AD 734339

TECHNICAL REPORT
72-20-GP

DEVELOPMENT OF A NEW ACCEPTANCE CRITERION FOR M-1 HELMETS
Phase I: Analyses of Data and Development of Inspection Plan

by
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and
R. E. Maringer

Battelle Memorial Institute
Columbus Laboratories
Columbus, Ohio

Contract No. DAAG17-68-C-0138

November 1971

UNITED STATES ARMY
NATICK LABORATORIES
Natick, Massachusetts 01760

General Equipment & Packaging Laboratory

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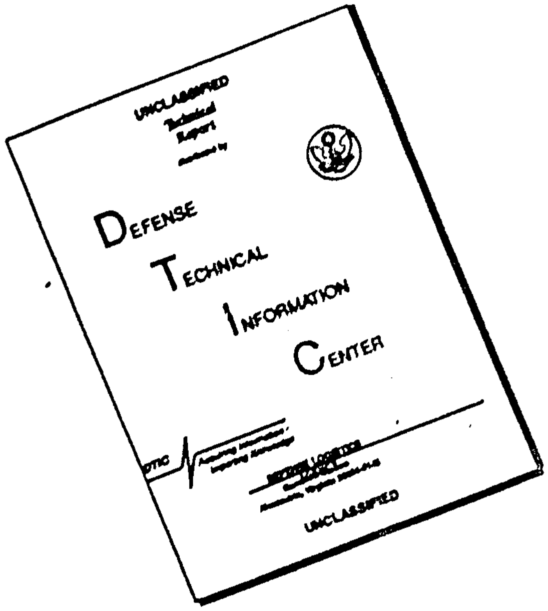

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Security Classification

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(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Battelle Memorial Institute Columbus Laboratories 505 King Ave., Columbus, Ohio 43201	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

Development of a New Acceptance Criterion For M-I Helmets; Phase I, Analyses of Data and Development of Inspection Plan

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Phase Report, 8 May, 1968 through 18 October, 1968

5. AUTHOR(S) (Last name, first name, initial)

Rudnick, A., G. H. Beatty, and R. E. Maringer.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
November 1971	46	

8a. CONTRACT OR GRANT NO. DAAG17-68-C-0138 b. PROJECT NO. Production Engineering 728012.12 c. Task No. 5-19 d.	9a. ORIGINATOR'S REPORT NUMBER(S) 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. AVAILABILITY/LIMITATION NOTICES

This document has been approved for public release and sale; distribution unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	U. S. Army Natick Laboratories Natick, Massachusetts 01760

13. ABSTRACT

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DD FORM 1 JAN 64 1473

Unclassified

Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Tests	8					
Aluminum alloys	9					
Body armor	4					
Ballistic properties	8					

Approved for public release;
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AD____________

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Prepared under Contract No. DAAG17-68-C-0138

Project Reference:
Production Engineering
728012.12

November 1971

General Equipment & Packaging Laboratory
U. S. ARMY NATICK LABORATORIES
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FOREWORD

This report was prepared by Battelle Memorial Institute, Columbus Laboratories for the U. S. Army Natick Laboratories under Contract No. DAAG17-68-C-0138. The study covered by this report was carried out over the period May through September 1968 and is the first of two phases specified by that contract. Mr. C. W. Davis served as project monitor.

This study uses work done under Contract No. DA19-129-AMC-1005(N) as a basis. Work under that contract was reported in "A Study of Ballistic Protective, Chemical, and Physical Properties of 200 M-1 Helmets and 200 Helmet Blanks"— Battelle Memorial Institute, July 28, 1967.

The authors would like to express their appreciation to Mr. Davis and his colleagues at Natick Laboratories for their guidance and significant contributions on this study.

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ABSTRACT

Data obtained on a previous study of M-I helmets were analyzed to provide the basis for implementation of thickness as the inspection parameter for helmet protection. A strong, linear relationship between ballistic limit (the current inspection parameter) and thickness was found. This relationship serves as the justification for the recommended change in inspection procedure. An inspection-by-attributes plan is recommended for use with the thickness inspection.

DEVELOPMENT OF A NEW ACCEPTANCE
CRITERION FOR M-1 HELMETS

Phase I: Analyses of Data and
Development of Inspection Plan

to

DEPARTMENT OF THE ARMY
U. S. Army Natick Laboratories

October 18, 1968

INTRODUCTION

During the period from June, 1966, through July, 1967, the U. S. Army Natick Laboratories sponsored at Battelle a study of the influence of various parameters on the ballistic resistance of M-1 helmets*. The details and results of that study are contained in our Summary Report, "A Study of Ballistic Protective, Chemical, and Physical Properties of 200 M-1 Helmets and 200 Helmet Blanks", dated July 28, 1967. The broad objective of that program was to evaluate the potential for replacing the current ballistic limit criterion for helmet acceptability with a simpler, less expensive, and preferably nondestructive method of inspection. It is the purpose of the current study to translate the findings of the initial study into the design of a usable inspection system.

Reviewing briefly, the initial study involved a detailed investigation of 200 sets of helmets and helmet blanks; each helmet and helmet blank set represented one heat-treatment lot. The following data were obtained:

On each helmet blank –

- Ballistic limit (V_p50) for T-37, .22 Caliber fragment simulators.**

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* Contract No. DA19-129-AMC-1005 (N).

** The fragment simulators are described in Military Specification MIL-P-46593A.

- Average thickness.
- Average hardness.
- Chemical composition.
- Tensile stress-strain properties in directions parallel and transverse to the rolling direction.

On each helmet –

- Thickness of each of 96 locations in the helmet.
- Hardness of each of 96 locations in the helmet.
- Metallographic analysis of the rim area of each helmet.
- Ballistic data as follows (T-37, .22 Cal. fragments simulators were used): On the average, 42 rounds were fired into each helmet. The data obtained were: location of point of impact, impact velocity, and a notation of whether or not the fragment simulator penetrated. These data were used to compute V_p50's for the entire helmet and for selected portions of the helmet.

In addition, deformation patterns in formed helmets were studied.

The data were analyzed to find relationships among the various parameters. Particular emphasis was placed on finding relationships between each of the parameters (including V_p50 of the blanks) and a V_p50 of the helmet. In this regard, various V_p50's were calculated for each helmet, viz., a V_p50 for the whole helmet, for the top part (crown) alone, and for the bottom part alone. Also, ballistic data from all 200 helmets were combined to allow computation of a V_p50 for each of 96 locations in the helmets.

Of the parameters studied, only thickness was found to have had both enough variability among and within helmets and sufficient influence on V_p50 to be of potential value as a replacement for the ballistic test. The use of thickness as an inspection criterion could have many advantages over the current V_p50 test. The inspection procedure could be nondestructive, inexpensive, and relatively rapid; also, 100 percent inspection might be practical.

Certain key points remained to be studied before a replacement of ballistic inspection could be justified. First, while the relationships obtained between thickness and V_p50 were highly encouraging, they were not sufficiently strong to justify implementation of the change. There were, however, indications that further analyses would reveal stronger correlations. Assuming a sufficiently strong relationship existed, two other basic questions would have to be answered regarding future inspection plans: where should thickness be measured and how should it be measured?

The current two-phase study is directed at these issues. Phase I had as its objectives (1) further investigation of the V_p50-thickness correlation, (2) determination of the most appropriate places to monitor thickness in a helmet, and (3) the formulation of associated inspection plans. The approach involved, primarily, further analysis of data obtained under the earlier contract. The objective of Phase II is to develop an effective means for accomplishing the measurements in a production situation. This report describes the procedures followed and results obtained in Phase I of the study.

SUMMARY

Analyses of thickness and ballistic data for M-1 helmets indicate that the current ballistic acceptance criterion (of a 900 fps ballistic limit to .22 Caliber fragment simulators) can be replaced by an equivalent acceptance criterion based on helmet thickness. The change can result in a less expensive, more rapid, and nondestructive inspection with no decrease in helmet quality and an increase in confidence in the inspection. The above conclusions are based on data from 200 helmets, each taken from a different heat-treatment lot of helmet material. Over 19,000 thickness measurements and data from 8,400 ballistic impacts on these helmets were used to provide the required information.

By arranging the data from the 8400 ballistic impacts into 340 sets of essentially uniform thickness, it was shown that the ballistic limit (V_p50) is related to thickness (t) of a point on a helmet by the linear equation,

$$V_p50 = 57 + 24,900\ t,$$

where V_p50 is in feet per second and t is in inches. The correlation coefficient for the data was 0.98; the standard deviation of V_p50 about the above equation was 17 fps. The versatility of the above equation was demonstrated in several ways. In particular, by using for t the average thickness of helmets, the equation provides a good prediction of the ballistic limit of helmets. In fact, it is reasoned that the above equation provides a better estimate of the "true" V_p50 of a helmet than is normally obtained from actual ballistic tests.

Having established the value of using thickness as a helmet acceptance criterion, questions relating to the details of the inspection were addressed. In particular, the question of the most effective places to be measured was considered at length. There were open several possibilities of specific measurements that might be made. In an attempt to maintain certain aspects of the sense of the current ballistic tests, the possibilities were narrowed to either average thickness of the crown or the minimum thickness of the helmet. It is recommended that both possibilities be left open until we have had an opportunity to investigate the relative costs of performing these measurements. This will be done early in Phase II.

It is recommended that inspection by attributes be used when implementing thickness as the inspection parameter. The specific plan recommended utilizes an inspection sample of 80 helmets per heat-treatment lot. The lot would be accepted if not more than one of the 80 helmets inspected had inadequate thickness; the lot would be rejected if two or more helmets were found to be substandard. The operating characteristics of the proposed inspection plan are not identical with those of the current ballistic inspection. In particular, both the producer's and consumer's risks (at the current acceptable quality level and limiting quality, respectively) are reduced. Although the differences are not considered significant, the fact that both risks are reduced should make the recommended plan acceptable to both the helmet manufacturer and the Government.

BALLISTIC LIMIT-THICKNESS CORRELATION

Background

An inspection or quality-control procedure usually involves an indirect evaluation of the ability of the product to serve its intended function. This is accomplished by measuring a parameter (usually referred to as the quality characteristic) the magnitude of which is related to the ability of the product to serve its intended function. The effectiveness of the inspection depends on the sensitivity of the intended function to the parameter inspected, and the reliability of the relationship between the two. These quantities (sensitivity and reliability) can be expressed in terms of a plot of intended function versus inspection parameter. The sensitivity will be given by the slope of the curve of best fit; reliability will be related to the amount of scatter about the curve of best fit.

In the case of the M-1 helmets under consideration, a third factor enters. The "intended function" of the helmet is not well defined. Current practice, based largely on experience, is to use the ballistic limit, V_p50 (for T-37, .22 Caliber fragment simulators), as a criterion of helmet acceptability. Because of the difficulty in quantitatively defining the functional requirements of a helmet, any attempts to establish a new inspection technique must relate to the V_p50. In a sense, then, the V_p50 is treated as the intended function of the helmet, and the new inspection technique must be rated on the basis of how well it describes (or predicts) the Vp50. This presents additional difficulties because of certain inherent limitations of the V_p50 when applied to helmets, as will be discussed.

The first step, then, in finding a new inspection technique for M-1 helmets is to identify a parameter which bears a sufficiently sensitive and reliable relationship to the V_p50. This step was taken in our initial study, which, as noted, indicated that thickness could be a suitable parameter. Thickness appeared to be linearly related to V_p50. The sensitivity of V_p50 to thickness (i.e., the slope of a V_p50-thickness plot) was found in our previous study to be about 20 feet per second per 0.001 inch based on V_p50's for all or parts of helmets and corresponding average thicknesses. This was considered to be adequate sensitivity for an effective inspection tool. The scatter of data on a plot of V_p50 versus average thickness of helmet was greater than desirable (the correlation coefficient was about 0.69). The study also indicated, however, that the correlation could be improved by appropriate selection of the areas in which thickness is measured.

The first and most crucial step in the study was to see if a more reliable correlation between V_p50 and thickness could be established from the data of our previous study. Having established such a correlation, details of the inspection procedure could be formulated.

Data Available

Our earlier study resulted in what may be the most complete set of ballistic and property data available on M-1 helmets. These data provided an excellent basis for studying V_p50-thickness correlations. Of particular interest to this effort were a total of 19,000 thickness measurements and 8,400 pieces of ballistic data for the 200 helmets studied. Each of the helmets was taken from a different heat-treatment lot.* Of the 200 helmets, 30 were manufactured by the McCord Corp. and 170 by the Ingersoll Products. Helmets in this report are identified by heat-treatment-lot number. A number preceded by an M is a McCord helmet; a number preceded by an I is an Ingersoll helmet.

A coordinate system was used to identify the locations at which the various measurements were made. The coordinate system, shown in Figure 1, consisted of five circumferential bands, denoted by letters A through E, 32 essentially rectangular zones, denoted by whole numbers 1 through 32, and 96 discrete points, three in each zone, identified by adding the decimal 0.1, 0.2, or 0.3 (depending on its position in a zone) to the zone number.

The five circumferential bands were formed as follows (see Figure 1). Using as a center the uppermost point of the helmet, six concentric circles were drawn having the following radii measured over the helmet surface: 1-1/4 in., 2-1/2 in., 2-3/4 in., 5 in., 6-1/4 in., and 7-1/2 in. These were then divided into the 32 zones by radial line, as shown in Figure 1. Of the three points in each zone, one

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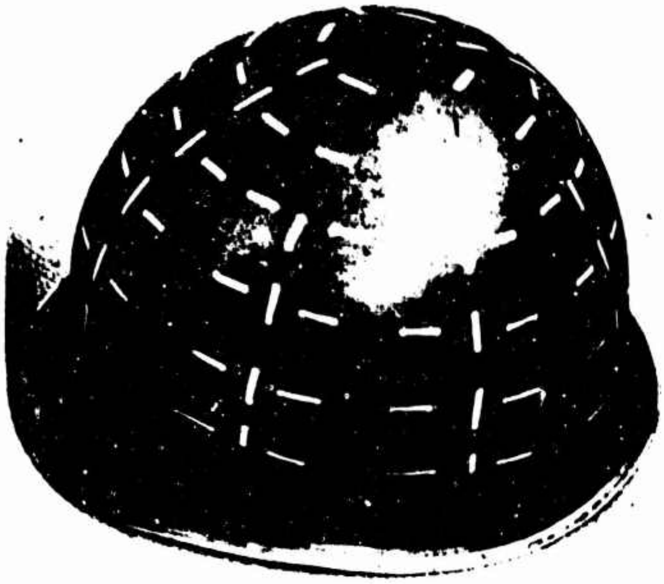
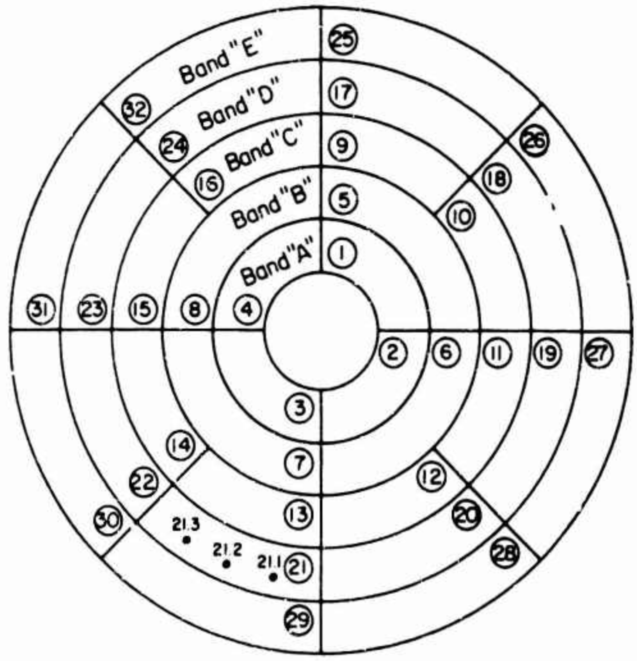
*The term "heat-treatment lot" refers to a group of helment blanks from one heat of steel that were rolled and heat-treated together. Helmets made from one heat-treatment lot of blanks normally constitute a day's production of about 5,000 helmets. The helmet inspection procedures specified in Military Specification MIL-H-1988E are based on samples taken from each heat-treatment lot.



a. Photograph of Helmet With Zones Laid Out



b. Map of Helmet (Zone Numbers Are Circled)

FIGURE 1. COORDINATE SYSTEM FOR HELMETS

(denoted 0.2) was located at the center of the zone and the other two approximately half way from the center to the edge. The individual points were identified as decimals 0.1, 0.2, and 0.3, going clockwise through the zone, as illustrated for zone 21 in Figure 1(b).

Thickness was measured at each of the 96 points to ±0.0001 inch. Subsequently, ballistic tests were performed with T-37, .22 Caliber fragment simulaters using the following procedure*:

(1) The helmets were firmly supported by a positioning fixture which allowed rotation of the helmet to assure normal impact at any of the 96 identified points.

(2) One shot was fired into the center (0.2 position) of each of the 32 zones, starting with the thinnest and progressing in the order of increasing material thickness. After firing into the midpoint of each of the 32 zones, additional rounds were fired as required to establish the ballistic limits. An average of 42 rounds was fired into each helmet.

(3) The powder load was varied for each round in an attempt to produce alternate penetrations and nonpenetrations.

(4) Penetration was considered to be complete if the impacting projectile or any fragment thereof, or any fragment of the test panel (helmet) managed to pierce a 0.02-inch-thick 2024-T3 aluminum witness plate located 3 inches behind the impact point. An impact was termed a nonpenetration if there was no hole made in the helmet. The term partial penetration was used to describe an impact that pierced the helmet but not the witness plate. (Except where otherwise noted, partial penetrations were grouped with non-penetrations in computing ballistic limits).

(5) Records kept included the location of impact point, impact velocity, and a notation as to whether the round was a penetration, partial penetration, or nonpenetration.

Ballistic limits (V_p50) were calculated by averaging the five lowest impact velocities resulting in complete penetrations and the five highest impact velocities resulting in partial or nonpenetrations,

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* A detailed description of the procedure and the test setup is given in our July 28, 1967 report. In general, the procedures followed those specified in Military Specification MIL-STD-662A, Ballistic Acceptance Test Method for Personal Armor Material.

provided that the difference between the highest and lowest of these ten velocities (termed the "range of mixed results") did not exceed 125 fps. If the range of mixed results did exceed 125 fps, the V_p50 was taken as the average of the seven lowest penetrating velocities and the seven highest nonpenetrating velocities.*

Correlations Obtained in Previous Study

Using these data, a ballistic limit was calculated for each helmet as a whole, for the helmet crown (Bands A, B, and C) and for the lower portion of the helmet (Bands D and E). These V_p50's were plotted against the respective average thickness and a least-squares regression line was calculated. The equations obtained were (V_p50 in fps and average thickness, t avg., in inches):

(a) For whole helmets

$$V_p50 = 277 + 19,400 \text{ t avg.}$$

correlation coefficient = 0.69.

(b) For helmet crowns (Bands A, B, and C)

$$V_p50 = 178 + 21,700 \text{ t avg.}$$

correlation coefficient = 0.74.

(c) For lower portions of helmets (Bands D and E)

$$V_p50 = 357 + 18,300 \text{ t avg.}$$

correlation coefficient = 0.70.

Closer analysis indicated that a much stronger correlation should exist between V_p50 and thickness than was indicated by the data of ballistic limit versus average thickness of helmets or portions of helmets. To appreciate this, it is of value to consider in greater detail the significance of the ballistic limit as applied to helmets.

The concept of a ballistic limit was intended to be applied to armor of essentially uniform thickness. The thickness of M-1 helmets,

* This procedure for calculating V_p50 conforms to Military Specification MIL-STD-662A. Ballistic Acceptance Test Method for Personal Armor Material.

however, is quite nonuniform; typically the maximum thickness in a helmet is about 30 percent greater than the minimum thickness (it will be shown that this variation corresponds to about a 250 feet per second variation in ballistic limit). Because of the nonuniform thickness, the five (or seven) lowest penetration velocities used to compute the V_p50 almost always were those that impacted the thinner sections and the five (or seven) highest nonpenetrating velocities were almost always associated with the thicker portions of the helmets. An interesting consequence of this is that the penetration velocities used to compute the V_p50's were generally lower than the nonpenetration velocities.

The method for computing the V_p50 of helmets is reasonably effective in averaging the ballistic limits associated with the various thicknesses encountered. Thus, the V_p50 for helmets tends to represent an average for the helmet. In fact, the average thickness of the 10 (or 14) points used in the calculation of V_p50 tends to be close to the overall average thickness of the helmet.* However, data for an individual helmet might favor either a high or a low value of V_p50 depending on the locations and velocities of the particular shots fired into that helmet. As a result, the least-squares fit to a body of helmet V_p50 versus average thickness data might be expected to give a reasonable description of the V_p50-thickness relationship for the material. However, the scatter about that line might be unrealistically great. An indication that such might be the case is given by the fact that the correlation coefficients associated with portions of helmets (upper and lower sections) were somewhat higher than for the whole helmet. This is attributed to the relatively small variation in thickness within each of the portions (the crown tends to contain the thinner zones and the lower portion tends to contain the thicker zones).

A more convincing demonstration was provided in our earlier study by combining the data from the 200 helmets to allow computation of V_p50's for each of the 96 points.** These were plotted against the average thickness of the 10 (or 14) points used to compute the V_p50. The least-squares line associated with these data had a correlation coefficient of 0.84. These findings were sufficiently encouraging to warrant the further analyses conducted in the current study.

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*The regression line for a plot of helmet average thickness versus average thickness of the points used to compute V_p50 indicates that the two values differ by about 0.0003 inch over the entire range covered.

**For instance, all ballistic data pertaining to point 13.2 were collected and a V_p50 calculated.

New V_p50-Thickness Correlation

It was desired to take maximum advantage of the large quantity of data available to develop a meaningful correlation between ballistic limit and thickness. It was also desired that the V_p50's be representative of essentially uniform-thickness conditions, which follows from the intended use of the ballistic-limit concept. The following method was employed. The 8400 pieces of data [impact velocity, V, thickness of impacted point, t, and a notation as to whether the round penetrated (P) or not (N)] were arranged in order of increasing thickness. The distribution of thicknesses for these data is shown in the histogram of Figure 2. Starting with the minimum thickness point (0.0297 inch), a set of data was established that included at least 10 nonpenetrations and 10 penetrations. A second data set was formed by finding the next set of data containing at least 10 penetrations and 10 nonpenetrations. In this way 340 data sets were formed. Except for the very first set, the thickness range within any data set was less than 0.0005 inch, with all but about 15 sets having thickness ranges of zero or 0.0001 inch (the limit of sensitivity of the thickness measurements). Thus, the objective of having essentially uniform-thickness conditions was closely met. Also, the use of a minimum of 20 points provided a realistic amount of data from which to calculate a V_p50.

V_p50's were calculated using the procedure described earlier. An indication of the reliability of the V_p50's so calculated is given by the fact that only about one-fourth of the sets had ranges of mixed results (difference between maximum and minimum velocities used to compute the V_p50) in excess of 125 fps. The average range of mixed results for the 340 sets was 104 fps.

The calculations were, of course, done by computer. The data print-out included the impact velocities and corresponding thicknesses of each of the 10 or 14 points used to compute the V_p50 of each set; the average of these thicknesses; and the range of mixed results. A computer plot of V_p50 versus thickness for the 340 data sets is given in Figure 3. The correlation coefficient between V_p50 and thickness is 0.98 (perfect correlation is given by a coefficient of one). The least-squares regression line is also plotted in Figure 3. This line has the equation:

$$V_p50 = 57 + 24,900\ t \qquad (1)$$

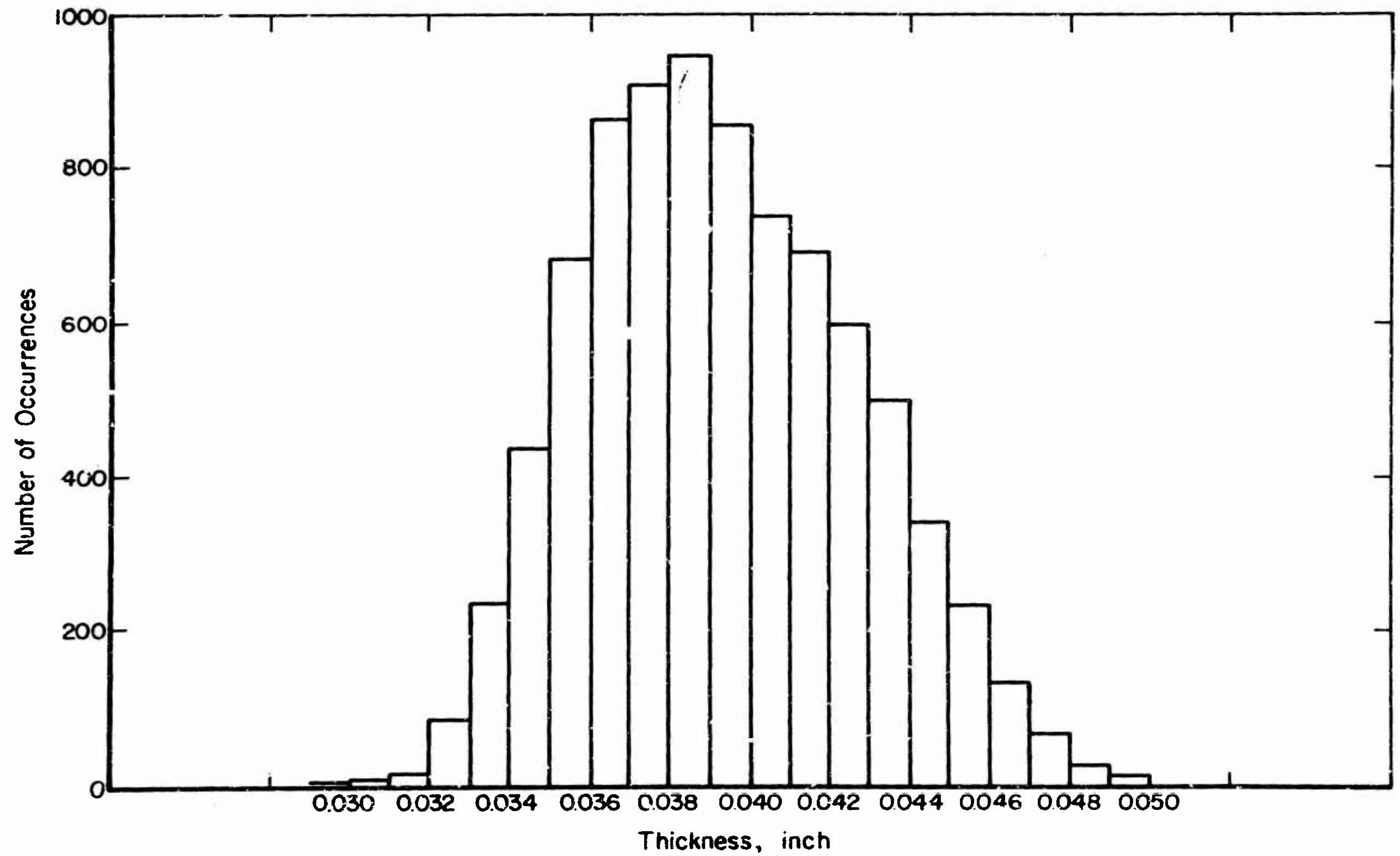

FIGURE 2. HISTOGRAM OF THICKNESSES OF THE 8403 POINTS OF BALLISTIC IMPACT

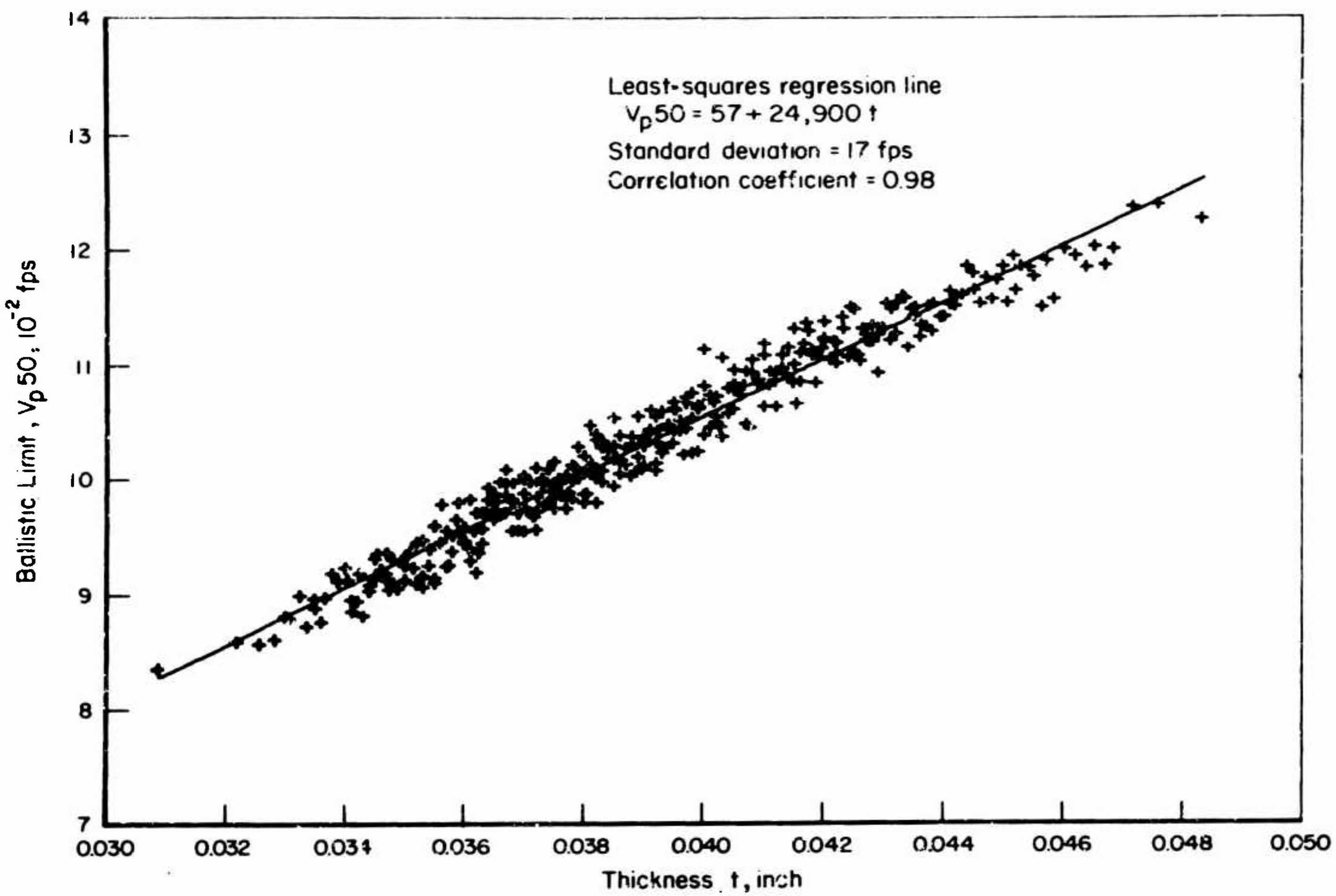

FIGURE 3. V_p50 VERSUS THICKNESS FOR 340 SETS OF ORDERED DATA

(V_p50 in fps, t in inches). The standard deviation about the regression line is 17 fps. The correlation achieved lends considerable confidence to the use of Equation (1). Because of the importance of the V_p50-thickness relationship to the recommended helmet acceptance criterion, steps were taken to further verify Equation (1) and to investigate its applicability to helmets.

The method used to obtain Equation (1) is subject to the criticism that the results may have been influenced by the order in which the data were fed into the computer. As noted, the data were first ordered by thickness. Because of the large amount of data, any one data point might have been placed in any of several sets. For example, five data sets were formed from the 115 points having a thickness of 0.0385 inch. In establishing the five data sets, the computer simply sought the first combination of at least 10 penetrations and 10 nonpenetrations, then the second such combination, etc. Thus the specific data points occurring in any group depended upon the order in which the data were fed into the computer; i.e., the arrangement of the punch cards containing the raw data. The cards were arranged according to helmet; all data pertaining to a given helmet were in one group. The arrangement within a given helmet was in increasing order of thickness. The sequence of helmets was random.

To check the possibility that the arrangement of raw data influenced the V_p50-thickness relationship of Equation (1), a subroutine was added to the computer program which mixed the data before performing the ordering by thickness, set-formation, and V_p50-calculation functions. This provided a second correlation involving 337 data sets. The results were, for all practical purposes, identical with Equation (1).* The only significant difference was a somewhat lower standard deviation [16.3 fps for the mixed data compared with 17.4 fps associated with Equation (1)].

Another question that arises is associated with the number of data points used per set. This was investigated by performing the calculation using sets containing a minimum of 15 penetrations and 15 nonpenetrations (rather than 10 and 10). The resulting equation was

$$V_p50 = 60 + 24,900\ t \quad , \tag{2}$$

*Before rounding, the constants in Equation (1) were:

$$V_p50 = 57.397 + 24,921\ t \quad .$$

The mixed-data routine gave

$$V_p50 = 57.448 + 24,925\ t \quad .$$

the correlation coefficient was 0.98 and the standard deviation 15 fps. Equation (2) differs from Equation (1) by 3 fps over the entire range. For all practical purposes, Equations (1) and (2) are identical.

A somewhat different approach was suggested by Mr. Charles Davis and Mr. William Curley of Natick Laboratories. Their approach was to establish data sets based on constant thickness independent of the amount of data at each thickness value. Working with the current data, and using thicknesses between 0.033 and 0.039 inch, they arrived at the equation:

$$V_p50 = 56.7 + 25,000\ t \qquad (3)$$

which differs from Equation (1) by less than 5 fps for the range of thicknesses involved.

The above evidence strongly supports Equation (1) as an effective relationship between ballistic limit and thickness for Hadfield steel in the condition prevalent in M-1 helmets.* The significance of the correlation in terms of actual helmet V_p50's is considered below.

Application to Helmets

It was noted earlier that the V_p50 of a helmet tends to reflect the average thickness of the helmet. Stated another way, the V_p50 will tend to equal the V_p50 of a sheet of material in the same worked condition and having a uniform thickness equal to the average thickness of the helmet. We are now in a position to test this statement by comparing the helmet V_p50 versus average-thickness data with Equation (1).

Figures 4, 5, and 6 are plots of V_p50 versus average thickness for entire helmets, helmet crowns (Bands A, B, and C) and lower parts of helmets (Bands D and E), respectively. Included in the graphs are the least-squares fit for the data and a plot of Equation (1) in which t is taken as average thickness of the appropriate part of the helmet. It

*It is important to note that Equation (1) applies only to the range of material conditions found in M-1 helmets. Our earlier study showed that while the V_p50 was not sensitive to variations in the degree of cold working within the range encountered in M-1 helmets, it could be a function of conditions outside this range. In particular, annealed helmet blanks were found to have a higher V_p50 than as-worked metal in the helmets (after correcting for thickness differences).

is seen that Equation (1) provides a reasonable fit in Figures 4 and 5 (entire helmets and crowns). The fit is not as good for the lower parts of helmets (Figure 6).

It is important to note that the above comparisons of Equation (1) with the least-squares fits to helmet data do not necessarily serve as a test of the value of Equation (1). In fact, the opposite may be true: i.e., the degree to which the helmet V_p50-thickness data fit Equation (1) is an index of the quality of the data. To explain this apparent inversion, let us examine further the significance of the ballistic limit concept as applied to helmets.

One can consider that there is a "true" V_p50 associated with any given helmet. The V_p50 obtained by ballistic testing is an attempt to "measure" this true V_p50 and, like any measured quantity, is only an estimate of the true value. By the same token, a helmet V_p50 computed from Equation (1) using t = average helmet thickness, also provides an estimate of the V_p50. The question is which provides the better estimate, the V_p50 obtained by ballistic testing or the V_p50 calculated from Equation (1).

An insight into the relative merits of these two estimates can be gained by recalling the earlier discussion of the use of the V_p50-concept on material of nonuniform thickness. On the basis of the data in Figure 3 and the high correlation to this data provided by Equation (1), it is reasonable to state that the ballistic limit is linearly related to thickness. Thus, the true helmet V_p50 is the simple average of the V_p50's of all points on the helmet.

The effectiveness of the ballistic test in estimating the true V_p50 depends upon two conditions (or some fortuitous combination of the two): (1) that the 10 (or 14) points entering into the computation of V_p50 have an average thickness equal to the average thickness of the helmet and (2) that each of the 10 (or 14) velocities used be the V_p50 of the point of impact or they differ from these V_p50's in such a way that the differences will average out (e.g., if all penetration shots are 25 fps high and all nonpenetration shots are 25 fps low). As noted earlier, Condition (1) was met reasonably closely on the average, although individual helmets departed from this condition significantly. An estimate of the degree to which the Condition (2) is met was obtained by computing a

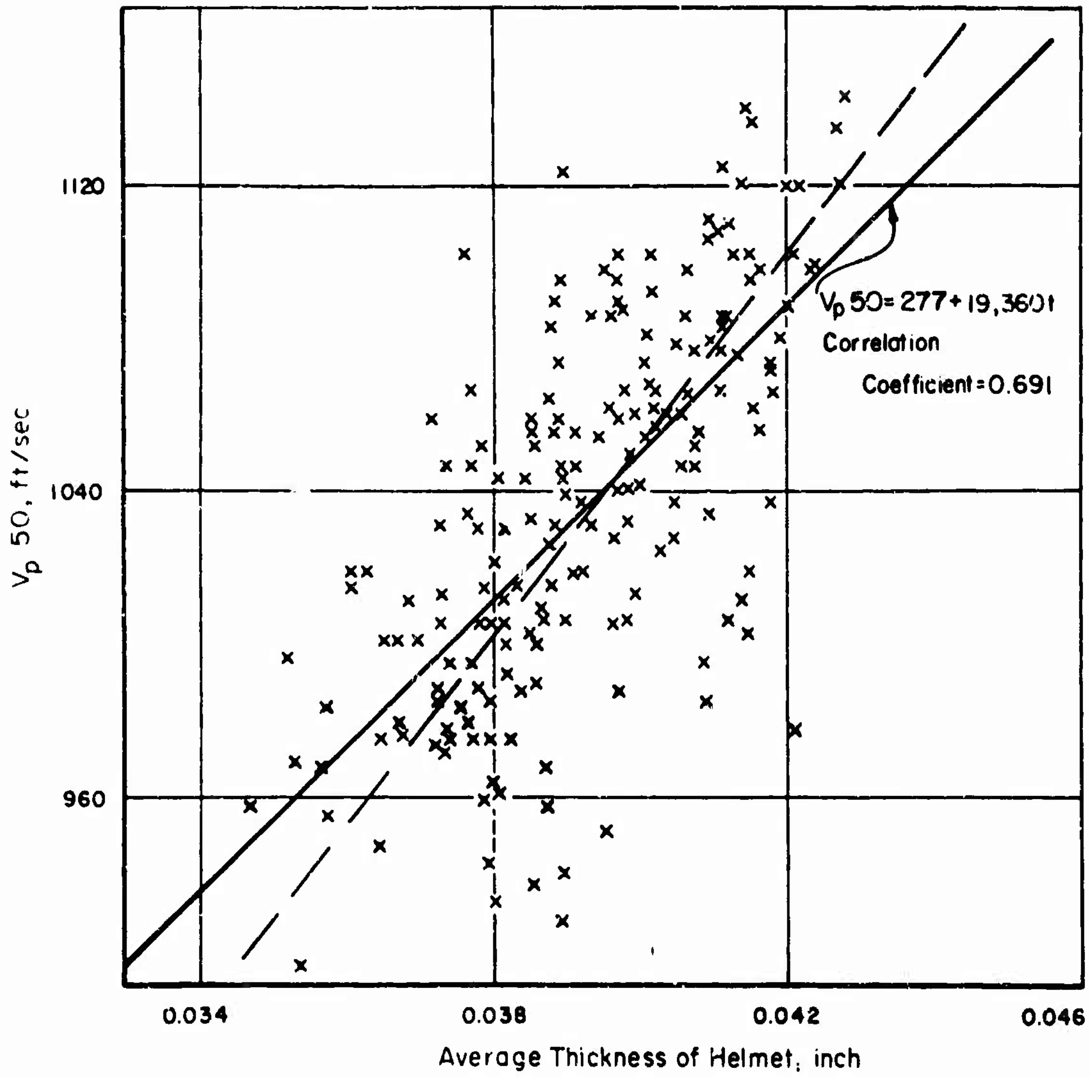

FIGURE 4. HELMET V_p50 VERSUS AVERAGE THICKNESS

Solid line is least-squares fit to data; dashed line is plot of Equation 1.

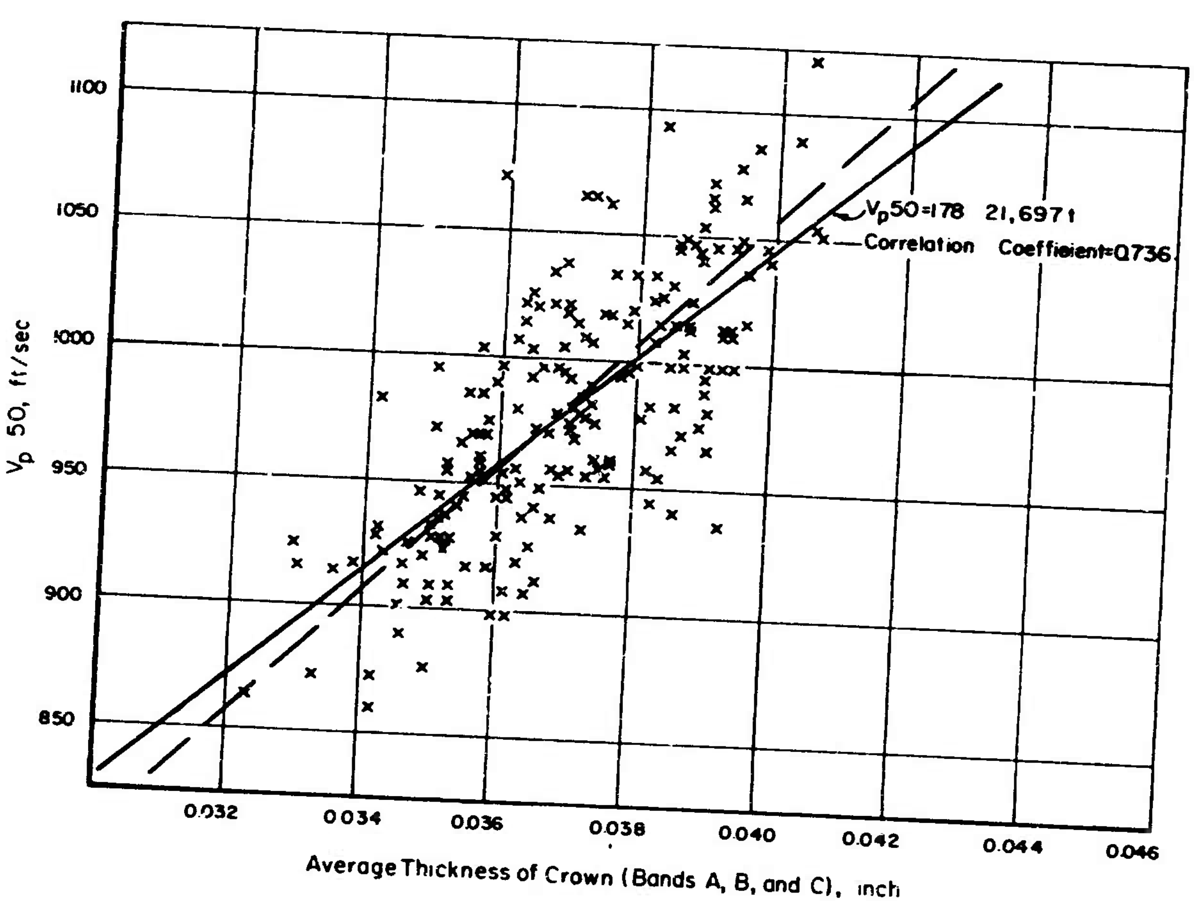

FIGURE 5. V_p50 VERSUS AVERAGE THICKNESS OF CROWN

Solid line is least-squares fit to data;
dashed line is plot of Equation 1.

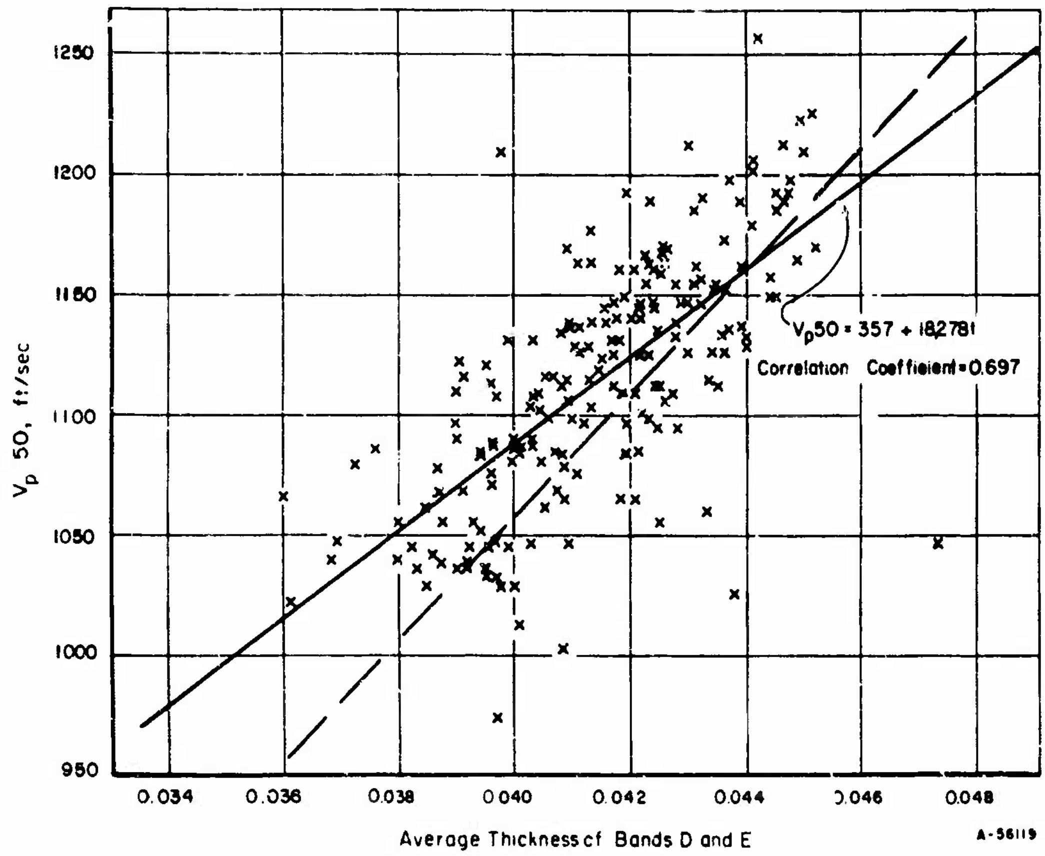

FIGURE 6. V_p50 VERSUS THICKNESS FOR BANDS D AND E

Solid line is least-squares fit to data;
dashed line is plot of Equation 1.

regression line for helmet V_p50 versus the average thickness of the 10 (or 14) points used to compute the V_p50. Such correlation essentially assures that Condition 1 is met. The resulting equation was

$$V_p50 = 209 + 21,000\,t \quad . \tag{4}$$

The associated correlation coefficient was 0.79 (compared with 0.69 for the correlation based on overall average thickness). Most of the remaining data scatter associated with Equation (4) can be attributed to deviations from Condition 2, i.e., the velocities used to compute V_p50's for individual helmets were not representative of the V_p50's at the points of impact.

Comparison of Equation (4) with Equation (1) indicates there is little difference between the two regression lines over the range of thicknesses covered by Equation (4) (0.035 to 0.046 inch). The maximum difference in V_p50's computed from the two equations is 15 fps.

The above evidence indicates that individual values of V_p50 for helmets can be either high or low estimates of the true V_p50 with about equal probability in either direction. Reasonable confidence in a helmet V_p50 obtained by ballistic tests can be justified only by averaging V_p50's from several "identical" helmets.

In contrast, consider the estimate of helmet V_p50 obtainable by using Equation (1). Here again there are two principal conditions involved: (1) that the measured average thickness [to be used in Equation (1)] is a good estimate of the true average thickness and (2) that Equation (1) is, in fact, valid. Without expanding on the point, it can be stated that a good estimate of average thickness is relatively easily obtainable and, furthermore, the closeness of the estimate to the true value can be evaluated statistically. With regard to the second condition, the validity and versatility of Equation (1) has been demonstrated.

Based on the above, it is concluded that a better estimate of V_p50 for helmets can be calculated from Equation (1) than can be obtained by ballistic tests.

Further Verification of Ballistic Limit-Thickness Correlation

Although not essential to this discussion, it is of interest to examine an additional correlation which not only lends credence to the validity of Equation (1) but provides additional insight into the significance of the ballistic limit. The ballistic limit is usually considered to be that velocity at which 50 percent of impacting projectiles will penetrate. Alternatively, the ballistic limit is sometimes considered to be that impact velocity at which a projectile will just be stopped; i. e., had it impacted at a slightly higher velocity it would have penetrated completely. It will be recalled that the data taken during the ballistic tests included a notation for impacts which made a hole in the helmet but not in the witness plate. These were termed partial penetrations. There was an average of about six such occurrences on each of the helmets tested. Figure 7 is a plot of impact velocity versus thickness for partial penetrations on 43 helmets. Equation (1) is also plotted on the graph. Although there is considerable scatter, it is seen that Equation (1) provides a good description of the trend of the data. It would thus appear justifiable to consider the V_p50 as an estimate of the velocity to just stop a projectile.

Remarks

The above findings can be summarized as follows:

(1) Equation (1) ($V_p50 = 57 + 24,900\ t$) correlates ballistic limit versus thickness data for Hadfield steel in the condition found in M-1 helmets with a correlation coefficient of 0.98 and a standard deviation of 17 fps.

(2) By using for t in Equation (1) the average thickness of a helmet, or any part thereof, a value of V_p50 for the helmet (or part thereof) is obtained which is believed to be a better estimate of the "true" V_p50 than can be obtained by ballistic testing of helmets.

These findings lend considerable support and confidence to the replacement of the current ballistic inspection by a thickness

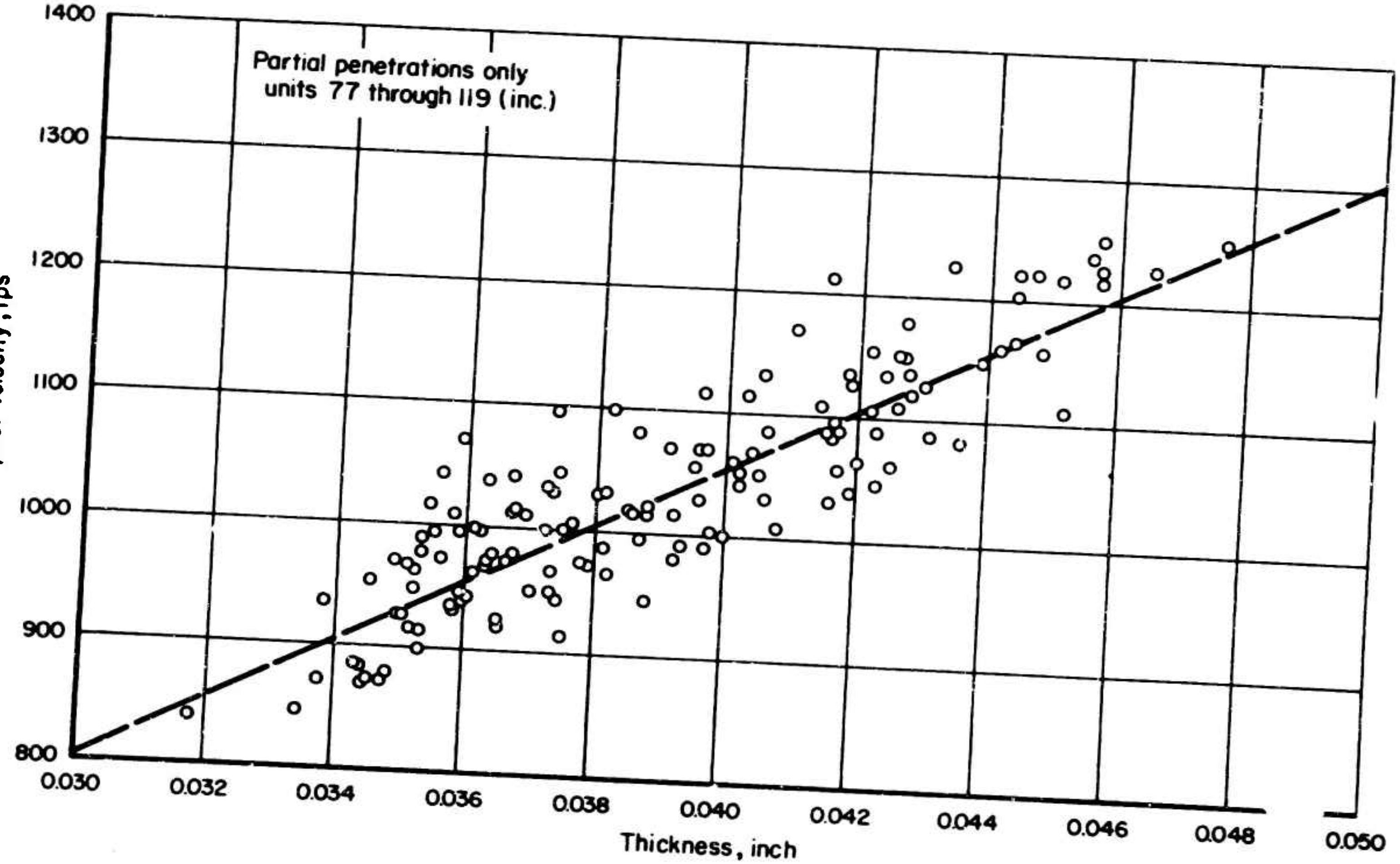

FIGURE 7. IMPACT VELOCITY VERSUS THICKNESS FOR "PARTIAL PENETRATIONS"
Dashed Line is a Plot of Equation (1).

inspection. Not only will thickness measurements be easier and less costly to perform, but greater confidence can be placed in the inspection. This is expanded upon in the next section.

As another consequence, not directly related to inspection, it is now possible to estimate the V_p50 associated with any point on the helmet. An example is given in Figure 8, where the thicknesses at various locations in an "average" helmet have been converted to V_p50 values using Equation (1). One possible application of this procedure might be to correlate field head injuries with position of the impact point. It might be that a revision in die design could effect a favorable change in thickness distribution in helmets.

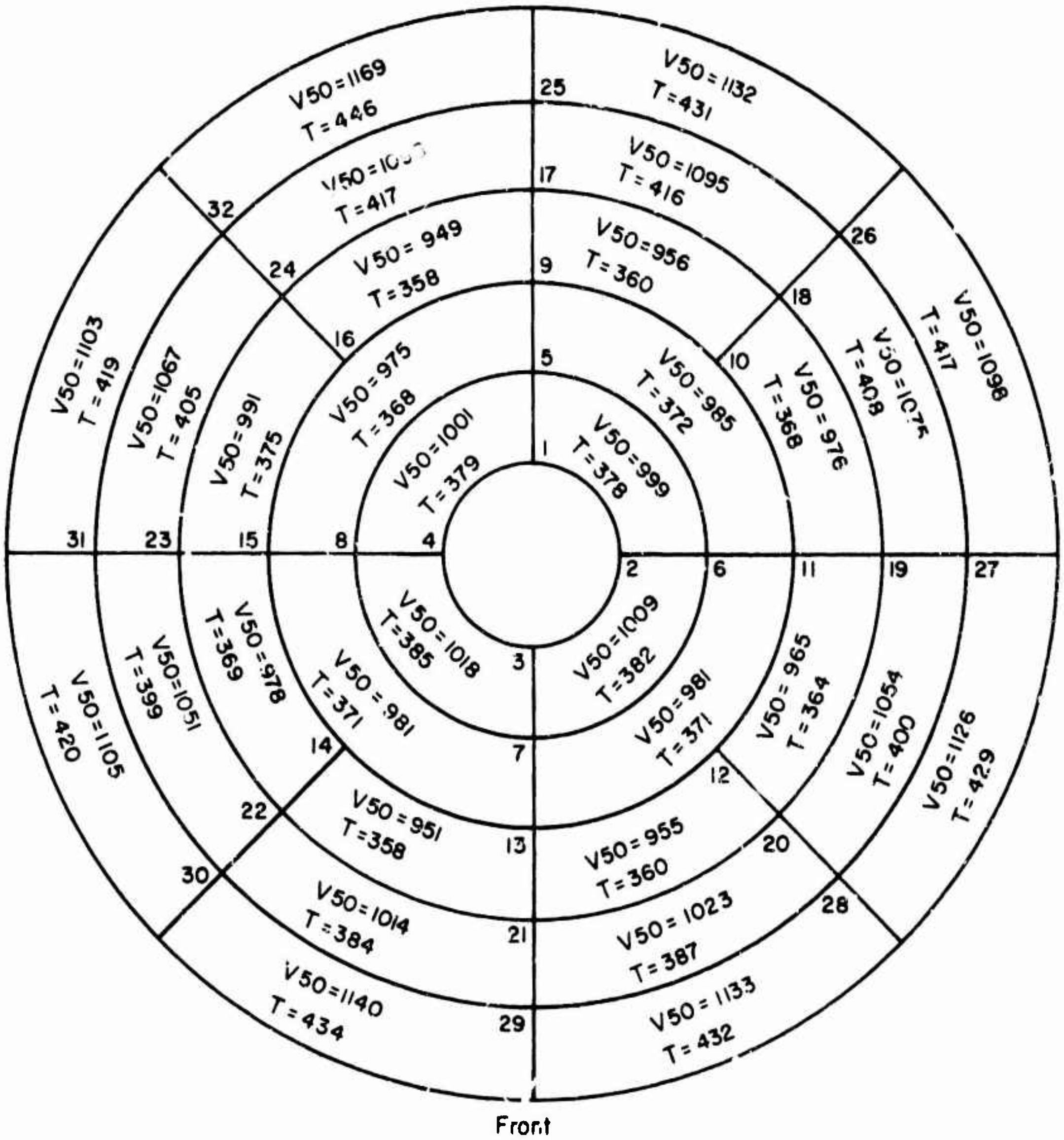

FIGURE 8. VARIATION OF V50 WITH POSITION IN AN AVERAGE HELMET

V50 = Ballistic Limit in fps, T = Thickness in Inches x 10^4.

APPLICATION OF V_p 50-THICKNESS CORRELATION TO HELMET INSPECTION

Having established the justification for replacing the current ballistic inspection of helmets by a thickness inspection, we can now address the problem of finding the most appropriate places to measure the thickness. Some of the possibilities include overall average thickness, average thickness of part of the helmet, minimum thickness in helmet, and thickness of one or more selected points. These choices are narrowed by considerations involved in changing from one inspection criterion to another. These include the following:

(1) It is necessary to maintain the level of helmet quality currently prescribed by the helmet specification (MIL-H-1988E).

(2) It is necessary to maintain at least the level of confidence provided by the current inspection.

(3) It is desirable (but not necessary) to maintain the "sense" of the current inspection.

(4) It is desirable that the inspection be as simple, inexpensive, and rapid as possible within the constraints of Items 1 and 2 above.

(1) Maintain Level of Helmet Quality

To maintain the current level of helmet quality (i.e., protection offered by the helmet) requires that there be some relationship between the current specification minimum acceptable ballistic limit and the proposed minimum acceptable thickness. The current specification requires a helmet ballistic limit of at least 900 fps when tested in accordance with MIL-H-1988E. An obvious way to assure that current helmet quality will be maintained is to set a minimum acceptable average thickness corresponding to a V_p50 of 900 fps. The thickness average would have to be taken over the crown of the helmet since that is the part involved in the current ballistic inspection. Other methods are possible. If, for example, a strong correlation can be established between V_p50 of the whole helmet and that of the upper section, the current quality could be maintained by setting an appropriate minimum acceptable level of overall average helmet thickness.

Even more freedom in setting a thickness criterion that assures maintaining current quality can be gained by considering the basis for the 900 fps requirement. Several years ago, prior to the institution of the current ballistic limit inspection, the V_p50's of 90 presumably acceptable helmets were evaluated. The average of these V_p50's was 990 fps and the standard deviation among them was 26.9 fps; the minimum helmet V_p50 obtained was 919 fps. It was reasoned that helmets having a ballistic limit within three standard deviations of the mean (about 910 fps) would be acceptable. This value was then rounded off to 900 fps. An analogous method could be used to establish a minimum acceptable-thickness value. Such a procedure would, for example, allow minimum thickness in a helmet to be used as a criterion of acceptability. More will be said about this approach later.

(2) Maintain Level of Confidence

There are two aspects to this item. One relates to the statistics of sampling and will be discussed in a subsequent section. The other aspect has to do with the relationship of the inspected parameter to the intended function. It has been noted that the ballistic limit of M-1 helmets (to T-37, .22 Caliber fragment simulators) is itself only an indirect index of the intended function of a helmet. For want of a more direct index, this ballistic limit must be regarded as a criterion. It appears, however, that a more reliable estimate of the ballistic limit is provided by thickness measurement than by ballistic testing. On this basis, it can be presumed that thickness measurements can provide a greater level of confidence than can the current ballistic test.

(3) Maintaining the "Sense" of the Current Inspection

This is a desirable but not a necessary condition. There is an understandable reluctance to change specifications which have served satisfactorily for a period of time. This reluctance can be reduced by maintaining at least the sense of the inspection to be replaced.

The sense of the current ballistic inspection can be carried over to a thickness inspection most directly by basing the new inspection on the average thickness of the helmet crown (Bands A, B, and C in Figure 1). This follows since:

(a) The current ballistic inspection is limited to the crown.

(b) The helmet V_p50 tends to reflect the average V_p50 of the area covered by the inspection which, in turn, is linearly related to the average thickness of the area covered.

The use of minimum thickness in a helmet as the inspection criterion might appear to radically change the sense of the inspection. However, it was found that there is a reasonably high correlation between minimum and average helmet thickness (correlation coefficient = 0.85). Thus, while inspecting for the average thickness of the upper parts of helmets would more closely retain the sense of the current inspection, inspecting for minimum thickness would not cause a drastic change in sense.

(4) Simplicity of Inspection

Considerations of maintainance of helmet quality and confidence in the inspection (Items 1 and 2 above) indicate that the new inspection could be based on overall helmet average thickness, average thickness of the upper part only, or minimum thickness in the helmet. A consideration for maintaining the sense of helmet inspection leads to a preference for measuring the average thickness of the upper part of the helmet, but this does not exclude using minimum thickness as a criterion. A similar conclusion is reached on the basis of simplicity of inspection. Thus, if an average thickness is to be monitored, it would appear simpler to monitor a portion of the helmet (such as the crown) rather than the entire helmet. Further simplification would result if the thickness of one or more specific points in helmets were found to be closely related to the average thickness. The unlikelihood of finding such fixed locations is demonstrated by considering the distribution of thickness within individual helmets.

Examination of histograms of thicknesses in each of a number of helmets indicated a wide variety of patterns. Three examples are given in Figure 9. It is apparent from the dissimilarity of thickness

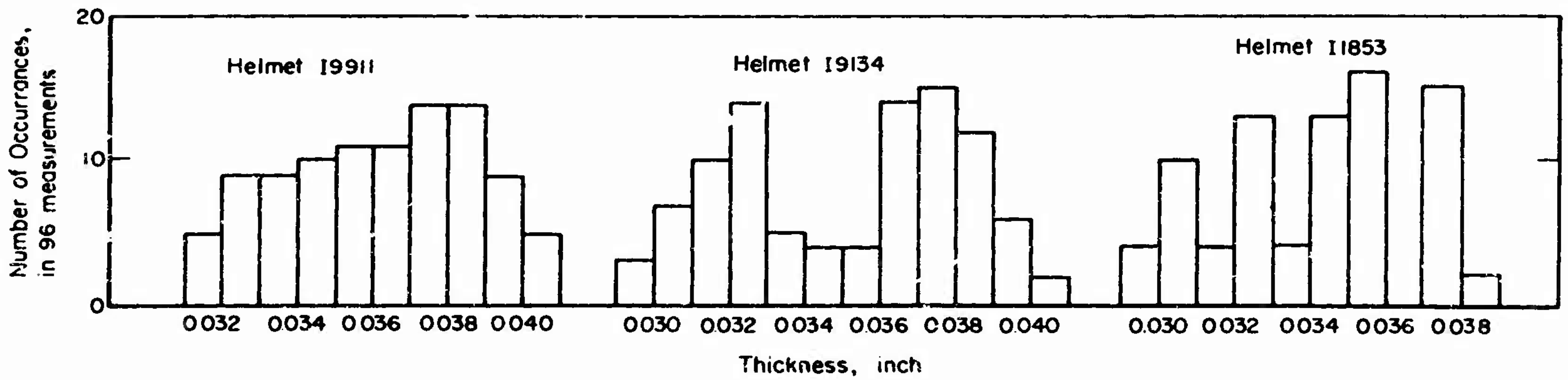

FIGURE 9. HISTOGRAMS SHOWING THICKNESS DISTRIBUTIONS IN THREE HELMETS

distributions that relative frequency of occurence of a particular thickness cannot be used as a criterion.

Nor can any one location be depended upon to give a reliable indication of either minimum or average thickness. Figure 10 shows the frequency of occurrence of minimum thicknesses in various zones of the helmet. Figure 11 gives the corresponding distribution for maximum thickness. While the minimum values occur almost exclusively in the upper parts of helmets and the maximum thicknesses in the lower parts, there is a reasonably wide scattering of locations of these extremes.

Because of the simplicity that would result from being able to measure the thickness at a fixed location, an examination was made at the distribution of points having thicknesses within 0.001 inch of the minimum thickness and ±0.0005 inch of the (overall) average thickness. It was reasoned that if a single location could be found having a very high probability of being close to either of these quantities, the inspection plan might be altered appropriately to account for the slight relaxation in rigor. The distribution of such points is shown in Figures 12 and 13. A maximum of 200 occurrences is possible at any one point. It is seen that no point has more than 88 occurrences, which is not sufficiently high to be of value.

In view of the above it is concluded that the two most reasonable quantities to be monitored in an inspection are the average thickness of the helmet crowns and the minimum thickness of helmets. Since these are closely related, the choice between them should be made on the basis of which can be most simply monitored. Preliminary considerations in that regard tend to favor minimum thickness which could utilize a scanning device. Averaging would require, in addition, an integration of measurements. On the other hand, if the device utilizes discrete point measurements, a better estimate can be achieved of average than of minimum thickness. We recommend that the final decision on this matter be left open until we have begun Phase II of this study and settled on a particular thickness-measuring method. The inspection plans to be discussed here will consider both average thickness of the crown and minimum thickness.

Minimum Acceptable Thickness Levels

On the basis of the above findings and discussions, it is recommended that the current ballistic-testing specification for M-I

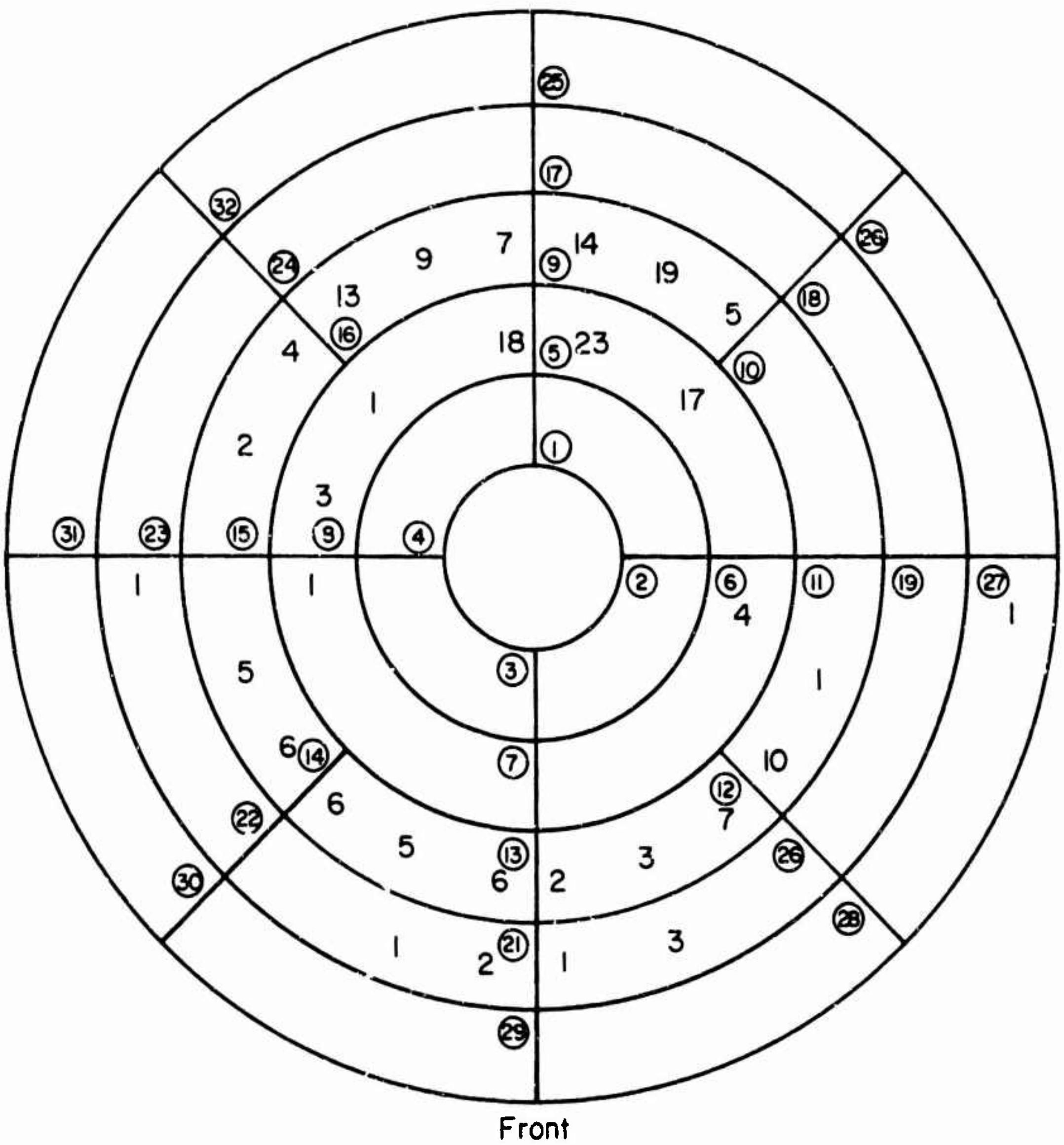

FIGURE 10. LOCATIONS OF MINIMUM THICKNESS IN HELMETS

Zone numbers are circled. Other numbers indicate number of times the minimum thickness occurred at that position.

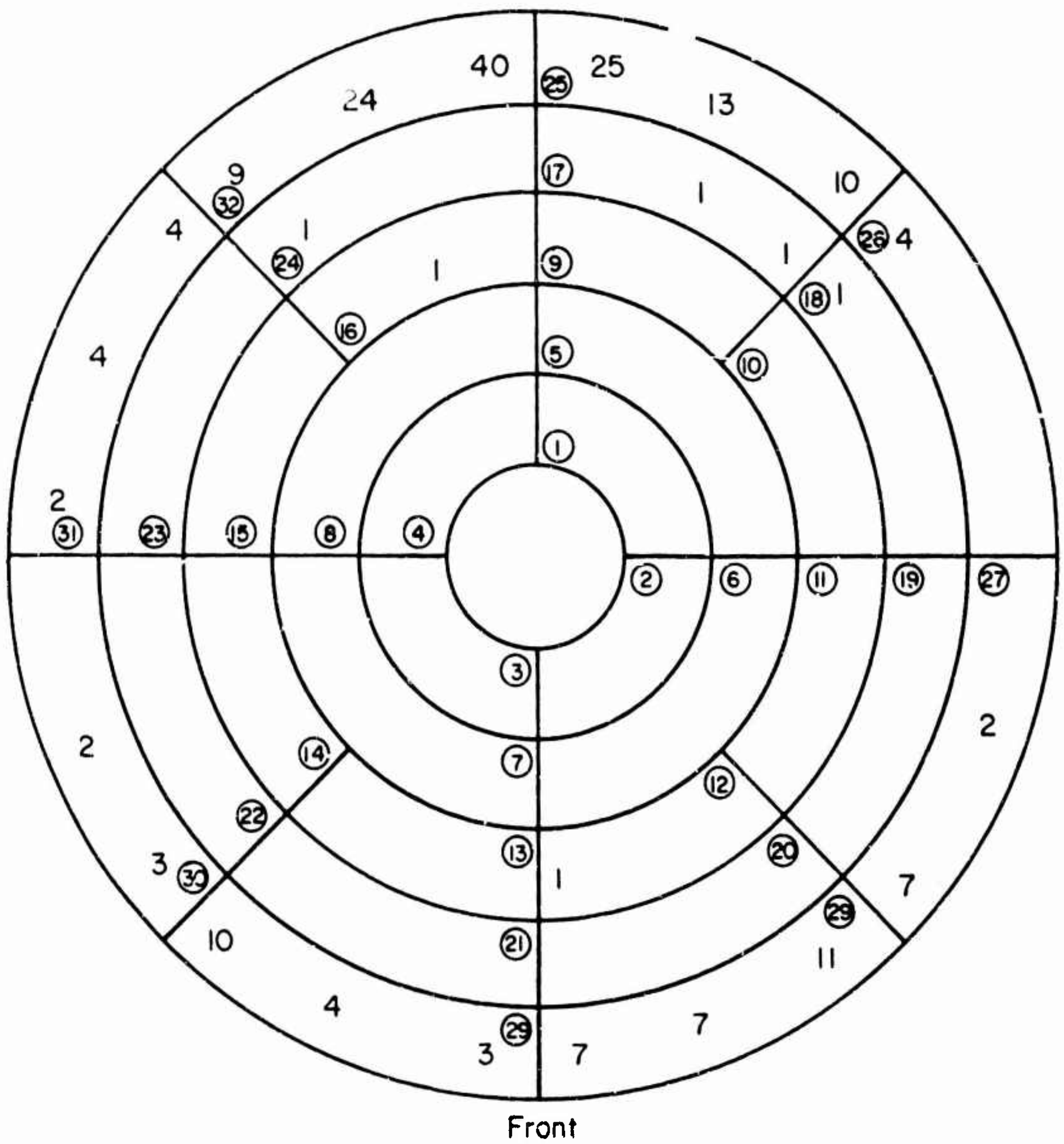

FIGURE 11. LOCATIONS OF MAXIMUM THICKNESS IN HELMETS

Zone numbers are circled. Other numbers indicate number of times the maximum thickness occurred at that position.

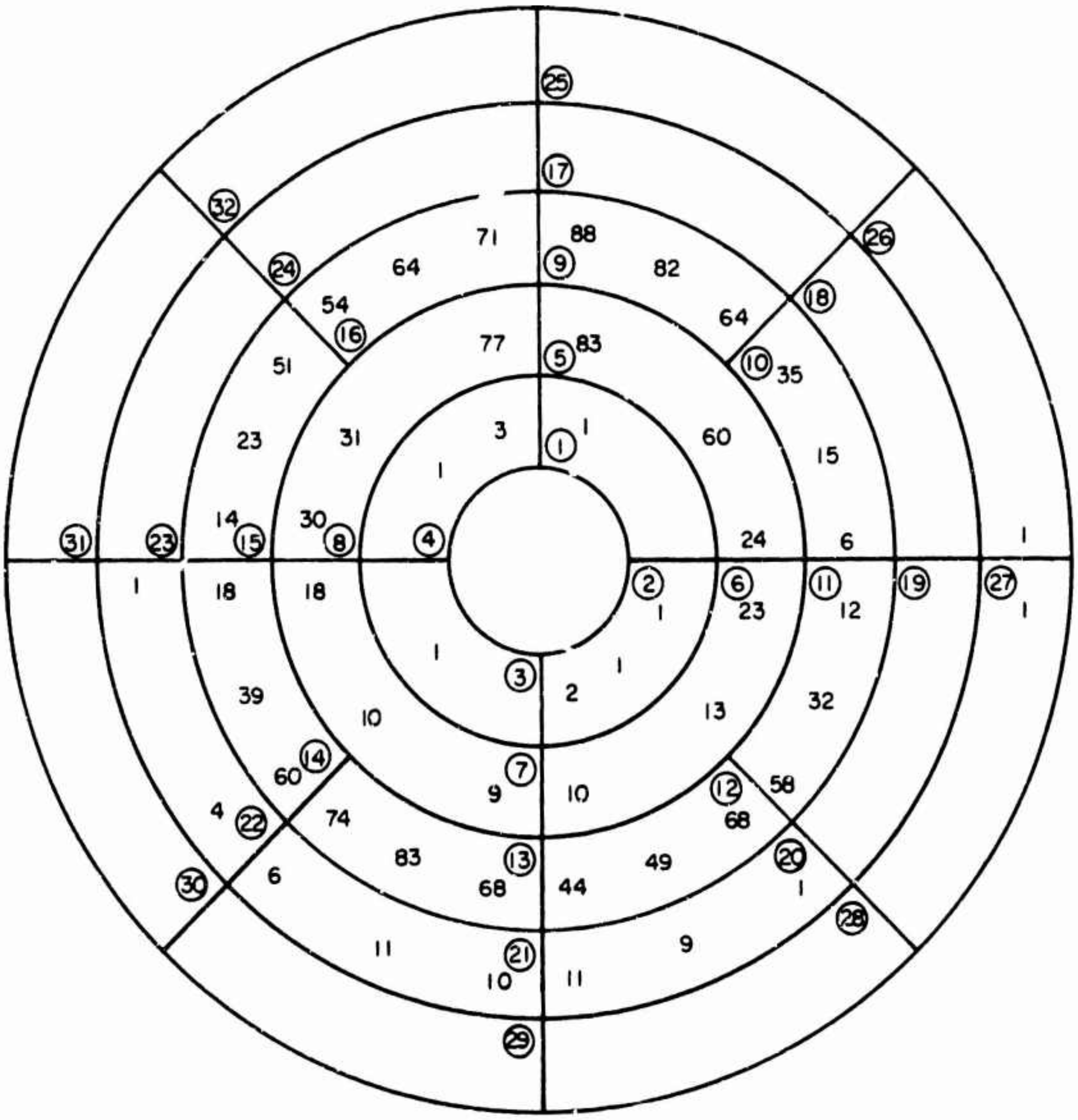

FIGURE 12. LOCATIONS OF POINTS HAVING THICKNESS $t_{min} < t < t_{min} + 0.001$ INCH

Zone numbers are circled. Other numbers indicate number of occurrences at that position.

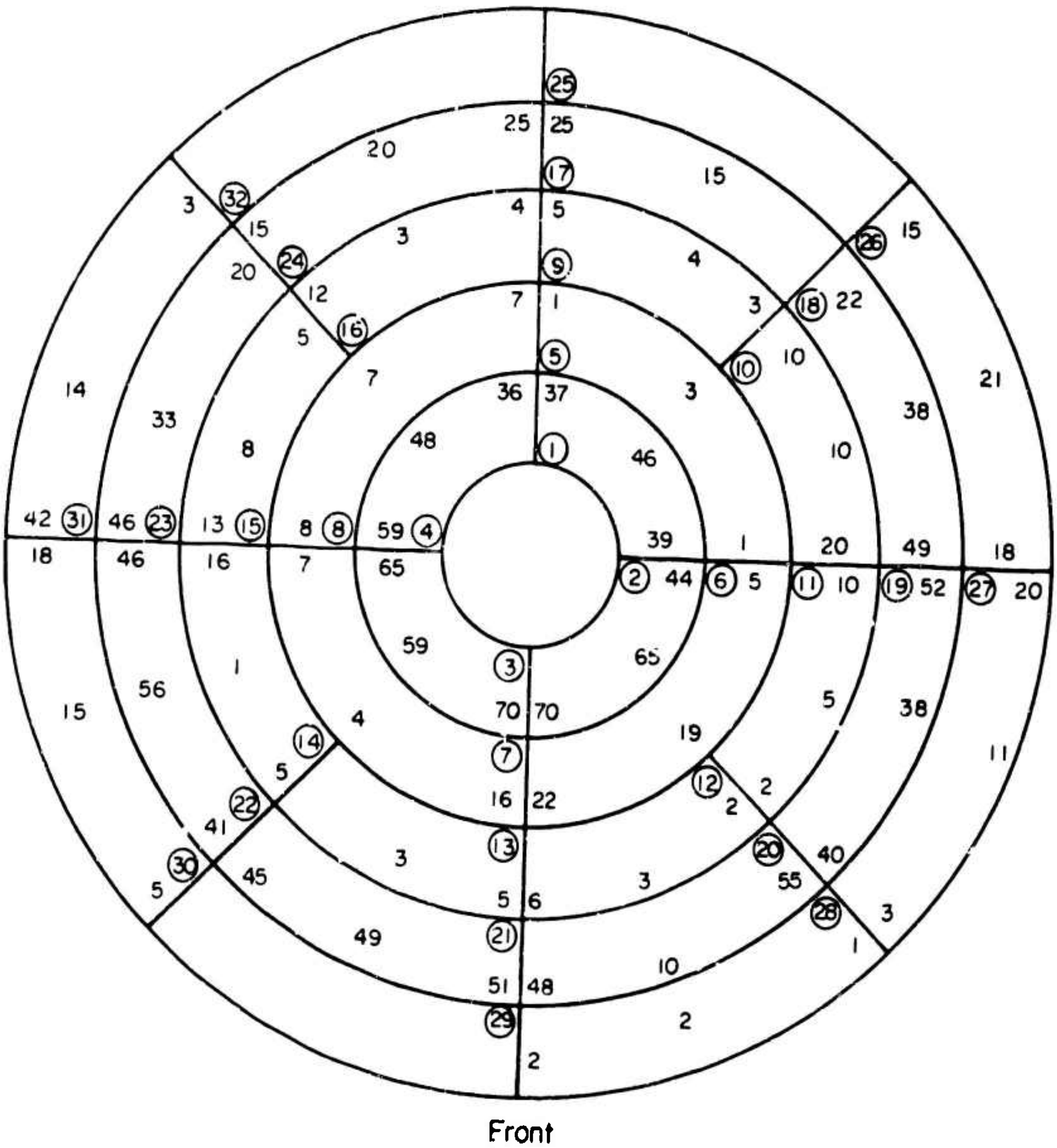

FIGURE 13. LOCATIONS OF POINTS HAVING THICKNESS WITHIN ± 0.0005 INCH OF AVERAGE HELMET THICKNESS

Zone numbers are circled. Other numbers indicate number of occurrences at that position.

helmets be replaced witn an inspection based on either average thickness of helmet crowns or minimum thickness in helmets. The method for establishing lower limits of acceptability on these was discussed earlier and will be reviewed briefly here.

Minimum Acceptable Average Thickness of Crowns

Using Equation (1), the current specification of a minimum V_p50 of 900 fps translates to a minimum acceptable average thickness of crowns of t_{avg} = 0.0338 inch. It is of interest to compare this value with one computed on the basis of standard deviations. Using our data, the V_p50 of crowns of the 200 helmets studied had an average value of 980.8 fps and a standard deviation of 49.96 fps*. The difference between the mean value (980.8 fps) and the lowest acceptable value (900 fps) is 80.8 fps or 80.8 ÷ 49.96 = 1.617 standard deviations from the mean average thickness of crowns. The mean average thickness of crowns was 0.037 inch; the standard deviation of average crown thicknesses was 0.00175 inch. The lower acceptable average crown thickness would then be

$$t = 0.0037 - 1.617 \times 0.00175 = 0.0341 \text{ inch.}$$

Thus the minimum acceptable value obtained by standard deviations is within 0.0003 inch of that set on the basis of the V_p 50-thickness relationship of Equation (1). It is recommended that the minimum acceptable average crown thickness be set at the rounded value of 0.034 inch, if this quantity is to be used as the inspection-quality characterization.

Minimum Acceptable Value of Minimum Thickness in a Helmet

The absolute minimum thickness in a helmet cannot be obtained directly from the V_p50-thickness relationship because the V_p50

* A word of explanation is in order about the distribution of V_p50's found in this study and that resulting from Natick's study of 90 helmets some years ago. While the mean values from the two studies are about the same, the standard deviation here is almost twice that found in the earlier study. The difference can be attributed to the fact that whereas our 200 helmets represented 200 heat-treatment lots, the earlier 90 helmets came from only about 15 heat-treatment lots. In fact, 21 of the 90 helmets tested came from a single lot. Thus, whereas our data represent lot-to-lot variations, the earlier data are more representative of within-lot variations that would, of course, be expected to be smaller than lot-to-lot variations.

relates to an average thickness. To obtain a limit for this quantity it is necessary to use the distribution of minimum thicknesses among the 200 helmets. The mean value was 0.0345 inch and the standard deviation was 0.0018 inch. The minimum acceptable value corresponding to 1.617 standard deviations is:

$$t = 0.0345 - 1.617 \times 0.0018 = 0.0316 \text{ inch.}$$

It is recommended that the single minimum acceptable thickness in a helmet be set at 0.032 inch, if this quantity is to be used as the inspection quality characteristic.

Relationship to Current Thickness Specifications

The current specification for M-1 helmets (MIL-H-1988E, 9 April 1968) includes thickness measurements as a criterion of acceptability. Paragraph 3.4.1.1 specifies that the thickness of twelve points* be measured and that their average be not less than 0.033 inch and the minimum measurement be not less than 0.031. These criteria are less severe than the thickness criteria proposed here. Consideration of the distribution of minimum thicknesses (Figure 10) reveals that there are only about 30 out of 200 chances that the minimum thickness will fall in one of the 12 points specified. Our recommendations are based on closer estimates of the true average or minimum values. The above differences are not considered significant. In effect, the current thickness criteria is less severe than the current ballistic-limit criteria.

It should be noted that the proposed inspection will amount to a restatement of the current thickness requirements (both as to acceptable thickness magnitudes and the means of measurements), as well as an elimination of the current ballistic-testing requirements.

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* The twelve points correspond to the following points in our notation (See Figure 1): 1.2, 2.2, 3.2, 4.2, 5.2, 6.2, 7.2, 8.2, and the points halfway betwee 9.3 and 10.1, 11.3 and 12.1, 13.3 and 14.1, 15.3 and 16.1.

SAMPLING INSPECTION

Definition of Terms

Inspection Lot

In the present application, an inspection lot may be defined as a group of helmets separated to undergo the acceptance procedure and accepted or rejected as a whole by the inspection of a random sample containing relatively few helmets. Each lot should represent, as nearly as possible, the output of one machine or process during one interval of time, so that all helmets in the lot have been produced under essentially the same conditions. Subject to this restriction, the economics of sampling favor using a large lot size.

Current practice for M-I helmets is to use a heat-treatment lot, defined earlier, as the inspection lot. An average heat-treatment lot consists of about 5000 helmets and normally constitutes a day's production. Actual lot sizes may vary from about 3000 to 7000 helmets. Since all blanks from a heat-treatment lot are from a single heat of steel and were all rolled and heat treated together, it would appear reasonable to assume that the heat-treatment lot satisfies the above criteria for homogeneity.

Inspection Sample

A sample from each lot supplies the information on which the decision to accept or reject the lot is based. It is important that the sample drawn from each lot be representative of the quality of that lot. This may be accomplished, for example, by assigning each helmet a number and selecting specimens for inspection by using a table of random numbers. Alternatively, if helmets are arranged without regard to their quality, the sample can be drawn by using a constant-interval technique. For example, every 50th helmet might be selected for inspection. The necessity for establishing a formal procedure to assure that the inspection sample is representative depends on the degree to which there is a tendency for systematic within-lot variations in quality. We do not have data available on which to base a final judgment in this regard. It is suggested that the sampling procedure currently being used for ballistic inspection be retained when implementing thickness as the acceptance criterion.

Quality Characteristics

Quality characteristics are those properties of a unit of product (helmet, for example) that may be evaluated according to the requirements of a specification or other standard. Failure to meet requirements with respect to quality characteristics is usually described in terms of defectives. The quality characteristic of interest here is either average thickness of helmet crowns or minimum thickness in helmets.

It is usually assumed that the quality characteristic is measured without error. This assumption is frequently unrealistic. It is believed that measurement error in the recommended thickness inspection will be small relative to sampling error, but this has not been established conclusively. This matter is scheduled for further investigation in Phase II of the current program.

A "lower specification limit" on the quality characteristic (in the current case thickness, denoted t_L) must be selected to serve as the criterion of acceptability for individual helmets. Values for t_L were derived previously. If average thickness of the crown is used, t_L will be 0.034 inch; if minimum thickness in the helmet is used, t_L will be 0.032 inch.

Acceptance Test

An acceptance test is a set of rules for deciding, on the basis of an inspection sample, whether to accept or reject the lot from which the sample was drawn. Values of the quality characteristic of the units in the sample provide the data on which an estimate of the percent of defective items in the lot is based.* The lot is accepted or rejected depending on whether the estimated percent defectives is below or above an acceptable level.

Two types of acceptance plans, sampling by variables and sampling by attributes, are of interest here.

Sampling by Variables. Sampling inspection by variables can be used when (1) the quality characteristic being monitored (thickness, for example) can be expressed quantitatively, and (2) the statistical distribution of that quality characteristic is known. If these measurements follow a normal distribution, the sampling plans in MIL-STD 414

*This estimate of percent defectives is not always calculated explicitly; it is implicit in the calculations leading to an accept/reject decision.

are applicable. The current helmet inspection using V_{50} as the quality characteristic utilizes an inspection by variables plan.

The thickness data at hand relate to lot-to-lot variation, whereas the statistical information required to use sampling by variables is for within-lot variation. Thus, the information required to use sampling by variables is not currently available.

The important advantage of sampling inspection by variables over sampling inspection by attributes is that, for any desired degree of protection, fewer helmets have to be inspected to judge the acceptability of the lot. This advantage is at least partially offset by the calculations and record keeping associated with sampling by variables (see discussion of present inspection plan). The advantage of inspecting fewer helmets will be relatively unimportant if thickness inspection is instituted because of the simplicity with which thickness measurements can be obtained.

Sampling by Attributes. Sampling inspection by attributes can be used when the sample unit (a helmet, for example) can be classified simply as defective or nondefective (e.g., the thickness is above or below a specified minimum value). In such cases, the sampling plans in MIL-STD 105D are applicable.*

The important advantage of sampling inspection by attributes over sampling inspection by variables is that no assumptions are required concerning the statistical distribution of the quality characteristic. Another advantage is the ease of application of the acceptance test. A lot is accepted if fewer than a specified number of the inspected items are found to be defective, otherwise the lot is rejected.

Operating Characteristics

The consumer is willing to accept all lots having a smaller percent defective than some specified value. Since, however, the inspection plan provides only an estimate of the actual percent defective, there is a finite probability that a lot containing more defectives than the specified value will be accepted and that a lot containing fewer defectives than the specified value will be rejected. For a given inspection plan the probability of accepting (and, consequently, the probability of rejecting) a lot can be determined theoretically as a function

*Battelle has a computer program that can be used to generate sampling inspection plans by attributes in addition to those given in MIL-STD 105D.

of the actual percent defectives in the lot. A plot of probability of acceptance versus the true percent defectives in a lot is referred to as an operating characteristic curve ("OC" curve). There is an OC curve associated with any given inspection plan and this OC curve completely describes the performance of the plan. In Military Specifications OC curves are selected on the basis of the "acceptable quality level" (AQL), which is defined as the maximum percent defective that can be considered satisfactory as a process average.

A schematic OC curve is shown in Figure 14. It is customary to describe the OC curve by two points, denoted A and B in Figure 14. Point A is associated with the probability α, called the "producer's risk", of rejecting a lot containing some (small) specified percent defective. The term producer's risk is used since the consumer would be willing to accept all lots having a percent defective equal to or less than the specified value. Point B is associated with the probability β, called the "consumer's risk", of accepting a lot containing a percent defective which the consumer considers the maximum acceptable.

Present Inspection Plan

The current inspection procedure requires selecting 15 helmets from each inspection lot of from 3201 to 8000 helmets, and obtaining the V_P50 for each by ballistic testing. The arithmetic mean ($\bar{X}$) and standard deviation(s) of these fifteen V_P50 measurements are next computed and used to obtain a "quality index", defined as $Q_L = (\bar{X} - 900)/s$, which in turn is used to obtain an estimated lot percent defective (P_L) from Table B-5 of MIL-STD 414. This value of P_L is compared with M = 0.503, the maximum allowable percent defective corresponding to a sample size of 15 and an acceptable quality level of 0.15 percent, from Table B-3 of MIL-STD 414. The lot meets the acceptability criterion if P_L is equal to or less than M. The calculations required in this acceptance test procedure are illustrated by Example B-2 in MIL-STD 414.

The operating characteristics of this sampling plan by variables are given by the curve corresponding to sample size Code Letter G and acceptable quality level 0.15 percent in Table A-3 of MIL-STD 414. This curve indicates that lots with fewer than 0.15 percent defective helmets will be rejected with a probability no greater than five percent (producer's risk), and that lots with more than 7.2 percent defective helmets will be accepted with a probability no greater than five percent (consumer's risk).

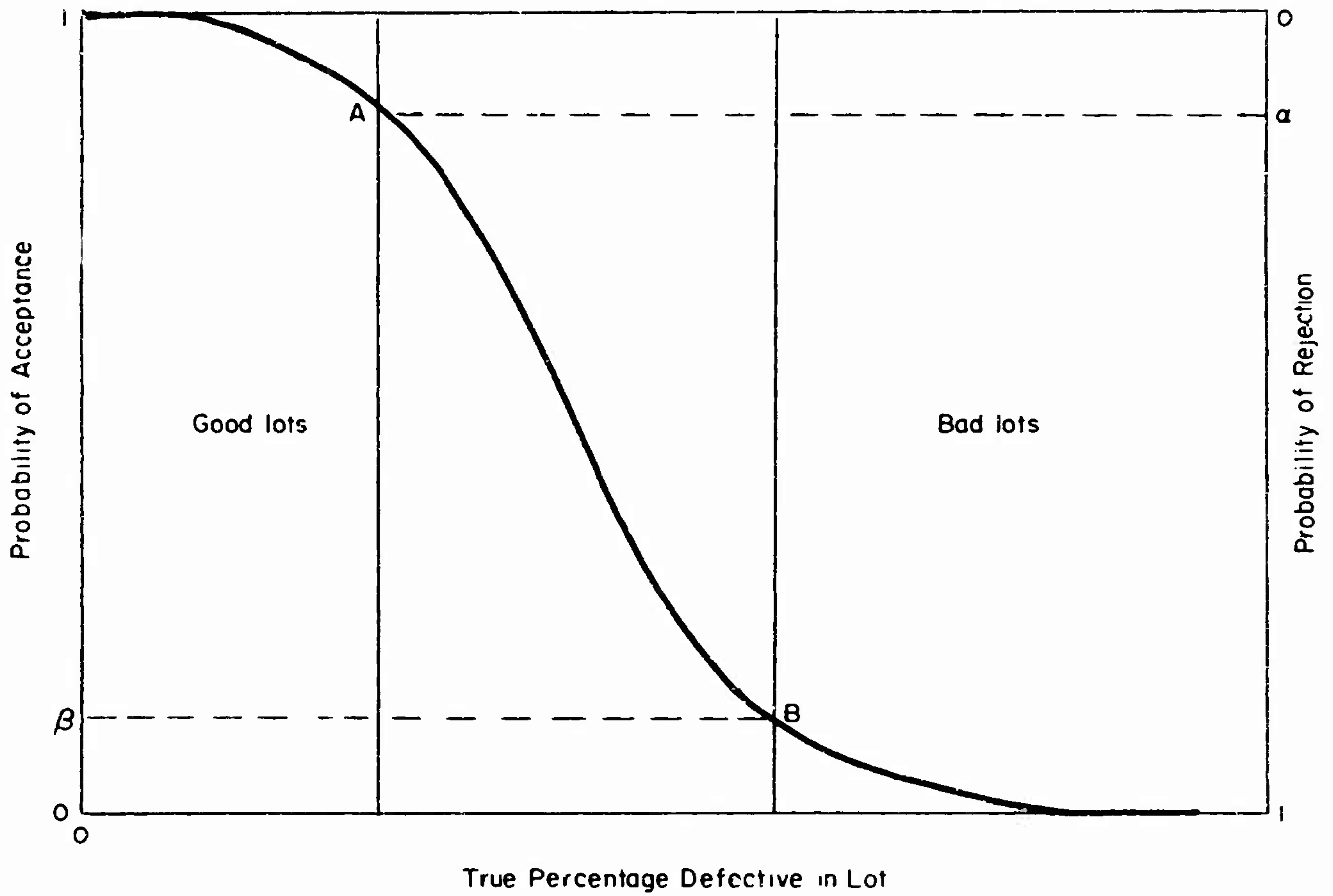

FIGURE 14. OPERATING CHARACTERISTICS OF A SAMPLING INSPECTION PLAN

Recommended Inspection Plan

As noted, inspection by attributes will be more appropriate than inspection by variables when replacing the current ballistic inspection by thickness inspection. In selecting a particular plan it was desired to (1) use a plan completely described in MIL-STD 105D, (2) involve a reasonable sample size, and (3) adhere as closely as possible to the operating characteristics of the current inspection plan (it is not possible to find an attributes plan which exactly matches the operating characteristics of the variables plan currently being used). The plan described below is based on the above considerations and is recommended for adoption.

Lot Size: 3201 to 10,000 helmets (more specifically, the lot size should be the heat-treatment lot as currently used).

Sample Size: 80 helmets per lot.

Quality Characteristic and Specification Limit: Phase II of this study will provide an objective basis for choosing one of the two following quality characteristics and associated specification limits.

(1) If the average thickness of a helmet crown is equal to or greater than 0.034 inch, classify the helmet as nondefective; if the average thickness of a helmet crown is less than 0.034 inch, classify the helmet as defective.

(2) If the minimum thickness in a helmet is equal to or greater than 0.032 inch, classify the helmet as nondefective; if the minimum thickness is less than 0.032 inch, classify the helmet as defective.

Acceptance Criterion: If not more than one helmet in the sample if defective, accept the entire lot; if two or more helmets in the sample are defective, reject the entire lot.

The AQL for this plan is 0.65 percent defective. The operating characteristics of this plan are given on Page 46 of MIL-STD 105D by the curve labeled 0.65 in Chart J and by the entries in the column headed 0.65 in Table X-J-1.

The OC curve for the recommended inspection plan is compared with the OC curve for the current inspection plan in Figure 15. It can be seen that the proposed plan gives a higher probability of accepting lots having fewer than 4.2 percent defective helmets, but a reduced probability of accepting lots with more than 4.2 percent defective hel-helmets.

As a direct comparison of the two plans, it will be recalled that in the current inspection plan there is a 5% producer's risk of rejecting lots containing 0.15% defective helmets. In the recommended plan the probability of rejecting such a lot is only 0.8%. Also, in the current plan there is a consumer's risk of 5% that lots containing 7.2% defective helmets will be accepted. The probability of accepting such a lot is only 1.8% in the recommended plan.

The differences in operating characteristics between the current and the recommended inspection plans are not considered significant as concerns ultimate helmet quality. In any event, the fact that both the consumer's and producer's risks are reduced should make the recommended plan acceptable to both the helmet producer and the government.

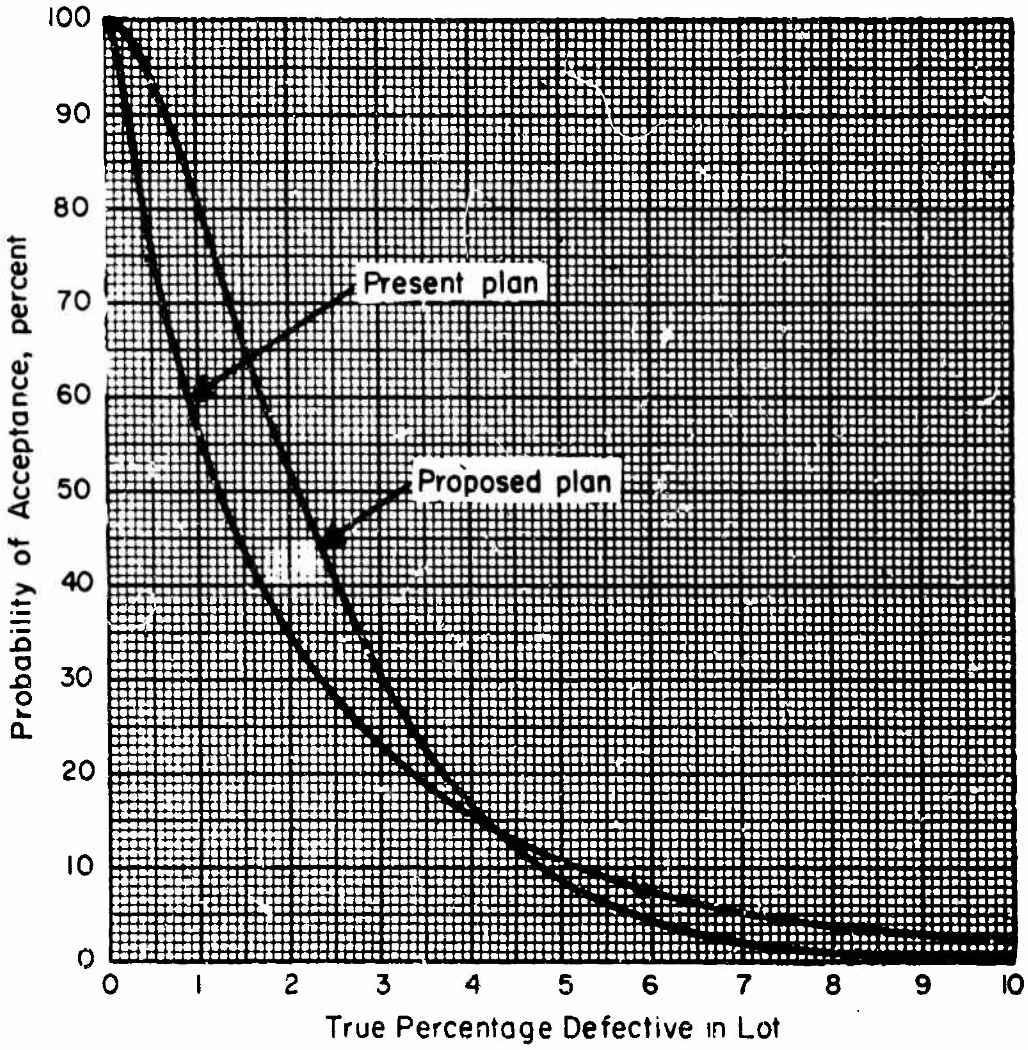

FIGURE 15. OPERATING CHARACTERISTIC CURVES ASSOCIATED WITH PRESENT AND PROPOSED SAMPLING PLANS

CONCLUSIONS AND RECOMMENDATIONS

The most significant conclusions of this study are:

(1) A strong, linear relationship exists between V_p50 (for fragment simulators) and thickness of Hadfield steel as found in M-I helmets. The relationship is $V_p50 = 57 + 24,900t$ (V_p50 in fps, thickness, t, in inches).

(2) The V_p50 of a helmet can be computed by substituting average helmet thickness for t in the above equation. Similarly, the V_p50 for any portion of a helmet can be computed by using the corresponding average thickness. The value of V_p50 so computed is a better estimate of the "true" V_p50 than can be obtained by ballistic tests on a single helmet.

(3) Helmet quality, as currently indicated by a minimum V_p50 of 900 fps, can be maintained if

   (a) the average thickness of helmet crowns is no less than 0.034 inch, <u>or</u>

   (b) the minimum thickness at any point in a helmet is no less than 0.032 inch.

   Although other criteria could be developed (e.g., average thickness of the entire helmet), the above come closest to maintaining the sense of the current inspection.

Based on the above conclusions and the fact that thickness measurements are simpler, more rapid, less expensive and can be made with greater confidence in the results than is the case with ballistic testing, the following recommendations are made:

(1) That the current helmet inspection based on ballistic testing with fragment simulators (Paragraph 3.4.1.3 of MIL-H-1988E) be replaced by an equivalent inspection based on thickness

(2) That the quality characteristic of the new inspection be either (a) average thickness of helmet crowns or (b) minimum thickness in helmets. (The choice can be made primarily on the basis of economics of sampling. A specific recommendation in this regard will be made in Phase II of this study. The lower specification limit would be 0.034 inch if (a) is chosen, it would be 0.032 inch if (b) is chosen.)

(3) The following inspection plan be instituted:

(a) The current method of selecting helmets for sampling be retained

(b) A sampling by attributes inspection plan be used

(c) A sample size of 80 helmets per heat-treatment lot be used

(d) The lot be accepted if no more than one helmet does not meet the thickness requirements; the lot be rejected if two or more helmets do not meet the thickness requirements

(4) The current thickness specifications (Paragraph 3.4.1.1 of MIL-H-1988E) be dropped.

The above inspection plan, although having slightly different operating characteristics than the current plan, should assure approximately the same quality helmets without imposing additional stringency upon the producer.