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A SYSTEMS EFFECT STUDY ON THE EVALUATION OF LIGHTWEIGHT BODY ARMOR

William J. Sacco, et al

Edgewood Arsenal
Aberdeen Proving Ground, Maryland

June 1973

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TECHNICAL REPORT

EATR 4729

A SYSTEMS EFFECT STUDY ON THE EVALUATION OF LIGHTWEIGHT BODY ARMOR

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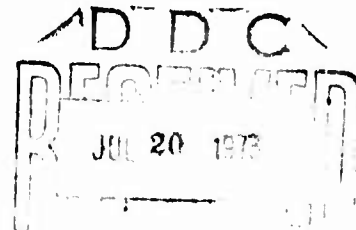
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June 1973

DEPARTMENT OF THE ARMY

Headquarters, Edgewood Arsenal

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13 ABSTRACT

Innumerable efforts have been made to evaluate the armored vest and to provide means of ranking different vests as to their order of effectiveness. Methods devised to decide whether one vest is better or optimal have failed or have been at most only partially successful. Most of the ranking methods and measures of goodness have relied upon fragment simulators, penetration measures, etc., which in turn have been based upon ballistic measures and properties only. In this report, we put forth the premise that such measures, based solely upon ballistic properties, are inadequate and that, unless the procedure utilizes, or can be related to, physiological measures, medical assessment, or wounding criteria, the proposed measure will fail. The only purpose of the armored vest is to reduce the number of casualties resulting from fragment impact. To emphasize the medical and physiological basis we described the armored vest as a thoracic defense system. The thoracic defense system, of course, includes the body's self-regulating and adaptive systems, but we hope that these will be adequately described in terms of a serious, nonserious wounding model. In this report, we shall only allude to such a model, leaving its complete description to a later report, and instead shall give some of our preliminary thoughts on ranking methods and fragment simulators. The ranking methods and the fragment simulator model will use familiar variables – and others – that we believe may be related or important to a wounding model.

14. KEYWORDS

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FOREWORD

The work described in this report was authorized under Project 1J662713DJ40 (Natick), Clothing and Equipment Techniques (U), and Project 1T062110A027 (BRL), Wound Ballistics (U). This work was started in December 1971 and completed in September 1972.

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DIGEST

Innumerable efforts have been made to evaluate the armored vest and to provide means of ranking different vests as to their order of effectiveness. Methods devised to decide whether one vest is better or optimal have failed or have been at most only partially successful. Most of the ranking methods and measures of goodness have relied upon fragment simulators, penetration measures, etc., which in turn have been based upon ballistic measures and properties only.

In this report we put forth the premise that such measures, based solely upon ballistic properties, are inadequate and that, unless the procedure utilizes, or can be related to, physiological measures, medical assessment, or wounding criteria, the proposed measure will fail. The only purpose of the armored vest is to reduce the number of casualties resulting from fragment impact. To emphasize the medical and physiological basis, we describe the armored vest as a thoracic defense system. The thoracic defense system, of course, includes the body's self-regulating and adaptive systems, but we hope that these will be adequately described in terms of a serious, nonserious wounding model. In this report, we shall only allude to such a model, leaving its complete description to a later report, and instead shall give some of our preliminary thoughts on ranking methods and fragment simulators. The ranking methods and the fragment simulator model will use familiar variables, and others, that we believe may be related or important to a wounding model.

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A SYSTEMS EFFECT STUDY ON THE EVALUATION
OF LIGHTWEIGHT BODY ARMOR

I. INTRODUCTION.

Many efforts have been made to evaluate the armored vest and to provide means of ranking different vests as to their order of effectiveness. Most of the ranking methods and measures of goodness have relied upon fragment simulators, penetration measures, etc., which in turn have been based upon ballistic measures and properties only.

In this report, we emphasize that such ranking methods should include physiological measures and medical assessment. To emphasize the medical and physiological basis, we describe the armored vest as a thoracic defense system. The thoracic defense system, of course, includes the body's self-regulating and adaptive systems, but we hope that these will be adequately described in terms of a serious, nonserious wounding model. In this report, we shall only allude to such a model, leaving its complete description to a later report, and instead shall give some of our preliminary thoughts on ranking methods and fragment simulators. The ranking methods and the fragment simulator model will use familiar variables, and others, that we believe may be related or important to a wounding model.

II. FRAGMENT THREATS.

Numerous attempts have been made to simulate munition fragments, and the wide range of fragment characteristics has given rise to a question as to whether any fragment simulator can adequately represent munition fragments. Fragment characteristics vary according to material casing; munition design; intended use of munition; and say fragment shape, size, mass, and velocity. Examination of such characteristics yields a problem of tremendous complexity.

Suppose there exist threat classes $T_1, \ldots, T_n$ with associated probabilities of occurrence $p_1, \ldots, p_n$. We associate a given threat class with a weapon class such as hand grenades or mortars. We represent each class by a finite set of vectors which characterizes the fragments from that class. Such a vector, a, will have components, say, for mass, initial fragment velocity, and shape factor. We let A denote the set of all such vectors; we also let $p(a/T_j)$ be the probability of the occurrence of a given threat T_j.

We now ask the question: Can we find a set $\beta = \{\beta_1, \ldots, \beta_k\}$ of fragments or some class of prototypes or objects which in some sense "best" approximates the set A? The β's may be elements of A, or they may be elements of a different geometric shape. To be more precise, the β's are descriptors of the objects with which we intend to simulate the class of fragments from all threats. A partition of A will be induced by β and the objective function. We first define our objective function in general terms letting intuition guide the reader in regard to the meaning of suitable measures. In general terms, let E_a be the "effectiveness" of fragment a upon the target. E_a is then a measure or a set of measures, dependent upon the fragment, the vest, and the medical, physiological, or wounding effects, which relates to the effectiveness of the fragment. Similarly, we

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let E_{β_j} be the effectiveness of β_j. The β's are the descriptors of objects which will best represent the collection of threats which may be directed against the target. Now each β_j will have associated with it a class of fragment descriptors. These classes are defined for each β_k and β_j as the sets

$$S_j = \left\{ a \mid d(E_{\beta_j}, E_a) < d(E_{\beta_k}, E_a) \text{ for all } k \neq i \right\}$$

where $d(E_{\beta_j}, E_a)$ denotes a "distance" measure defined on the effectiveness space. The β's are now chosen so as to minimize the expression

$$F(\beta_1, \ldots, \beta_k) = \sum_{\beta_j} \sum_{a \epsilon S_j} q_a d(E_{\beta_j}, E_a)$$

where

$$q_a = \sum_{i=1}^{n} p_i P(a \mid T_i)$$

denotes the probability of occurrence of a.

The $\left\{ \beta_1^0, \ldots, \beta_k^0 \right\}$ which satisfies

$$F(\beta_1^0, \ldots, \beta_k^0) \leq F(\beta_1, \ldots, \beta_k)$$

is the set of fragments which best simulates the collection of threats. Rewriting $F(\beta_1, \ldots, \beta_k)$ as

$$F(\beta_1, \ldots, \beta_k) = \sum_{\beta_j} \sum_{a \epsilon S_j} \sum_{i=1}^{n} p_i P(a \mid T_i) d(E_{\beta_j}, E_a)$$

shows that the β's are clearly dependent upon the threat T_i, its probability of occurrence, and the fragment "effectiveness."

The above definition of the fragment descriptor set can be illustrated as follows. For each fragment, there corresponds a 'descriptor vector a; and, to each a, there corresponds an effectiveness measure, E_a:

Now we choose a set of objects, which may or may not be actual fragments derived from any threat but whose descriptor set, or its component descriptors, can be defined in terms or variables used to define the descriptors of the actual fragments. The descriptors, $\beta_1, \ldots, \beta_k$, again, may or may not be in the fragment descriptor set. In any event, we consider the union of the set of β's and the descriptor set.

For each β_j, we determine its effectiveness set E_{β_j} and then we determine the set of a's, in the descriptor set, whose effectiveness measures are not too different from the effectiveness measure of the β_j. If E_{β_1}, E_{β_2}, E_{β_3} are the effectiveness measures of β_1, β_2, and β_3, we have:
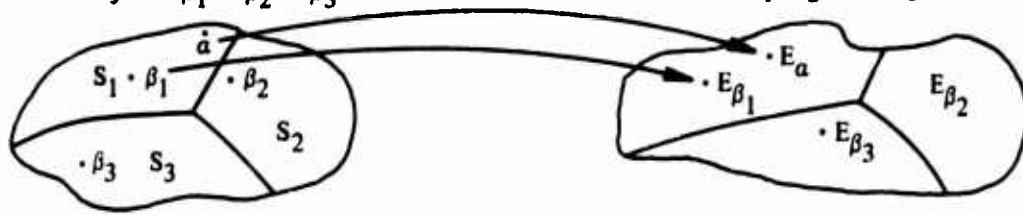
D = Descriptor Set   Effectiveness Set

We collect all $a\epsilon D$ such that their corresponding E_a's lie closest, say, to E_{β_1}. These a's are assigned to the set S_1.

The simulation or the determination of the simulators which "best" describe the collection of all threats is an optimal procedure for the stated objective function. Note that the procedure would have to be repeated for each set or collection of possible threats, in particular for each threat, every pair of threats, etc. However, it is possible that a suboptimal solution is acceptable. One could, for example, obtain optimal collections $\beta_1^i, \ldots, \beta_r^i$ for each threat T_i and then for any collection of threats, say T_1 and T_2, use the collection

$$\bigcup_{i=1}^{2} \bigcup_{j=1}^{r} \beta_j^i$$

as the class of simulators. In this case, all computations could be performed in advance and one would not need to obtain optimal collections for all threat combinations.

The class of β's which "best" approximates the class of fragments is the first phase of the development of the fragment simulator. The second phase is concerned with the set P of γ's associated with each a, where γ is a vector which characterizes the threat in terms of target variables, such as range, striking velocity, location on target, and striking angle. Thus, each a gives rise to a set of γ's. Keeping in mind that a potential use of the fragment simulator is for experimental uses, we note that the γ's must correspond to conditions under which the experiment should be performed and remain representative of the actual field conditions. Therefore, for our collection of β's, we need to determine a set of simulators for the γ's. The process by which this new class of simulators is obtained is entirely analogous to that which was used to obtain the β's. Just as an a gives rise to a set of γ's, we wish to determine a set of simulators which result from a β. Now β_i is a representative of a set S_i; that is, all $a\epsilon S_i$ have been assigned to β_i. We define

$$S_i' = \{ \gamma | a \rightarrow \gamma, \text{ for all } a\epsilon S_i \} .$$

S_i' is the set of all γ's which corresponds to the set of a's in S_i. We wish to find a set of ρ's, viz., $\rho_1^i, \ldots, \rho_s^i$, which best represents the set S_i'. We choose as our objective function

$$G^i(\rho_1^i, \ldots, \rho_m^i) = \sum_{\gamma\epsilon S_j'} q_\gamma d(\gamma; \rho_1^i, \ldots, \rho_m^i),$$

where

$$q_\gamma = \sum_{a \epsilon S_i} q_a P(\gamma | a)$$

and

$$d(\gamma, \rho_1^i, \ldots, \rho_m^i) = \min \left\{ d(\gamma, \rho_1^i), \ldots, d(\gamma, \rho_m^i) \right\} .$$

We choose the set of ρ's such that $G^i(\bar{\rho}_1^i, \ldots, \bar{\rho}_m^i)$ is a minimum; then,

$$G^i(\bar{\rho}_1^i, \ldots, \bar{\rho}_m^i) \leqslant G^i(\rho_1^i, \ldots, \rho_m^i) \text{ for all } (\rho_1^i, \ldots, \rho_m^i) .$$

Again we note that the ρ's may not correspond exactly to γ; however, the measurement space is the same. Furthermore, the ρ's are constrained to lie in a space which is obtainable or meaningful to the class of objects characterized by the β's, but they, of course, must not be too dissimilar to the class of objects which they approximate.

III. THE FRAGMENT SIMULATOR.

In the above, we have described the threats, their fragments, primary characteristics of the fragments, and what we shall call the secondary characteristics of the fragments. The threats we defined as weapon classes which in turn we represented as $A = \{ a \}$ where an a was a primary characteristic or set of measures of the fragment, such as its mass, initial velocity, shape factor, or some other measure which is characteristic of the fragment and not its relationship to the target. The secondary fragment characteristic we take as the P set, or such things as striking velocity, which may be a function of the range, angle of attack, and location on the target at which the fragment strikes. In other words, the secondary characteristics relate to the target and threat. The sets A and P have been characterized, represented, or simulated by the β's and ρ's, respectively. Therefore, we can define the collection

$$\left\{ \begin{array}{l} \beta_1 ; \rho_1^1, \ldots, \rho_m^1 \\ \cdot \\ \cdot \\ \cdot \\ \beta_k ; \rho_1^k, \rho_2^k, \ldots, \rho_m^k \end{array} \right.$$

as the *fragment simulator.*

In obtaining our fragment simulator, we used measures of effectiveness E_a. There are several meanings one can attach to the E_a sets depending upon the desired use of the simulator and the philosophy of relevance to the problem under consideration. For example, one measure or meaning of the E_a may be the probability of the occurrence of a serious wound given that the fragment a perforates a given vest. A simpler measure may be the probability of perforation of a given vest; this latter measure could then be used to obtain a vest score or ranking of vests relative

to the vest used in obtaining the simulator. Other measures, or E_a, could be related directly to wounding criteria, such as serious or nonserious wounds, physiological measures, or medical opinion or assessment.

There are several practical problems which arise by defining a fragment simulator as above. In particular, no data base exists which connects the fragment and its effectiveness; therefore, it is necessary to examine existing data and determine how these data can be used in some optimum fashion. At present, fragment mass distribution and fragment velocity data exist. Also present experiments with fragment penetration or damage use spheres, cubes, etc., of certain masses and velocities. The choice of masses, velocities, and other characteristics used seems to depend on some sort of an eyeball measure probably based upon experience. The question has been raised from time to time if such a characterization is justified. Above we have indicated that it is not, but can we do better with existing data? One alternative is to select, for example, fragment masses from a given mass frequency distribution in some sort of an optimal manner. In other words, we have the problem: Can we find a set of masses

$$\left\{ \xi_1^j, \xi_2^j, \ldots, \xi_K^j \right\}$$

for the prototypes which, in some sense, "best" approximates the fragment mass distribution associated with the threat T_j.

Rather than attacking the problem for each j, we shall consider a mix of weapons where the mix is weighted according to the probability of occurrence P_j of the threat j. The prototype masses ξ_k can be determined as follows: Let $P(m_j|T_i)$ be the probability of occurrence of the fragment mass m_j conditioned on the occurrence of the threat T_i. Furthermore, for simplicity, let us assume that the mass distribution function is continuous. Then letting

$$H(\xi_1, \ldots, \xi_K) = \sum_{k=1}^{K} \sum_{i \in I(T)} \int_{R(m,\xi_k)} |\xi_k - m| P(m|T_i) p_i \, dm,$$

where I (T) is the index set for the class of threats under consideration,

$$R(m,\xi_k) = \left\{ m \Big| \frac{\xi_{k-1} + \xi_k}{2} \leq m \leq \frac{\xi_k + \xi_{k+1}}{2} \right\} \quad 1 < k < K,$$

$$R(m,\xi_1) = \left\{ m \Big| 0 \leq m < \frac{\xi_1 + \xi_2}{2} \right\},$$

$$R(m,\xi_K) = \left\{ m \Big| \frac{\xi_{k-1} + \xi_k}{2} \leq m \leq \beta \right\}.$$

the quantity β is the largest mass in the distribution or the end point of the interval under consideration. The ξ_k's that we seek are those which minimize H. More descriptively we seek to find K-values of ξ in the interval $(0,\beta)$, when $0 < \xi_1 < \xi_2 < \ldots < \xi_K < \beta$ which minimizes $H(\xi_1, \xi_2, \ldots, \xi_K)$.

Now suppose we seek a single prototype mass which best describes the threat T_1 and T_2 occurring with probability p_1 and p_2, respectively. In this example,

$$H(\xi) = \int_0^\xi (\xi-m)P(m|T_1)p_1\, dm + \int_0^\xi (\xi-m)P(m|T_2)p_2\, dm$$

$$+ \int_\xi^\beta (m-\xi)P(m|T_1)p_1\, dm + \int_\xi^\beta (m-\xi)P(m|T_2)p_2\, dm$$

Now we wish to determine ξ^* such that

$$H(\xi^*) = \min_\xi H(\xi)$$

Differentiating $H(\xi)$ with respect to ξ and setting the resulting expression equal to zero we have

$$\int_0^\xi [P(m|T_1)p_1 + P(m|T_2)p_2]\, dm = \int_\xi^\beta [P(m|T_1)p_1 + P(m|T_2)p_2]\, dm.$$

Note that for only one threat the above expression specifies the median fragment mass as the "best" single mass. Thus, in this case, we would use this value of ξ^* as the prototype mass.

Now consider the case of two threats and two fragment masses. That is, we seek ξ_1^* and ξ_2^* such that

$$H(\xi_1^*, \xi_2^*) = \min_{0<\xi_1<\xi_2<\beta} H(\xi_1, \xi_2).$$

Here we have

$$H(\xi_1, \xi_2) = \sum_{i=1}^2 \int_0^{\xi_1} (\xi-m)P(m|T_i)p_i\, dm + \sum_{i=1}^2 \int_{\xi_1}^{\frac{\xi_1+\xi_2}{2}} (m-\xi_1)P(m|T_i)p_i\, dm$$

$$+ \sum_{i=1}^2 \int_{\frac{\xi_1+\xi_2}{2}}^{\xi_2} (\xi_2-m)P(m|T_i)p_i\, dm + \sum_{i=1}^2 \int_{\xi_2}^\beta (m-\xi_2)P(m|T_i)p_i\, dm$$

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As before, we set $\dfrac{\partial H}{\partial \xi_1} = 0$ and $\dfrac{\partial H}{\partial \xi_2} = 0$ and we obtain

$$\sum_{i=1}^{2} \int_{0}^{\xi_1} P(m|T_i)p_i\, dm = \sum_{i=1}^{2} \int_{\xi_1}^{\frac{\xi_1+\xi_2}{2}} P(m|T_i)p_i\, dm$$

and

$$\sum_{i=1}^{2} \int_{\frac{\xi_1+\xi_2}{2}}^{\xi_1} P(m|T_i)p_i\, dm = \sum_{i=1}^{2} \int_{\xi_2}^{\beta} P(m|T_i)p_i\, dm .$$

The first of the above two equations is identical with that derived for a single mass when $\beta = \dfrac{\xi_1+\xi_2}{2}$, and the latter equation maintains the symmetry of the ξ^* values; namely, equality of integrals, with respect to mass $\sum_{i=1}^{2} P(m|T_i)p_i$. These properties carry over to the general case and provide the basis for a general solution which we will formulate as a dynamic program. We define $h_n(\beta)$ as the minimum of H when n-values of ξ have been optimally chosen in the interval (O,β). In general we have the recursive relationship

$$h_n(\beta) = \min_{\xi_n} \left\{ h_{n-1}(a(\xi_n)) + \sum_{i\in I(T)} \int_{R(m,\xi_n)} |\xi_n - m|P(m|T_i)p_i\, dm \right\}$$

where $R(m,\xi_n) = \{ m|a(\xi_n) \leqslant m \leqslant \beta \}$ and where $a(\xi_n)$ is that value of m for which

$$\sum_{i\in I(T)} \int_{a(\xi_n)}^{\xi_n} P(m|T_i)p_i\, dm = \sum_{i\in I(T)} \int_{\xi_n}^{\beta} P(m|T_i)p_i\, dm .$$

Similarly, we may obtain a best set of fragment velocities and shapes. Like methods may also be used if we know the joint probability density function of the triple (m, v, s). This information is rather difficult and costly to obtain and is presently known only for a small class of weapons.

In the above, we have presented a method to obtain a proper set of masses directly from the mass frequency profiles of various weapons, such as mortars, grenades, etc. These masses are those to be used in the simulator. If the simulator uses cubes, then their masses should correspond to those determined by the above method. Similar remarks hold for their velocities,

shapes, and other pertinent factors. If joint probability distribution functions are known, then the proper set of values should be determined by a corresponding multi-dimensional program. In cases of two or more variables, it is doubtful that a dynamic program is feasible. In those cases, an n-dimensional search method would be more appropriate. We have recently written a computer program which performs such a search.

The above algorithm for the determination of the fragment masses assumes a continuous probability mass density function, whereas, in general, only discrete data are available. This poses no problem other than the determination of the a-values required in the program. We have discretized the above procedure and computed best fragment masses for various mixes of cannon, mortars, and grenades. The mass distributions and optimum fragment masses associated with each mix will be given in a forthcoming report. Figure 1 is a graph which shows the decrease in the objective function, h_n, as the number, n, of fragment masses chosen increases. The figure, for the example used, shows little decrease for more than five or six fragment masses chosen. This figure, it must be remembered, only represents a special case and in no way indicates that five or six fragment masses are all that is needed.
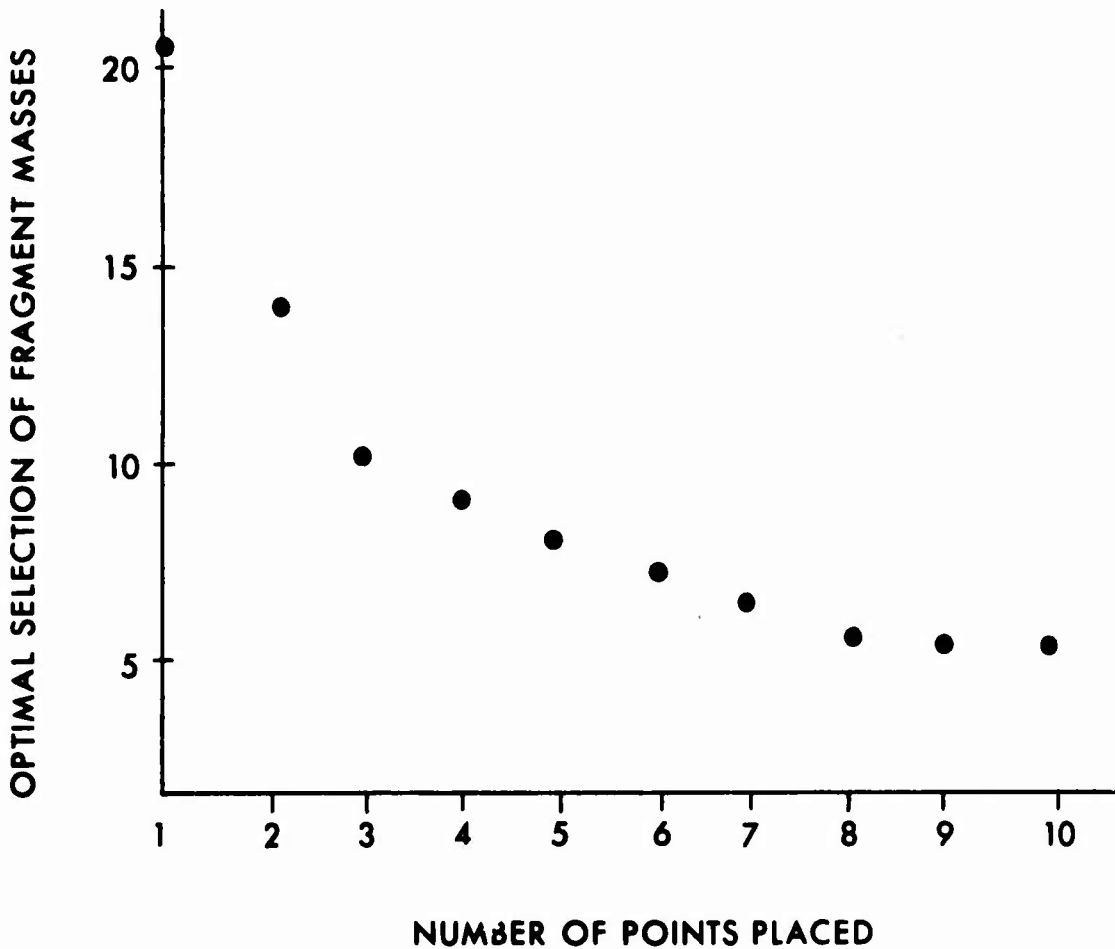

NUMBER OF POINTS PLACED

Figure 1. Optimal Selection of Fragment Masses

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The fragment masses selected by this procedure, the minimization of H, now correspond to the β's defined previously. Similarly, the ρ-set can be defined in an analogous manner. The resulting model then may be defined as a fragment simulator; although unoptimal in a general sense, it is optimal in regard to the chosen objective function and the real constraints of existing data bases.

IV.   THE THORACIC DEFENSE SYSTEM.

The thoracic defense system consists of the fragmentation vest, the body's natural defense and its self-regulating and adaptive processes. In most studies of the fragmentation vest and other body armor, the medical, physiological, and psychological factors are neglected, whereas analysis of the problem of determining the best armor material or vest shows that the answer must depend upon the threat, armor, ballistic measures, fragmentation characteristics, medical assessment, physiological measures, and wounding criteria. The evaluation of armor on the basis of ballistic measures alone has indicated incompleteness of definition in that conflicting results, crossovers, etc., have been obtained; thus, there still exists a need for a measure to express quality and performance of armor in shielding personnel from impacting fragments.

In this study, we shall be mainly concerned with the vest and its evaluation in terms of measures for variables that we can relate to a wounding model or to some model which is consistent with a wounding or medical assessment model. The evaluation of the vest shall consist of three phases: vest characterization and classification, a filtering phase, and an experimental phase. In turn, each phase is dependent on the threat and the medical evaluation phase.

Suppose there exist sets of vests V_1, V_2, ..., V_t, and suppose each vest can be characterized by a set of descriptors. For example, if V_1 is the set of fabric, unbonded vests, then to each vest within the class there corresponds a descriptor, say, areal density, number of plies, tenacity. In general, V_i is characterized by a set $\{ X \}$, where $X = (c_1, \ldots, c_r)$ and where r is the number of descriptors to describe the vest.

At this stage, it is unknown whether the initial classification of vests is sufficiently discriminatory; that is, if vests in category i and j give rise to nondistinguishable output, then these categories should be combined. In order to determine a "best" or working n-chotomy of vests, we proceed as follows: Let us consider an initial vest class, V_j, a sample $v_j^k \epsilon V_{j_\backslash}$, and a given collection of threats. The collection of threats is simulated by $\beta_1, \ldots, \beta_k$ and to each β_i there is associated a collection $\left\{ \rho_1^i, \ldots, \rho_m^i \right\}$ which describe the condition at the vest surface. The ρ-set gives such information as striking velocity, V_s, etc., associated with the β. For simplicity: Let β_i represent the fragment mass and initial velocity of the ith projectile and let the various ρ's associated with the β_i be the collection of permissible striking velocities, V_s. Now a fragment with an initial velocity V will have a striking velocity $V_s < V$ and for such a fragment and vest we obtain, by experimentation, the

probability of perforation, P_{cr}, of vest v_j^k with a fragment of given mass, initial velocity, and a striking velocity V_s. Note that if the fragment perforates the vest then the fragment has a new local descriptor ρ' at the back surface of the vest. In other words, if the fragment has a striking velocity V_s, then the residual velocity is $V_r \leqslant V_s$. Similar considerations apply to all other components of ρ. Furthermore, the fact that a projectile may perforate the vest does not mean that wounding results. Therefore, the probability of perforation, P_{er}, is conditioned on the residual values. The threshold level is such that no wounding results if ρ' is below this value. Now considering all threats (the β's and their ρ's), the probability of perforation of the given vest — to the extent that wounding may occur — becomes

$$P = \sum_j \sum_i P_{er} \ P(\beta_j) \ P(\rho_i^j | \beta_j) \ .$$

where

$$P(\beta_j) = \sum_{a \epsilon S_j} q_a \ . \ P(\rho_i^j | \beta_j) = \sum_{\gamma \epsilon S_j''} \sum_{a \epsilon S_j} P(\gamma | a) q_a$$

and

$$S_j'' = \left\{ \gamma \epsilon S_j' \, | d(\gamma, \rho_i^j) < d(\gamma, \rho_k), \text{ for all } k \neq i \right\}.$$

The sets S_j, S_j', and S_j'' require some modification if the fragment simulator is determined by the algorithm provided for the minimization of the function H. In particular, S_j is those fragments, of a finite collection, which are "closest" to the ξ-value chosen to represent the class of fragments in the interval. Recall that ξ_j is another name for β_j. S_j' and S_j'' can be interpreted analogously.

We now have, for each vest, an associated number P, say P^k. Equivalently, we have the pair (X, P^k), where X is the descriptor of vest v_j^k. Our problem now is to find all vests which give rise to approximately the same P^k; that is, in the interval $(P^k - \Delta, P^k + \Delta)$. If such classes can be determined, then we have obtained an n-chotomy of the vest set.

Given a vest, not used in obtaining our learning sets or pattern classes, we examine its descriptor vector and determine its "closest" neighbor with the use of an appropriate discriminant function. Determining the class k to which the given vest belongs gives a means of evaluating the vest; for, if it is found to be most likely of class k, then we can expect (if our model and discriminant function are chosen properly) that the output results are similar to the vests in class k. A further check on the given vest can be obtained by subjecting it to the next phase of the thoracic evaluation system — the filtering phase.

The filtering phase is a computer code dealing with projectile penetration in a multilayered material. In general, the vest is considered to be composed of several materials, $m_1, m_2, \ldots, m_p$. If the material properties of each layer are known (if equation-of-state parameters which allow description of the elastic-plastic behavior of the individual materials are sufficiently well known), then a computer code such as HELP may be utilized to compute the "flow" of the projectile through the vest and the resultant effect upon the vest.

The HELP code is a hydrodynamic, elastic-plastic code: it computes energy, momentum, velocity, etc., of the materials using hydrodynamic and material properties. The code is an axially symmetric – two space variables and time – hydrodynamic code. The output from this code contains the projectile velocity, its momentum and energy, as well as similar data in a finite number of locations within the vest materials. The depth of penetration and free surface velocity of the vest surface are also given. Such data as free surface velocity, penetration depth as a function of time, and rate of energy change give additional evaluation of the vest. This evaluation is only a ranking procedure.

Finally, if neither the characteristics test nor the filtering phase is definitive in categorizing the vest, then it must be subjected to the experimental phase. This phase is identical to that previously described in setting up the learning classes. The results are related to the wounding criteria and, of course, may give rise to an additional learning class.

V.   MEDICAL EVALUATION PHASE.

In this phase of the project, we deal with the most complex portion of the project; namely, the man. Conceptually, we may consider man to be merely a collection of self-regulating processes whose functions are to keep all physiological parameters within certain limits. Therefore, by investigation of the regulating processes – where the object is to prevent deviations of the physiological parameters from their equilibrium state – it is theoretically possible to understand the causes of pathological and other changes. Unfortunately, the discovery of the structure and establishment of the boundaries of normal operation and regions of instability are problems of extraordinary complexity.

First of all let us define a disturbance or stimulus as anything which causes tissue damage. Damage to tissue may lead to a variety of chemical, physiological, pathological, and psychological effects. We characterize the effects resulting from a disturbance by morphological, physiological, and biochemical variables. The morphological variables may include measurements of the temporary and permanent cavity, penetration depth, and orientation of the wound tract. The physiological and biochemical variables should include measurements which reflect the conditions of particular organ systems. The measurements may be used to categorize wounds into classes, such as serious and nonserious wounds. To be more specific, we shall describe a study that we are undertaking of seriously injured trauma patients in order to gain an improved understanding of the time-dependent traumatic process. Interactions with the University of Maryland Center for the Study of Trauma have enabled us to use their data bank which contains clinical, cardiovascular, metabolic, and therapeutic data on over 1,500 patients. The patients have been observed over a period of time ranging from less than 1 day to several weeks. During the course of treatment on an

individual patient, from 1 to 50 or more detailed sets of measurements are collected. The goals of the study are to determine physiological and biochemical profiles which reflect the severity of a patient's traumatic state, to determine probabilities of survival for different regions of *state space*, and to relate animal and human trauma. The principal analytical tools used in the study are pattern recognition and probability theory.

As a first step, exploratory analyses, using pattern recognition techniques, were conducted on a pattern profile consisting of 12 measurements selected by clinicians at the Trauma Center. The measurements were the systolic blood pressure, diastolic blood pressure, hemoglobin, hematocrit, fibrinogen, sodium, potassium, chloride, osmolality, blood urea nitrogen, glucose, and creatinine. The data consisted of initial and final profiles taken from 70 patients who survived and 70 patients who expired in the Trauma Center. Transformations, such as the Nonlinear Mapping, Eigenvector Plane Mapping, and the Discriminant Plane Mapping, were performed in an effort to find some structure in the data and to delineate various prognosis regions. Figure 2 gives the Discriminant Plane Mapping for the set FINAL LIVE (designated by A) and FINAL DIE (designated by B) profiles. Figure 3 gives the Discriminant Plane Mapping for the INITIAL LIVE (designated by L) and INITIAL DIE (designated by D) profiles. Figures 4 through 7 give trajectories (time sequences) of patients in the Eigenvector Plane. The region inside the circle is considered to be a good prognosis region. The numbers on the graphs indicate the day (following admission) in the hospital. Trajectories (in the Eigenvector Plane and the Discriminant Plane) are being obtained for current and former patients at the Trauma Center.

Similar pattern analyses have been performed on five subsystems; namely, kidney, liver, cardiovascular, respiratory, and blood components.

The reasons for analyzing the effects of trauma on separate body subsystems are twofold. First, this is the classical approach. Secondly, we believe this approach is most applicable to the study of wound ballistics, in particular to the selection of experimental animals for models of human response.

Figures 8 through 12 give a 5-day trajectory of a patient with a gunshot wound in the right chest.

Each of 57 physiological and biochemical measurements were analyzed for its "discriminatory power" by computing means, variances, histograms, and Confusion Probabilities for initial and final measurements of patients who lived (L) and died (D). As an example, tables I, II, and III give the summary of computations for systolic blood pressure, creatinine, and fibrinogen.

Histograms are displayed for the four classes FINAL LIVE, FINAL DIE, INITIAL LIVE, and INITIAL DIE. The numbers in the column labeled BIN are the midpoints of unit intervals. These numbers represent standard deviation units (where the standard deviations are computed from Class FINAL LIVE) as measured from the mean value for Class FINAL LIVE. The other columns are histogram bin probabilities for the respective classes.

Below the histograms are given the number of patients used in each computation and the mean and the standard deviation for each class.
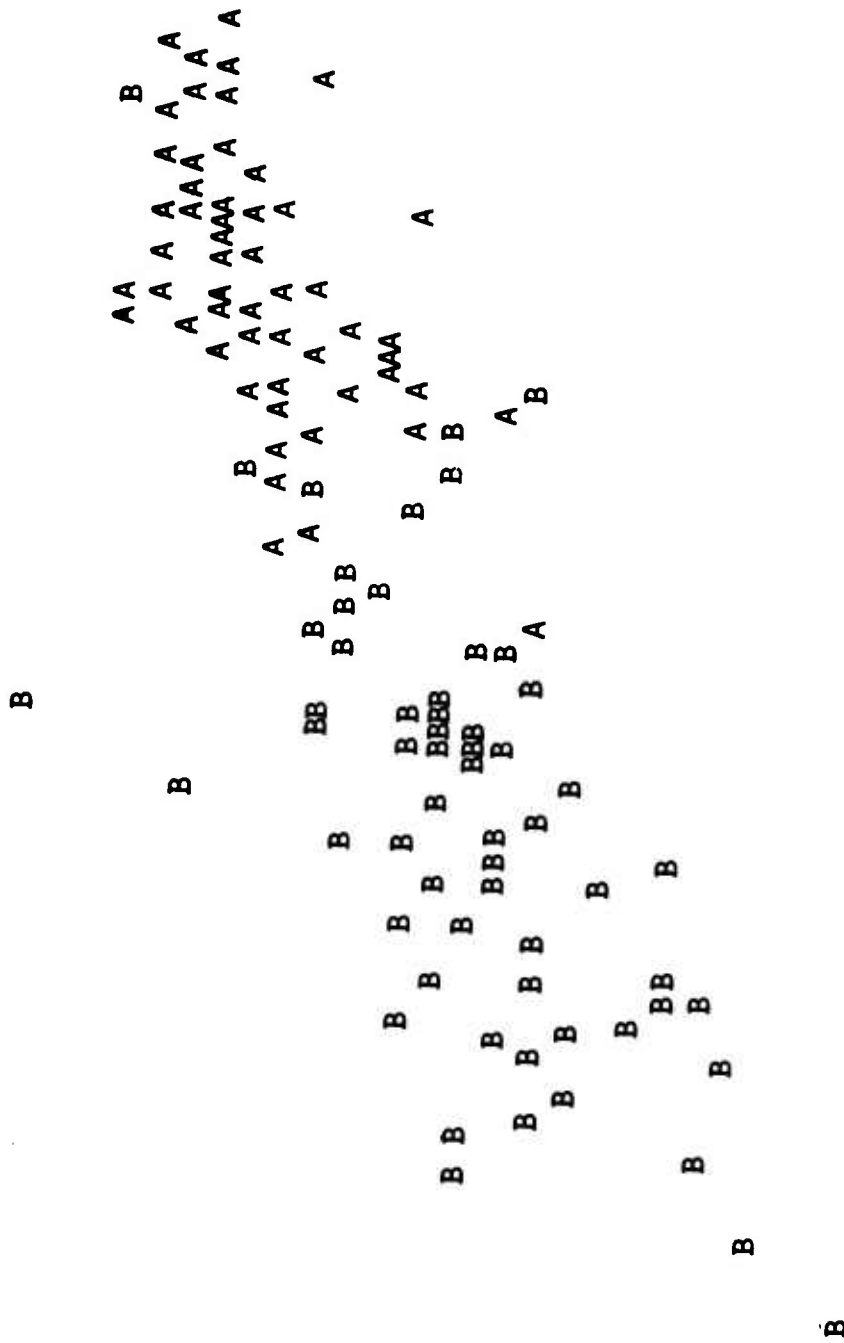
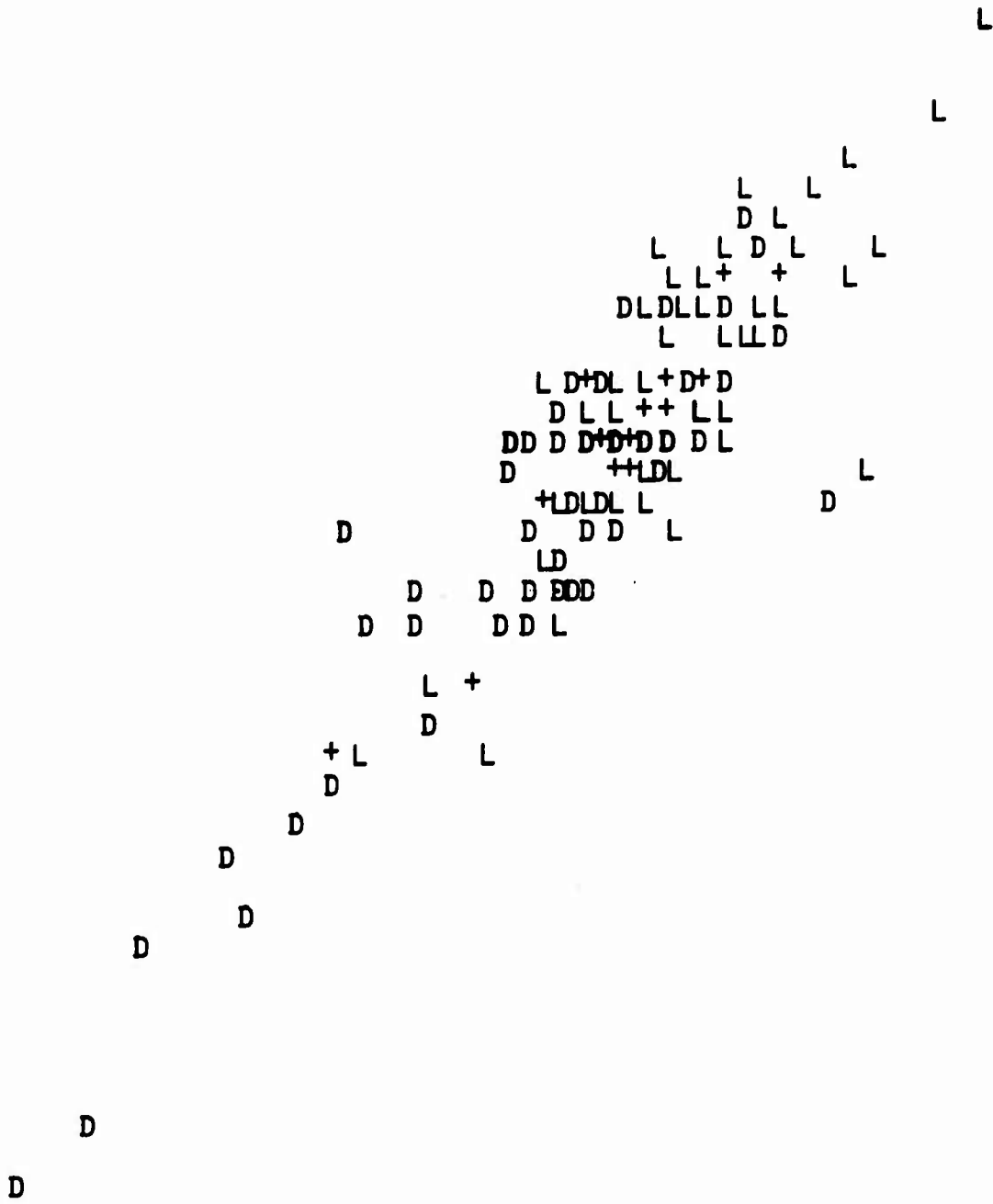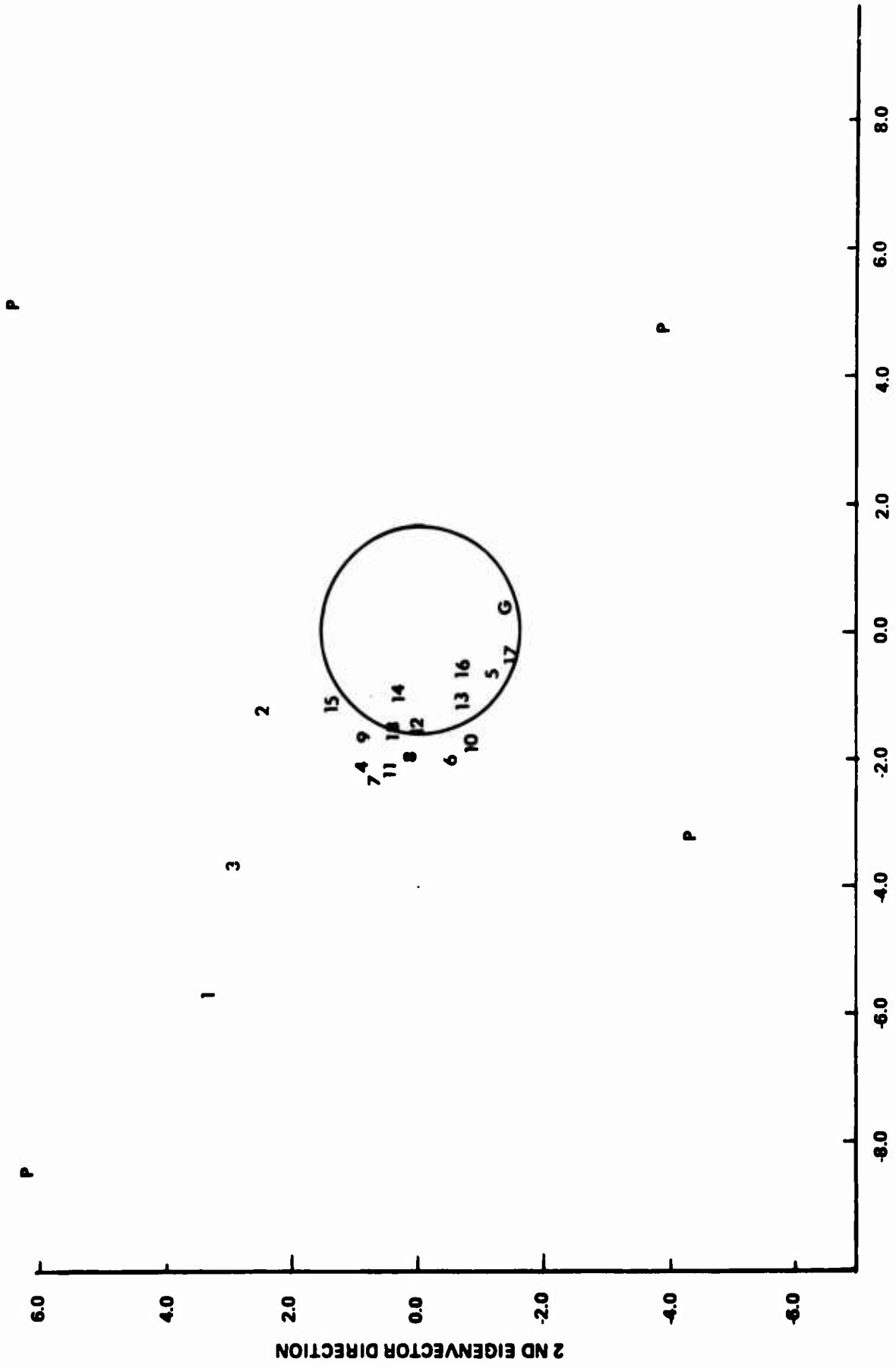Figure 2. Discriminant Plane Mapping – Final Live/Die Profiles

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Figure 3. Discriminant Plane Mapping – Initial Live/Die Profiles

Figure 4. Trajectories of Patient 290227S in the Eigenvector Plane

1 ST EIGENVECTOR DIRECTION

2 ND EIGENVECTOR DIRECTION

8.0   6.0   4.0   2.0   0.0   -2.0   -4.0   -6.0   -8.0

6.0   4.0   2.0   0.0   -2.0   -4.0   -6.0

P

P

P

P

G

Figure 5.   Trajectories of Patient 406_228S in the Eigenvector Plane

Figure 6. Trajectories of Patient CST 1370D in the Eigenvector Plane

1 ST EIGENVECTOR DIRECTION
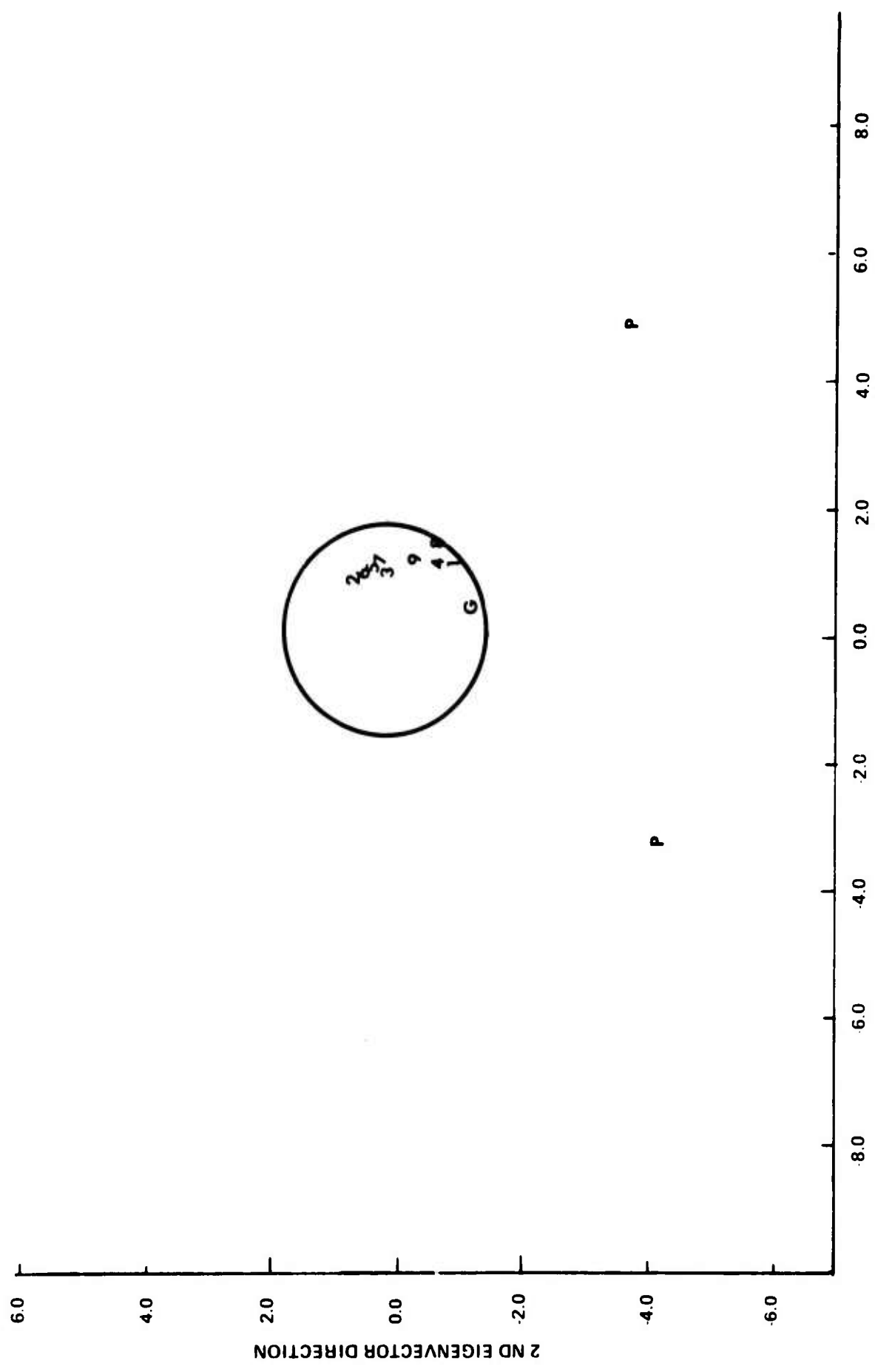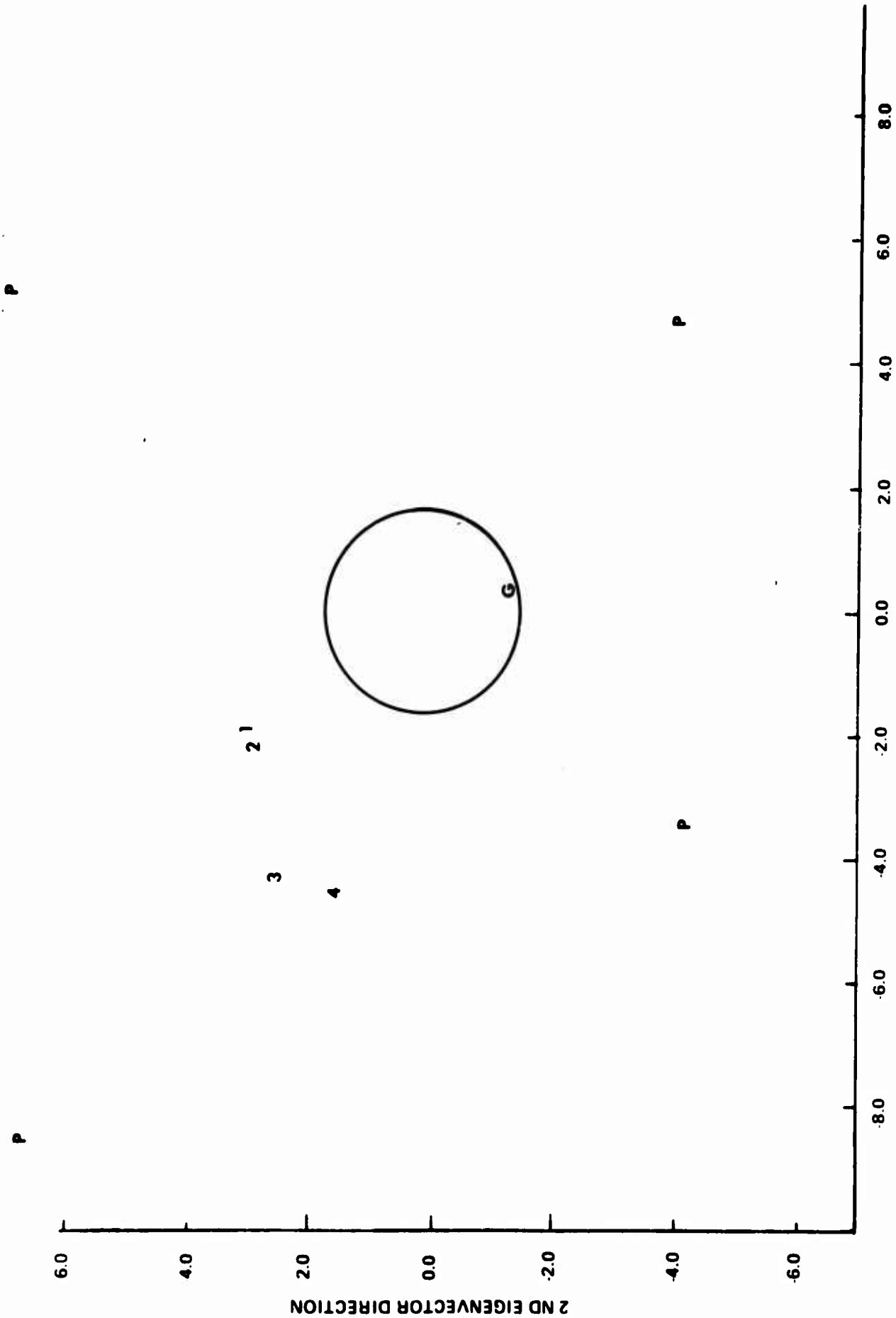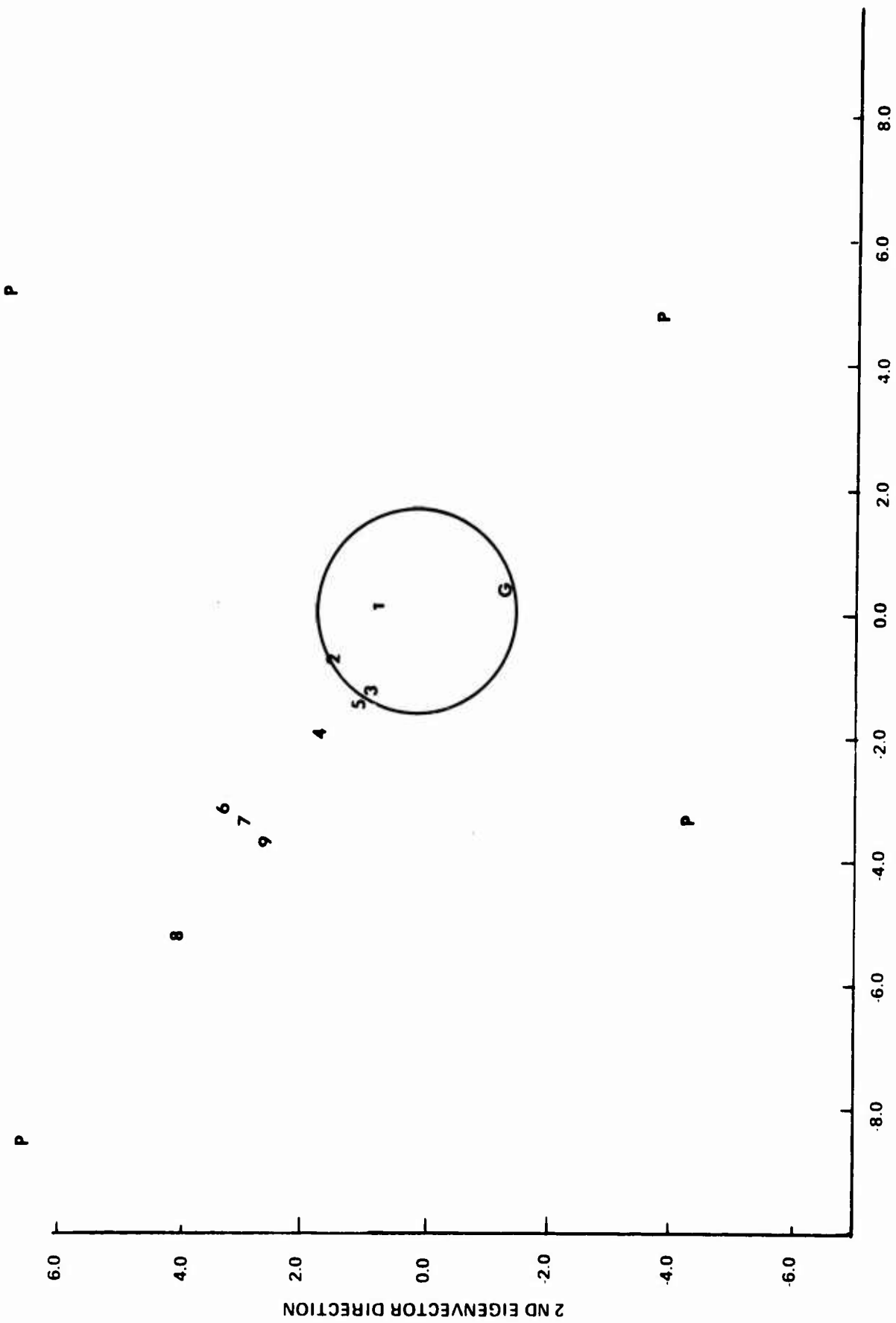
2 ND EIGENVECTOR DIRECTION

Figure 7. Trajectories of Patient 400034D in the Eigenvector Plane

1ST EIGENVECTOR DIRECTION

2 ND EIGENVECTOR DIRECTION

24

435332

DAY 2

K

C

B²

1

Figure 8. Five-Day Trajectory of Patient 435332, Second Day
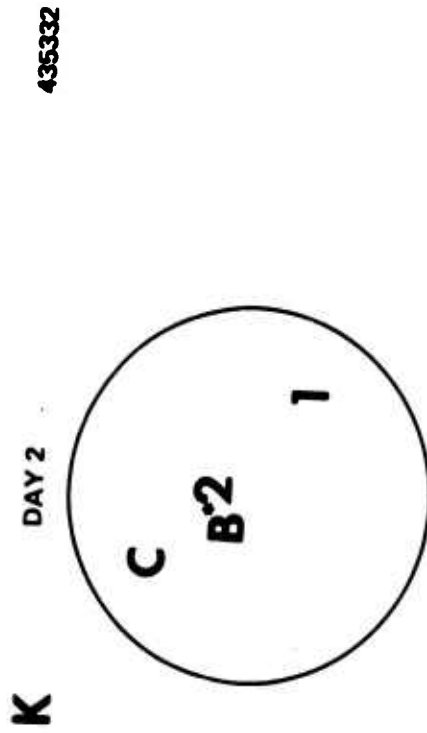
435332

DAY 3

B·K
C
1 2

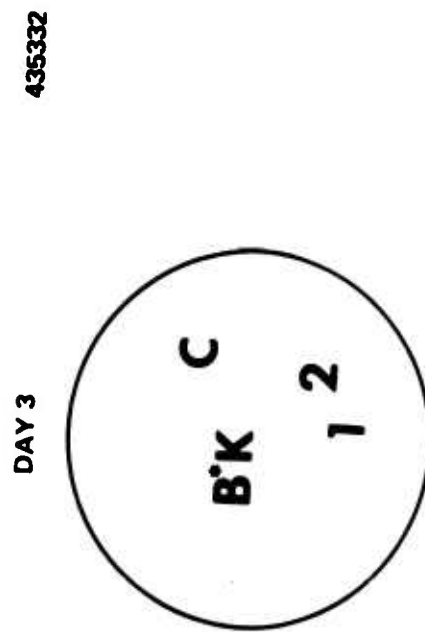Figure 9. Five-Day Trajectory of Patient 435332, Third Day
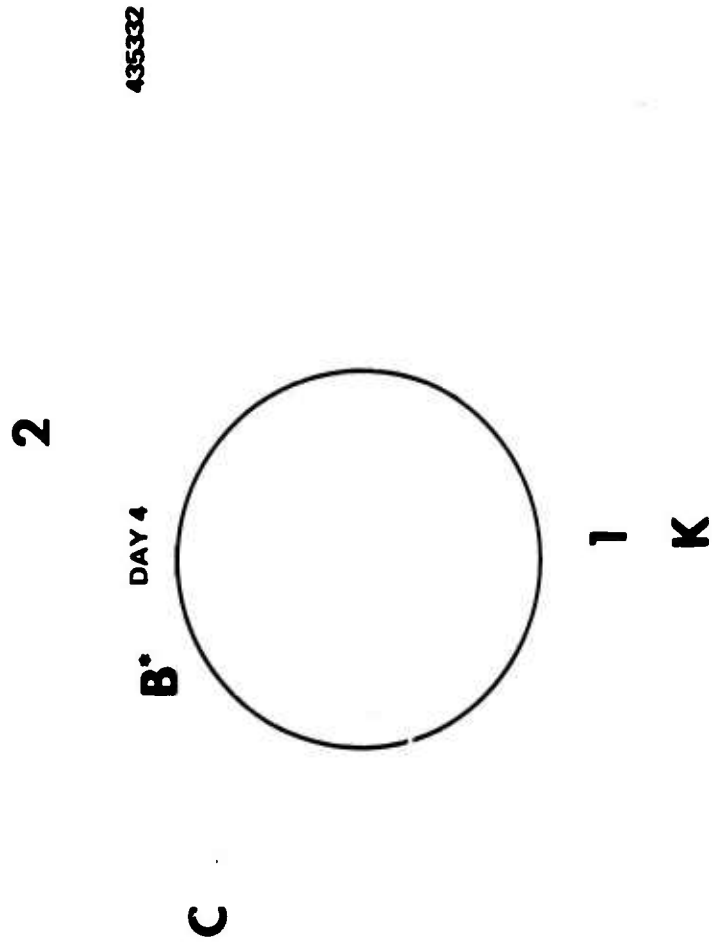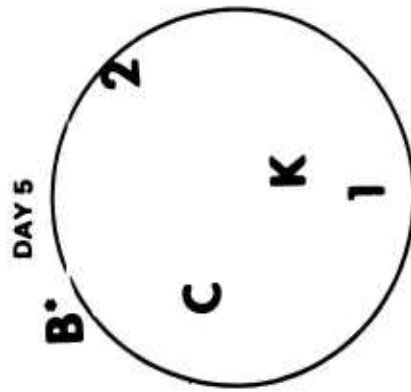
Figure 10. Five-Day Trajectory of Patient 435332, Fourth Day

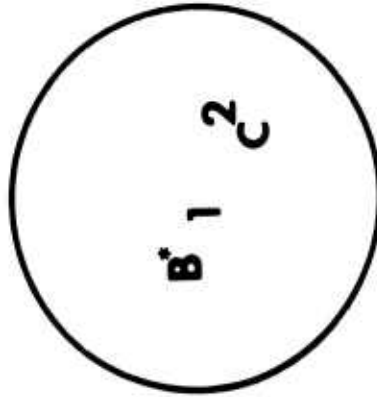Figure 11. Five-Day Trajectory of Patient 435332. Fifth Day

Figure 12. Five-Day Trajectory of Patient 435332, Sixth Day

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Table I. Summary of Computations for Systolic Blood Pressure

BIN	FINAL (L)	FINAL (D)	INITIAL (L)	INITIAL (D)
-10	0.000000	0.000000	0.000000	0.000000
-9	0.000000	0.000000	0.000000	0.000000
-8	0.000000	0.000000	0.000000	0.000000
-7	0.000000	0.000000	0.000000	0.000000
-6	0.000000	0.034285	0.000000	0.000000
-5	0.000000	0.097142	0.000000	0.006896
-4	0.000000	0.222856	0.014577	0.034482
-3	0.008823	0.228571	0.067055	0.137930
-2	0.035294	0.217142	0.166180	0.268964
-1	0.255881	0.068571	0.169095	0.179310
0	0.391173	0.051428	0.259474	0.124137
1	0.205881	0.039999	0.177842	0.131034
2	0.102941	0.028571	0.125364	0.089655
3	0.000000	0.005714	0.014577	0.013793
4	0.000000	0.005714	0.002915	0.013793
5	0.000000	0.000000	0.000000	0.000000
6	0.000000	0.000000	0.000000	0.000000
7	0.000000	0.000000	0.002915	0.000000
8	0.000000	0.000000	0.000000	0.000000
9	0.000000	0.000000	0.000000	0.000000
10	0.000000	0.000000	0.000000	0.000000
	340 out of	175 out of	343 out of	145 out of
	355 used	175 used	343 used	145 used
	0.127E 03	0.724E 02	0.120E 03	0.107E 03
	0.211E 02	0.378E 02	0.330E 02	0.378E 02

Confusion Probability between
  FINAL (L) and FINAL (D) is 0.232691
Confusion Probability between
  FINAL (L) and INITIAL (L) is 0.753473
Confusion Probability between
  FINAL (L) and INITIAL (D) is 0.568257
Confusion Probability between
  FINAL (D) and INITIAL (L) is 0.445015
Confusion Probability between
  FINAL (D) and INITIAL (D) is 0.596453
Confusion Probability between
  INITIAL (L) and INITIAL (D) is 0.778446

Table II. Summary of Computations for Creatinine

BIN	FINAL (L)	FINAL (D)	INITIAL (L)	INITIAL (D)
-10	0.000000	0.000000	0.000000	0.000000
-9	0.000000	0.000000	0.000000	0.000000
-8	0.000000	0.000000	0.000000	0.000000
-7	0.000000	0.000000	0.000000	0.000000
-6	0.000000	0.000000	0.000000	0.000000
-5	0.000000	0.000000	0.000000	0.000000
-4	0.000000	0.000000	0.000000	0.000000
-3	0.000000	0.000000	0.000000	0.000000
-2	0.000000	0.000000	0.000000	0.000000
-1	0.324908	0.018181	0.169549	0.035971
0	0.490972	0.118181	0.453284	0.172661
1	0.097472	0.099999	0.207612	0.201438
2	0.043321	0.154545	0.058823	0.187050
3	0.032490	0.118181	0.051903	0.086330
4	0.010830	0.090909	0.024221	0.115107
5	0.000000	0.072727	0.006920	0.050359
6	0.000000	0.099999	0.013840	0.035971
7	0.000000	0.090909	0.003460	0.028776
8	0.000000	0.081818	0.010380	0.021582
9	0.000000	0.018181	0.000000	0.035971
10	0.000000	0.036363	0.000000	0.028776
	277 out of	110 out of	289 out of	139 out of
	304 used	155 used	303 used	155 used
	0.100E 01	0.380E 01	0.157E 01	0.272E 01
	0.492E 00	0.268E 01	0.194E 01	0.210E 01

Confusion Probability between
 FINAL (L) and FINAL (D) is 0.320480
Confusion Probability between
 FINAL (L) and INITIAL (L) is 0.806952
Confusion Probability between
 FINAL (L) and INITIAL (D) is 0.392750
Confusion Probability between
 FINAL (D) and INITIAL (L) is 0.405915
Confusion Probability between
 FINAL (D) and INITIAL (D) is 0.751798
Confusion Probability between
 INITIAL (L) and INITIAL (D) is 0.579623

Table III. Summary of Computations for Fibrinogen

BIN	FINAL (L)	FINAL (D)	INITIAL (L)	INITIAL (D)
-10	0.000000	0.000000	0.000000	0.000000
-9	0.000000	0.000000	0.000000	0.000000
-8	0.000000	0.000000	0.000000	0.000000
-7	0.000000	0.000000	0.000000	0.000000
-6	0.000000	0.000000	0.000000	0.000000
-5	0.000000	0.000000	0.000000	0.000000
-4	0.000000	0.000000	0.000000	0.000000
-3	0.000000	0.000000	0.000000	0.000000
-2	0.064705	0.276835	0.247448	0.218750
-1	0.258822	0.355931	0.405612	0.453125
0	0.391173	0.231638	0.186224	0.218750
1	0.191176	0.079096	0.089285	0.070312
2	0.085294	0.050847	0.066326	0.031250
3	0.008823	0.005649	0.005102	0.007812
4	0.000000	0.000000	0.000000	0.000000
5	0.000000	0.000000	0.000000	0.000000
6	0.000000	0.000000	0.000000	0.000000
7	0.000000	0.000000	0.000000	0.000000
8	0.000000	0.000000	0.000000	0.000000
9	0.000000	0.000000	0.000000	0.000000
10	0.000000	0.000000	0.000000	0.000000
	340 out of	177 out of	392 out of	128 out of
	343 used	177 used	392 used	128 used
	0.429E 03	0.306E 03	0.309E 03	0.299E 03
	0.177E 03	0.192E 03	0.193E 03	0.170E 03

Confusion Probability between
FINAL (L) and FINAL (D) is 0.690762
Confusion Probability between
FINAL (L) and INITIAL (L) is 0.670469
Confusion Probability between
FINAL (L) and INITIAL (D) is 0.651655
Confusion Probability between
FINAL (D) and INITIAL (L) is 0.924650
Confusion Probability between
FINAL (D) and INITIAL (D) is 0.900644
Confusion Probability between
INITIAL (L) and INITIAL (D) is 0.917250

Below these are given Confusion Probabilities for each pair of classes. The Confusion Probability is a measure of the "difference" between two histograms. Let $\{f_i\}$, $\{g_i\}$, $i = 1, \ldots, n$ be the histogram bin probabilities for Class A and Class B, respectively. Then the Confusion Probability is defined to be

$$C_p = \sum_{i=1}^{n} \min(f_i, g_i)$$

C_p essentially measures the overlap between two histograms. If the two histograms are identical, $C_p = 1$; and, if there exists no overlap between two histograms, $C_p = 0$. The smaller C_p is, the more powerful we presume the physiological measurement to be for discriminating the two classes.

Throughout this paper, we have been interested primarily in fragments and their source, impact, effect, and characterization in regard to the evaluation of body armor. In attempting to evaluate body armor in terms of medical and physiological measurements, it becomes apparent that the problem is a subset of the class of problems involving energy imparted to the body; fragments striking the body, X-rays, and other forms of radiation upon the body add energy to the system. Energy, regardless of form or source, imparted to the body, results in a response modified or adapted to the maintenance of normal functions. The response may be chemical, physiological, or psychological or a functional reaction beyond normal limits of physiological change. This has been demonstrated in the above described trauma studies.

The energy imparted to the system or body may be described or labeled stress. The military requirement is to understand the stresses involved in the use of weapons and to find ways in which they can be prevented, counteracted, or ameliorated. Furthermore, we need the ability to predict susceptibility and degree of response to the stress before it is imposed. In the trauma studies, a variety of measures was used in an attempt to describe or measure metabolic and hormonal responses which in turn provide the means to prevent, counteract, or ameliorate the effects of the stress conditions applied to the system. The unification of the threat, body armor, and system or body function thus requires evaluation in terms of such measures. These measures, then, would be contained in the sets E_a previously described. Thus, one way of relating the evaluation of body armor to the total system is to relate the threat and armor with physiological measures by means of a stimulus or energy imparted to the body.

We derive our stimulus from the interface conditions. The interface is defined as the common boundary between the armored vest and the body. The interface conditions are functions of a, γ, and the vest; *that is*, they are functions of the threat, local conditions, and the vest. Fragments which neither perforate the vest nor cause wounding are neglected. In particular, the interface conditions may be thought of as a set similar to the p's as previously described or, more generally, may be descriptors of the impacting energy. We shall denote the interface conditions by vectors $e = (e_1, \ldots, e_i)$.

Now the medical evaluation phase is essentially the rationale which associates the interface condition e with a wound w and its measurement s. The measurements are then used to obtain a partition of the wound set. The procedure by which this will be accomplished is similar to that which was used in partitioning the fragment set. The procedure and model will be more fully described in a later report where we shall describe more fully the effectiveness set E_a.