to using a single headform for L and XL helmets. There were no appreciable differences among environments. Once again, the 10 percent standard is easily met by these data.

Data Set 3

Data Set 3 was from a test of Helmet 3, a repeat of the Helmet 2 tests, after a design change to the MICH. Figure 5-5 shows the BFD data by location, pooled over environments and helmet sizes.

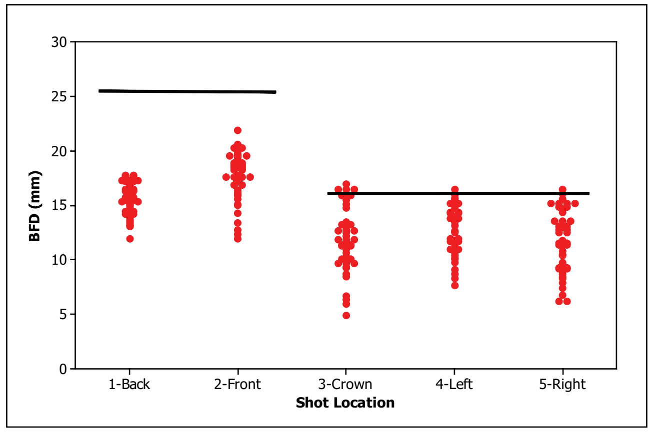

FIGURE 5-5 Backface deformation (BFD) measurements by location for Data Set 3. Specified limits of 25.4 mm and 16.0 mm are indicated by solid lines.

The Figure 5-5 plot shows that there is considerably less margin for the BFD data for the crown/left/right shot locations than there was for Helmet 2. Apparently, the design change increased the magnitude of the dents in the clay. Eight of the 144 BFDs in this group exceeded the 16.0-mm threshold. The upper 90 percent confidence limit on the probability of exceeding the limit, based on this outcome, is about 9 percent, so the 10 percent standard is met in this regard.

Figure 5-6 shows that the differences among shot locations for the XL helmet size have a pattern substantially different from those of the other three sizes.

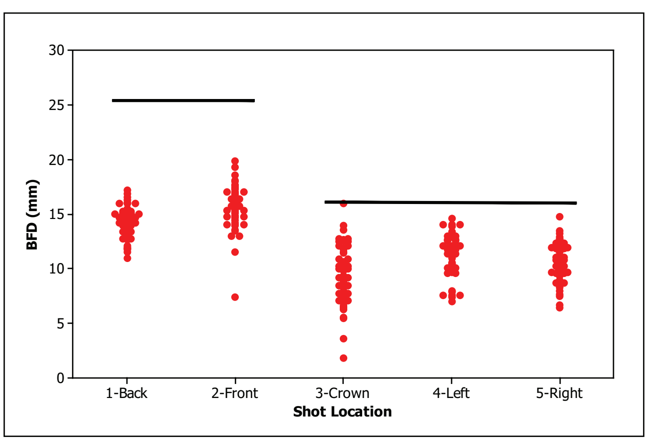

FIGURE 5-4 Backface deformation (BFD) measurements by location for Data Set 2. Specified limits of 25.4 mm and 16.0 mm are indicated by solid lines.

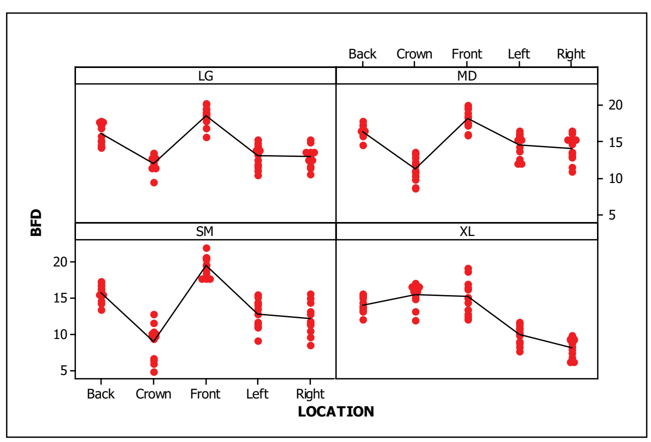

FIGURE 5-6 Backface deformation (BFD) measurements by location and helmet size for Data Set 3. NOTE: MD, medium; LG, large; SM, small; XL, extra large.

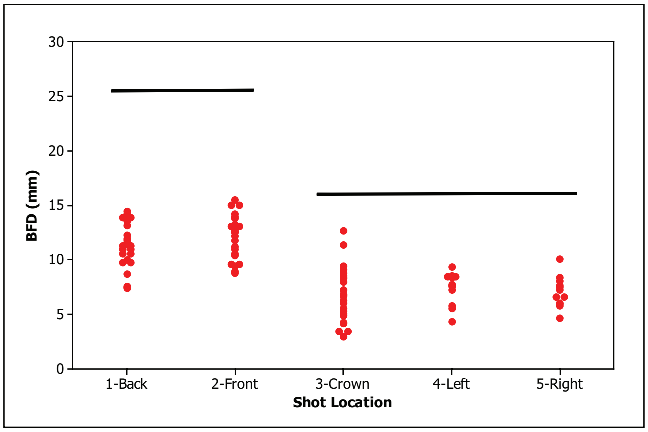

FIGURE 5-7 Backface deformation (BFD) measurements by location for Data Set 4. Solid lines are the specified limits of 25.4 mm and 16.0 mm.

Data Set 4

Data Set 4 was from a FAT for the enhanced combat helmet (Helmet 4). Three helmets, of each of four sizes, were tested at four different environments. However, because of excessive helmet damage, the DOT&E protocol was reduced to only two shots on each helmet.

Figure 5-7 shows the BFD data by shot location. There are 24 shots each in the back and front locations, 16 each in the crown, left, and right locations. Figure 5-7 shows that the BFD data for this helmet are well below their limits.

For the data sets analyzed by the committee, 8 of 816 BFD measurements exceeded their respective thresholds. All of these were for Helmet 3, which suggests something different about that helmet or the test procedure.

Finding 5-6. It is clear that manufacturers are capable of producing helmets for which the probability of failing the BFD protocol is very small.

Finding 5-7. Based on the available BFD data, one can make the following observations about heterogeneity:

- There are substantial differences in BFD data across helmet sizes.
- There is also a great deal of heterogeneity across locations. It was expected that there will be differences in BFD measurements between two shot-location groups: front and back versus crown, left, and right. This is reflected in the different BFD thresholds for the two groups. However, the data consistently indicate that BFD measurements at the front location are larger than those at the back, which is counter to the differences in stand-off at these locations. There is much less variability in the data among the other three locations: crown, back, and front.
- The effect of environments appears to be small. The same is also true for the effect of shot order.

5.4 IMPLICATIONS FOR FIRST ARTICLE TESTING PROTOCOLS

As shown in Table 4.1, the current DOT&E protocols involve testing 48 helmet shells: 12 each corresponding to sizes S, M, L, and XL. Of the 12 shells, 3 are conditioned in each of four different environments. Further, shots are taken at five different locations on the helmet. So, the committee looked at RTP and BFD data on a total of 240 shots. Chapters 6 and 7 describe in detail the pass-fail rules for FAT protocols for RTP and BFD, respectively. Briefly, the RTP protocol states that if there are 17 or fewer penetrations, the test is deemed to be successful. The BFD protocol is applied separately to the two groups of locations with different thresholds: back and front in one group and crown, left, and right in another. The specific approach involves computing 90/90 upper tolerance limits (UTLs), based on BFD measurements and the assumption that the data are normally distributed, and comparing the UTLs against their respective thresholds. If the UTL is smaller, the test is deemed successful; otherwise it is unsuccessful.

The plots of the BFD distributions in the previous section appear to be different across helmets and locations, and this raises the issue of pooling the data to implement the protocol. The differences in the two groups of locations (front and back versus crown, right, and left) are handled by implementing the protocols separately for the groups with different thresholds: 25.6-mm and 16-mm. Within the groups, differences noted at front and back locations indicate that the data should not be pooled and analyzed as a sample from a single normal distribution. DOT&E has proposed an analysis to check for differences in the mean and variances and pool the data only if the test is accepted. In addition to the complexity of the procedure, the statistical properties of the protocol are not valid when one applies a pre-test before implementing it.

In addition, the committee notes that helmets of different size are intrinsically different products: different-sized shells are manufactured from different molds and different manufacturing processes or settings (even if some of the equipment and process steps are common). Therefore, pooling the BFD data across different-sized helmets and treating the data as homogeneous does not seem appropriate. It also leads to the cumbersome process of pre-testing to see if the measurements have the same mean and variance before combining the data.

Recommendation 5-5. The Office of the Director, Operational Test and Evaluation, should revise the current protocols to implement them separately by helmet size.

This recommendation clearly involves a major change in the way helmets are currently tested. It will also require decisions on how the Department of Defense implements procurement decisions. For example, if a particular helmet size did not pass FAT and others did, DoD will need to decide whether the helmet sizes that passed FAT can be procured or not. The committee judges that such decisions should be left to the DoD and should be based on practical considerations rather than statistical properties of the protocol.

5.5 REFERENCES

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