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TECHNICAL REPORT

76-30-CEMEL

DEVELOPMENT OF A NEW INFANTRY HELMET

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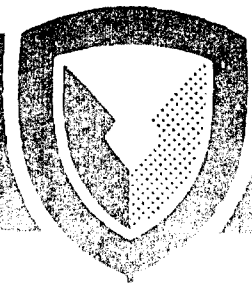APR 28 1977

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January 1976

UNITED STATES ARMY
NATICK RESEARCH and DEVELOPMENT COMMAND
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CEMEL-152

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The Army Materiel Development & Readiness Command interlaboratory helmet development program is outlined, and the steps taken to develop a new infantry helmet are reported. The results of studies ranging from anthropometry to wearability were synthesized into a military helmet design. Studies included a mathematical sizing model, human factors compatibility evaluations, heat transfer and transient deformation measurements, suspension system designs, and ballistic materials investigations. The resulting three size, one-piece, ballistic helmet offers significantly improved protection, fit, comfort, and stability over the standard M-1 helmet and nylon liner.

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DEVELOPMENT OF A ONE PIECE INFANTRY HELMET

1. INTRODUCTION

The subject of military helmets is an ancient one because a helmet not only provides protection for the head but also serves as an identification symbol for the entire armed force. The M-1 steel shell and plastic reinforced cotton liner were adopted by the U.S. Army in June 1941. An improved ballistic liner (nylon) was type classified in March 1961, and a more comfortable chin strap was adopted in 1972. However, all efforts by the Government and Industry to improve the suspension system to counter the numerous complaints from the field proved fruitless. The complaints from the field focused on the areas of stability, fit and comfort.

Analyzing these areas, one can conclude why improving the suspension system would offer only marginal relief to the soldier. The high center of gravity of the M-1 helmet system causes rotational forces which can not be corrected by a modification of the suspension system except by lowering the helmet on the head, which of course would interfere with vision. These forces may ultimately be reported in a complaint that the helmet is unstable, too heavy or uncomfortable.

The fit problem is clear when one considers that the M-1 helmet system is issued in one universal size. At least 50% of the troops would be expected to complain of poor fit. The rotational forces of the helmet onto the head are accentuated on the smaller half of the Army population. Comfort, too, may be linked to the instability of the helmet and may be manifested in complaints as the helmet being too heavy, causing headaches or irritating the head.

An additional problem that sometimes exists with the M-1 system is the misfit of the nylon liner inside the steel shell. This misfit can be caused by a slight distortion of the nylon liner or by molding the liner to the maximum tolerance dimensions and fabricating the steel shell to the minimum tolerance dimensions. The net result is that the steel shell rides slightly high on the nylon liner and has a tendency to wobble or separate from the liner when the soldier runs with his chin strap unfastened. This problem adds to the complaints of the helmet being too heavy, not fitting, and uncomfortable.

2. NEW HELMET PROGRAM

a. Objectives and Organization

The U.S. Army Natick Development Center (NDC), now the U.S. Army Natick Research and Development Command (NARADCOM), solicited and involved the expertise of other Army Materiel Development & Readiness Command (DARCOM) and Agencies in the preparation of a program for developing a new infantry helmet. The program was to emphasize ballistic protection and troop acceptability.

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Two approaches were to be taken with regard to ballistic protection:

1. Develop a helmet with increased ballistic protection and with the same weight as that of the M-1 system.

2. Develop a helmet with equal M-1 ballistic protection and with a weight less than that of the M-1 system.

Using either approach the helmet should be designed to make the most efficient use of the ballistic material. Therefore the helmet should be designed to come as close to the head as possible and cover as much of the head as possible consistent with the physical limitations and mission of the soldier.

The participating Agencies or Laboratories included the following:

US Army Natick Research and Development Command (NARADCOM), Natick, MA
US Army Human Engineering Labs (HEL) Aberdeen, MD
US Army Ballistic Research Labs (BRL) Aberdeen, MD
US Army Materiel System Analysis Agency (AMSAA) Aberdeen, MD
US Army Edgewood Arsenal (EA), Edgewood, MD
US Army Mechanics & Materials Research Center (AMMRC) Watertown, MA
US Army Research Institute for Environmental Medicine (ARIEM) Natick, MA
US Naval Research Laboratory (NRL) Washington, DC

The philosophy of this program began with the obvious assumption that to attain maximum protection to the head one should cover the entire head. Every design aspect reducing the ideal coverage was to be documented by a corresponding study recommending such a cut or standoff. This philosophy as depicted in Fig. 1 evolved into a helmet plan which was incorporated into the Personnel Armor System Technical Plan. The Technical Plan was approved by the Department of the Army in April 1970.

The work units of the initial plan and the inputs of the various laboratories or agencies are listed in Table I. Implementation of this plan necessitated the close cooperation of each of the participating Laboratories. Natick Research and Development Command managed and coordinated all work efforts as to content and timeliness.

The body of this report provides a description of the developmental phases of the new infantry helmet by citing the pertinent results of the work units as they apply and incorporating the abstracts of the detailed reports in the expanded bibliography.

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HELMET PROGRAM

MATERIALS (NBC-AMMRC)

WEIGHT PERCEPTION (HEL)

BALLISTICS (BRL)

HEAD COVERAGE (NBC-AMSAA)

CUT FOR NECK FUNCTION CLOTHING COMPATIBILITY (HEL)

MATH MODEL SIZING OF HEAD (BRL-NBC)

CUT FOR HEARING (HEL)

OFF-SET FOR TRANSIENT DEFORM. VENTILATION (EAL-ARIEM)

CUT FOR VISION GAS MASK (HEL)

PERFECT ARMOR

CASUALTY REDUCTION ANALYSIS (NBC-AMSAA)
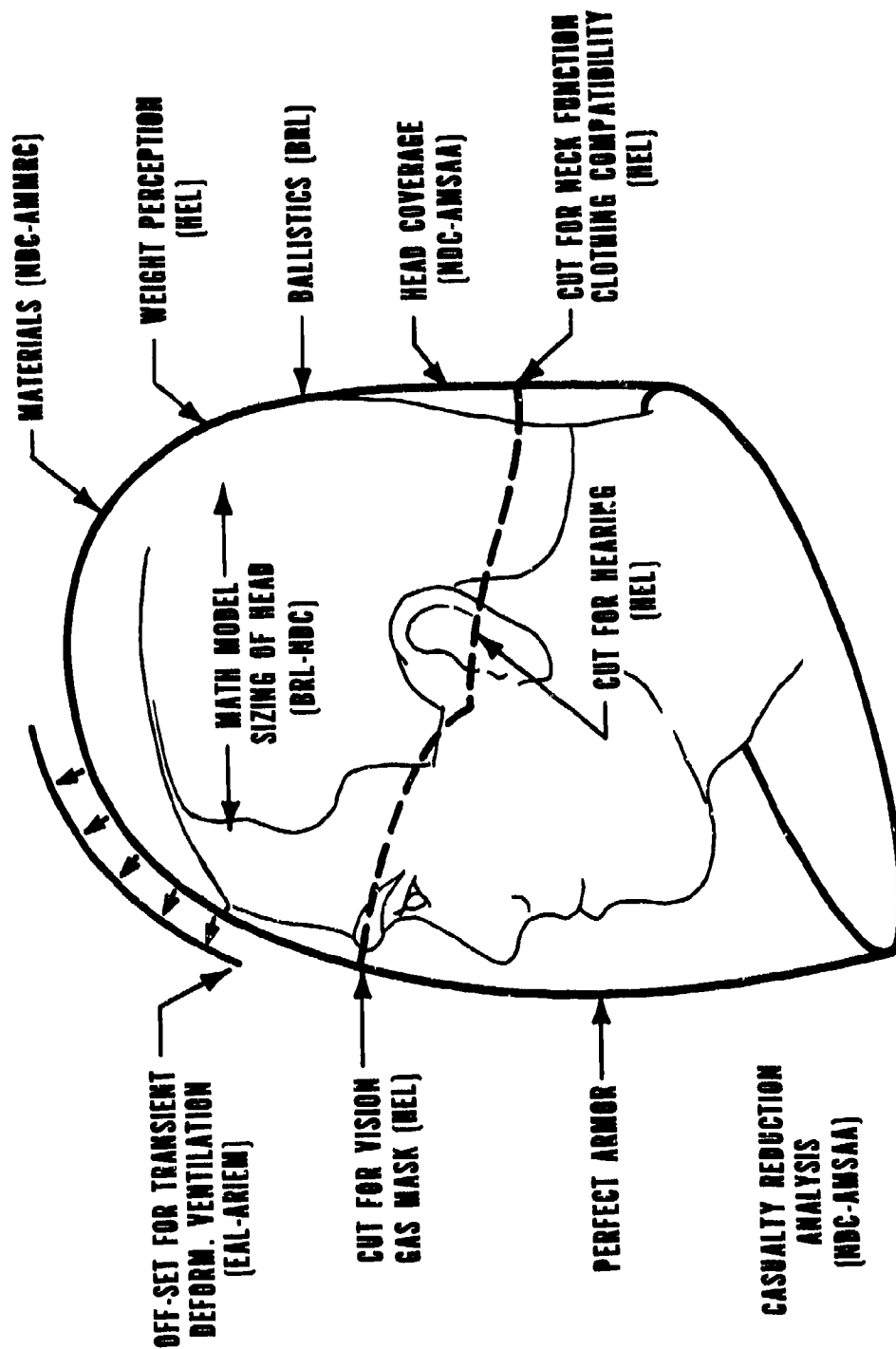
Figure 1. Helmet Program Responsibility Assignments

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TABLE I

PROGRAM WORK UNITS

Work Unit No.	Input Laboratory
1. Mathematical Model of the Head	BRL, NARADCOM
2. Verification of Math. Model of Head	NARADCOM
3. Configuration and Production of Research Prototypes	NARADCOM
4. Sizing Evaluation of Prototype Helmets	NARADCOM, HEL
5. Documentation of M-1 Helmet & Liner	HEL
6. Effect of Helmet Form on Hearing	HEL
7. Human Factors Engineering Support	HEL
8. Physiological Evaluation	ARIEM
9. Casualty Reduction Studies	NARADCOM, AMSAA
10. Casualty Criteria	BRL
11. Ballistic Testing	EA, NRL
12. Materials Program	AMMRC, NARADCOM
13. Tactical Doctrine Interface	NARADCOM, TRADOC
14. Threat Analysis	AMSAA
15. Systems Development Plan	NARADCOM
16. Reliability and Maintainability Criteria	NARADCOM
17. Suspension Studies	NARADCOM
18. Retrieval and Analysis of Design Data	NARADCOM
19. Fabricate Experimental Helmets	NARADCOM

TABLE I

PROGRAM WORK UNITS   (cont'd)

Work Unit No.		Input Laboratory
20.	Fabricate ET/ST Helmets	NARADCOM
21.	Coordinated Test Plan	NARADCOM
22.	Establishment of Utilization Doctrine	NARADCOM
23.	Production Engineering Effort	NARADCOM
24.	Establish Systems Specifications	NARADCOM
25.	Establish Type B2 MIL-STD-490 Critical Item Developmental Spec.	NARADCOM
26.	Establish System Technical Data Package	NARADCOM
27.	Engineering and Service Testing	NARADCOM TECOM/AMSAA
28.	Personnel and Training	NARADCOM
29.	Annual Technical Review of Plan	Program Working Committee

b. Background Studies

Two studies were initiated simultaneously to provide a uniform baseline for the entire program. The first study[1] consisted of the historical documentation of the M-1 helmet system. The second[2] established the state-of-the-art on a worldwide basis of helmet designs, materials and suspension systems. The documentation study traced the M-1 from its conception to the present day, confirmed all the systems shortcomings, and documented all modifications and attempts at improvements of the system. The state-of-the-art report consisted of a survey of foreign helmets from both friendly and unfriendly nations. From the final report one concludes that other countries have the same problems with their infantry helmet as the U.S. Army. The complaints of foreign troops also center about the areas of stability, fit and comfort.

3. SIZING

To design a close fitting helmet from a rigid ballistic material, one must first establish generalized shapes of heads for the Army population.

A review of the available anthropometric data revealed that large data gaps existed as to the shapes of human heads. Considerable data exist for point to point measurements on the head such as length, breadth, height and circumference, but no information was available as to the relation of any particular measurement with that of another, nor were there any intermediate points measured on any given head. In other words, spatial or three dimensional information was totally lacking from the data.

Under work unit #1 of the Helmet Program, the Ballistic Research Laboratories (BRL) were charged with the development of a mathematical model of the head using the available anthropometric data existing in the 1966 Army Anthropometric Survey by White and Churchill and the 1961 Survey of Army Aviators by White. BRL successfully developed a series of algorithms[3,4] which related the four basic head dimensions of circumference,

[1] Houff, C.W. and Delaney, J.P., "Historical Documentation of the Infantry Helmet Research and Development", Technical Memorandum 4-73, U.S. Army Human Engineering Laboratory, Aberdeen Proving Ground, MD. February 1973.

[2] McManus, L.R., "Protective Helmets of NATO and Other Countries", Technical Report 72-29-CE, US Army Natick Laboratories, Natick, MA, January 1973.

[3] Goulet, D.V. and Sacco, W.J., "Algorithms for Sizing Helmets", Memorandum Report No. 2185 Ballistics Research Laboratory, Aberdeen Proving Ground, MD, May 1975.

[4] Goulet, D.V. and Sacco, W.J., "Algorithmic Analysis of 1966 U.S. Army Survey and Conversion of Measurement Data to Prototype Headforms", Draft Memorandum Report, Ballistics Research Laboratory, Aberdeen Proving Ground, MD, 1975.

length, breadth, and height and by which the Army population was capable of being sized. The sizing algorithm yields various size systems (Table II). Although this is the first time an effort was made to relate the four basic dimensions, information was still lacking pertaining to the intermediate points necessary for describing the shapes of heads.

Several avenues of approach were taken to fill the missing data. The first approach, a long range solution, was the biostereophotometric method. This method involves a series of five pairs of cameras and a r lution of points into an x,y,z, coordinate system. This method, although it looked ver romising for body measurements, required much refinement in terms of head measurements. Consequently, due to the time involved to refine the technique, this method could not be of assistance to this program. A second approach, one which was thought would closely approximate a solution, was the "Prince Charming" method. This method involved the measuring of 600 soldiers at Ft. Devens, MA and by computer selected the individual soldiers that most nearly fit all the dimensions of each size category. Thirteen men were selected as Prince Charmings, brought to US Army Natick Research and Development Command and had their heads cast molded and pantographed. The cast model represented the subject's head with the hair matted down by a thin rubber cap. The pantograph stylus on the other hand penetrated the hair enabling the recording of x,y,z, coordinates for over 400 points on the subject's head.

Plaster male molds were made from each of the head castings. The pantograph data was used to obtain cutting tapes for a numerical controlled (NC) milling machine. Wooden heads were obtained from the NC method which more nearly represented the subjects heads.[5] It was hoped that each head mold would serve as an umbrella for its respective size category. But such was not the case. The "Prince Charmings" did not prove to be an adeqquate solution to the shaping problem. Individual bumps and contours of the model seidom matched the contours of other heads within the same size category. Thus, a new solution for gathering data on the contours of heads had to be found.

The idea was to measure heads from a known geometrical surface in such a way that the landmarks of the heads were always referenced to certain points in the geometrical surface. The idea reduced to practice consisted of a 14 inch (35.6 cm) diameter clear plastic hemisphere having 27 moveable probes on the surface. The spherical coordinates of each probe were known and each probe passed through the center of the sphere.

[5] Claus, W.D., Jr., McManus, L.R. and Durand, P.E., "Fabrication of Wooden Headforms with NC Techniques", *Journal of Numerical Control*, (pgs 15-22), October 1974.

TABLE II

Sizing Solutions in Millimeters
(From Goulet and Sacco, 1972)

| Number | Height | NONLINEAR PROGRAM | | Circumference |
		Width	Length	
1	145.8	170.0	217.9	610.0
2	145.8	170.0	217.9	611.4
	133.0	160.8	204.9	582.3
3	145.8	170.0	217.9	611.4
	136.8	164.1	209.0	593.4
	129.8	158.1	200.8	579.5
4	145.8	170.0	217.9	611.4
	138.7	165.1	209.0	598.9
	133.0	160.8	204.9	582.3
	129.2	158.1	200.1	576.8
5	145.8	170.0	217.9	611.4
	138.7	165.1	209.0	598.9
	133.0	160.8	204.9	585.1
	129.8	158.1	200.8	579.5
	126.0	154.8	196.7	568.5
6	145.8	170.0	217.9	611.4
	140.0	166.8	211.0	598.9
	136.8	164.1	208.3	593.4
	133.0	160.8	204.9	582.3
	129.8	158.1	200.8	576.8
	126.0	154.8	196.7	568.5
7	145.8	170.0	217.9	611.4
	141.3	167.8	213.1	604.5
	138.7	165.1	209.0	598.9
	136.8	163.0	206.9	590.6
	133.0	160.8	204.9	582.3
	129.8	158.1	200.8	575.4
	126.0	154.8	196.7	568.5
8	145.8	170.0	217.9	611.4
	141.5	167.8	213.1	604.5
	138.7	165.1	209.0	598.9
	136.8	163.0	206.9	590.6
	133.0	160.8	204.9	582.3
	131.7	159.2	200.8	580.9
	129.2	158.1	200.8	572.6
	126.0	154.8	196.7	568.5
9	145.8	170.0	217.9	611.4
	141.3	167.8	213.1	604.5
	138.7	165.1	209.0	598.9
	136.8	163.0	206.9	590.6
	133.0	160.8	204.9	582.3
	131.7	159.2	200.8	580.9
	129.2	158.1	200.1	572.6
	126.0	154.8	196.7	569.8
	122.8	152.1	193.3	557.4

The measuring process required restraining the subject's head in the Frankfort plane by a bite bar, then lowering the hemisphere over the head in such a way that the equatorial plane of the hemisphere was aligned with the subject's right tragus and right external cantus with the diameter passing through the right tragus. The vertical diameter plane was aligned with the subject's mid-saggital plane. The center of the hemisphere thus fell approximately midway between the subjects tragi (see Fig. 2). All 27 probes were depressed until they contacted the subject's head and the lengths of the probes were measured. Thus, the spherical coordinates of the 27 points on the head become known as well as the lengths of the rays emanating from a point between the tragi to the surface of the subject's head.

Two of these devices, called 3D Numerical Surface Descriptors, were constructed at the Natick Research and Development Center and were used to measure heats at Ft. Devens, MA. In Feb 1973, the heads of 106 subjects were measured, and in addition to the surface measurements, the four basic head dimensions were measured on each subject.

The test subjects were sorted into the BRL algorithm 9 size system according to their basic head measurements. However, in analyzing the nine size system with respect to the tolerances in the helmet molding process, it was obvious that the dimensions for many of the sizes would overlap one another. Therefore, three sizes were selected which represented the nine size system and had dimensions which would be practical for making molds. The sizes selected were 1, 6, and 9 of the 9 size system.

The subjects were resorted according to this modified 3 size system resulting in a distribution of 30%, 50%, and 20% for sizes 1, 6 and 9 respectively. The statistics for the probe readings for each size were determined by computer. In essence, the computer generated new sets of probe readings which would maintain the four basic dimensions for each size category.

The new probe data were given tc Mr. A. Petitto, a consultant sculptor to NARADCOM, and he, using one of the three dimensional surface descriptors, fashioned three headforms representing the three size categories (see Fig. 3). The probe data given to the sculptor and the corresponding head rays are presented in Table III. The headform dimensions are presented in Table IV.

It should be emphasized that the mission of the NARADCOM personnel at Ft. Devens, MA in February 1973, was to establish the shapes of size categories. The sizing system was already established by the BRL work based on the anthropometric data from over 6600 soldiers and 500 Army aviators. The 106 subjects measured with the 3 D surface descriptor were sufficient to establish the statistics on each probe to be used in shaping. The average range for each probe reading was 1.25 inches over the entire population.
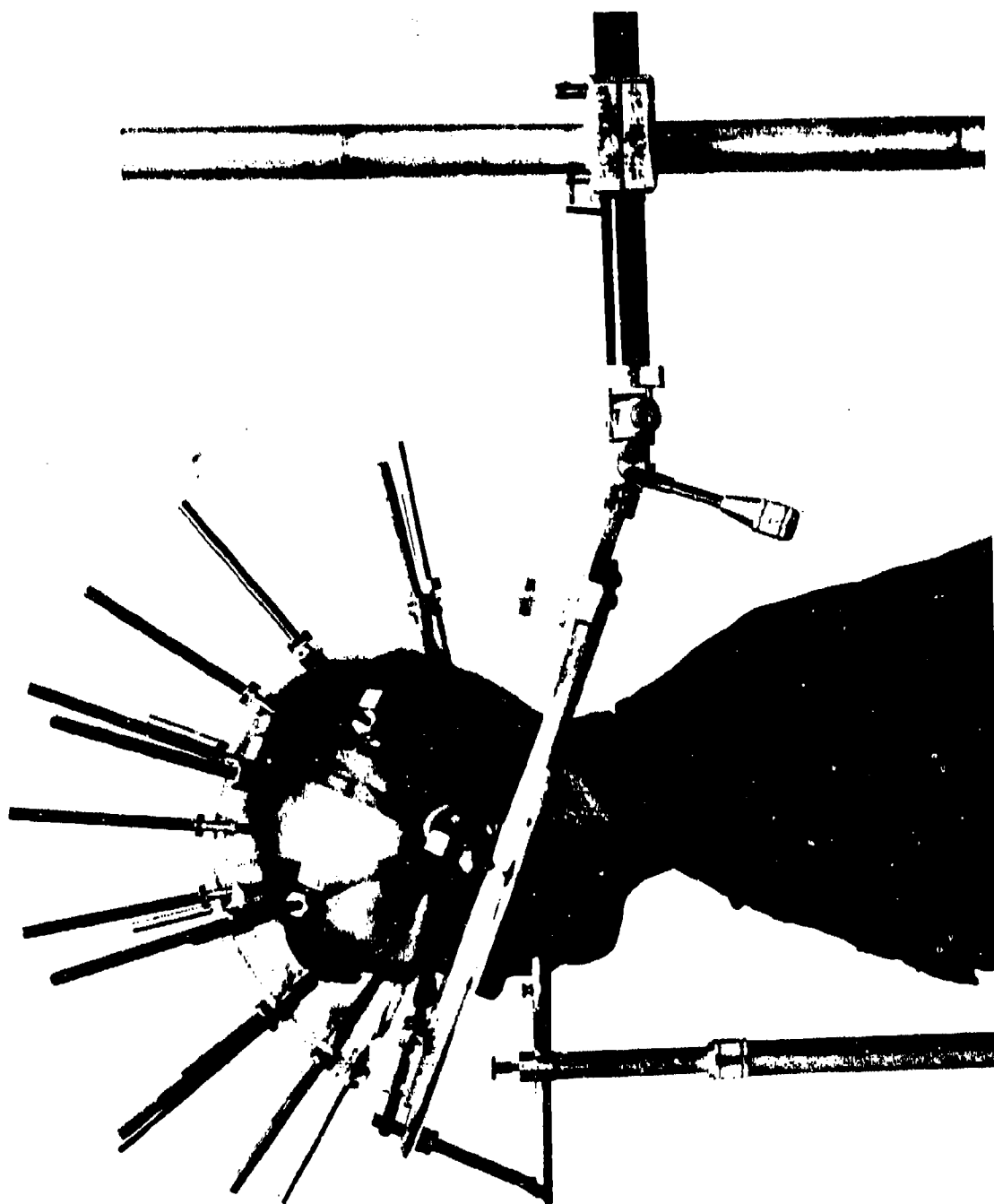
Figure 2. Head Contour Measuring Device

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Figure 3. Plaster Headforms

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TABLE III

PROBE READINGS USED BY THE SCULPTOR AND
RESULTING HEAD RAYS (mm)

Probe No.	Small Probe	Small Ray	Medium Probe	Medium Ray	Large Probe	Large Ray
1	56.6	69.8	58.8	72.0	56.6	69.8
2	65.0	78.2	68.3	81.5	71.9	85.1
3	85.3	99.0	87.1	100.8	92.2	105.9
4	65.5	78.7	66.6	79.8	73.4	86.6
5	56.4	69.6	55.1	68.3	56.4	69.6
6	89.2	103.1	92.2	106.1	100.3	114.2
7	94.7	108.6	95.8	109.7	102.6	116.5
8	106.2	121.8	108.2	123.8	114.6	130.2
9	107.7	123.3	108.7	124.3	115.8	131.4
10	111.5	127.1	112.3	127.9	120.7	136.3
11	112.0	127.6	113.5	129.1	120.7	136.3
12	107.4	123.0	109.7	125.3	117.1	132.7
13	83.3	97.0	86.4	100.1	90.7	104.4
14	91.7	105.6	93.7	107.6	100.8	114.7
15	93.7	108.5	96.3	111.1	101.9	116.7
16	73.9	87.8	74.9	88.8	83.6	97.5
17	99.3	114.9	101.6	117.2	110.0	125.6
18	76.2	90.1	79.0	92.9	88.9	102.8
19	88.1	102.0	92.2	106.1	101.1	115.0
20	83.1	96.8	84.1	97.8	90.9	104.6
21	90.7	104.6	92.0	105.9	99.6	113.5
22	90.4	105.2	91.7	106.5	99.6	114.4
23	72.4	86.3	72.9	86.8	81.5	95.4
24	98.6	114.2	98.8	114.4	106.7	122.3
25	76.5	90.4	74.9	88.8	84.3	98.2
26	87.9	101.8	90.7	104.6	97.8	111.7
27	72.9	86.4	77.2	90.7	85.3	98.8

TABLE IV

ANTHROPOMETRIC DIMENSIONS OF HEADFORMS* (mm)

Measurement	Small	Medium	Large
Arcs or Curvatures			
Head Circumference	555	572	602
Sagittal Arc	355	365	380
Minimum Frontal Arc	110	115	120
Bitragion-Coronal Arc	330	335	355
Bitragion-Crinion Arc	No measurement — no hairline		
Bitrag.-Min. Front. Arc	298	300	310
Bitragion-Subnasale Arc	285	290	290
Bitragion-Menton Arc	325	330	320
Bitrag.-Submandib. Arc	305	315	300
Bitragion-Inion Arc	No measurement over rigid ears		
Bitragion-Posterior Arc	No measurement over rigid ears		
Depths			
Head Length	195	200	209
Glabella-Wall	195	197	209
Sellion-Wall	195	196	209
Pronasale-Wall	225	229	239
Subnasale-Wall	208	214	222
Lip (Stomion)-Wall	209	217	224
Chin (Menton)-Wall	205	207	216
Larnynx-Wall	157	160	169
Ectocanthus-Wall	172	174	183
Tragion-Wall	101	101	109
Out. Canth.-Octobas. Sup.	72	79	75
Sellion-Tragion	96	107	107
Tragion-Ant. Chin Proj.	136	142	137
Head Diag., Inion-Pron.	195	199	212
Head Diag., Menton-Occ.	254	258	259
Breadths			
Head Breadth	151	158	169
Bitragion Breadth	148	149	149
Biauricular Breadth	200	201	207
Max. Frontal Breadth	103	110	113
Min. Frontal Breadth	92	98	100

TABLE IV

ANTHROPOMETRIC DIMENSIONS OF HEADFORMS* (mm)
(Continued)

Measurement	Small	Medium	Large
Heights			
Head Height (Trag-Vert)	120	122	129
Ectocanthus-Vertex	98	101	107
Glabella-Vertex	78	78	87
Sellion-Vertex	92	93	97
Pronasale-Vertex	130	132	139
Subnasale-Vertex	140	143	149
Stomion-Vertex	167	167	175
Menton-Vertex	209	213	215
Face			
Menton-Crinion	No measurement -- no hairline		
Face Length (Ment-Sell)	117	120	119
Menton-Subnasale	67	68	66
Chin Prominence	51	48	49
Face Breadth (Bizygom)	147	151	150
Bigonial Breadth	127	127	131
Biocular Breadth	99	103	106
Interpupillary Breadth	70	68	72
Interocular Breadth	32	35	36
Nose			
Nose Length (Sell-Subn)	51	56	55
Nasal Root Breadth	19	20	19
Nose Breadth (Interalar)	37	40	40
Nose Prominence	20	22	20
Mouth			
Philtrum Height	16	16	18
Lip-to-Lip Height	18	20	19
Mouth Breadth, Relaxed	56	57	59
Mouth Breadth, Smiling	No measurement -- no smile		
Ear			
Ear Length	77	75	76
Ear Length Above Trag.	32	34	34
Ear Breadth	38	39	40
Ear Protrusion	25	25	25

*Courtesy of Robert M. White, US Army Natick Development Center

Further, each probe range was subdivided into three size increments since the within-a-size probe data were used for shaping. A detailed report of the work on sizing and headforms is contained in Claus, McManus and Durand (1974).[6]

4. DETERMINATION OF STANDOFF DISTANCE

Simultaneous with the work on shapes and sizes of heads, other DARCOM Laboratories were conducting investigations to generate basic information pertinent to the design of the helmet. Studies included ventilation parameters, transient deformation, audio and visual envelopes, weapon and equipment compatibility as well as helmet weight perception and ballistic material evaluation. The transient deformation and heat transfer studies form the bases for selecting the proper standoff from the head.

The Bio-Physical Laboratories at Edgewood Arsenal, Edgewood MD conducted ballistic transient deformation evaluations on various helmet candidate materials.[7],[8] Transient deformation is defined as the maximum distance a given material will momentarily deflect when impacted by a missile of known mass fired at a non-penetrating velocity. This information was required in order to design the helmet with sufficient standoff from the head to protect against transient deformation impacts. The conclusion of these measurements is that a one half inch (1.3 cm) standoff is sufficient distance between the head and the helmet.

The heat stress problem was addressed by the Army Research Institute of Environmental Medicine (ARIEM). A fully instrumented "copper man", used to measure the insulation values and the vapor transmission coefficients of clothing systems, was used on the helmet problem. Descriptions of the test equipment and the methods used to evaluate ensembles are contained in Fonseca's survey report[9] of headgear. The physical model, the copper manikin, is sectioned with independent thermal controls so that the head alone can be considered the test section for headgear studies. The thermal characteristics of eight different helmets are shown in Table V. The designs vary greatly

[6] Claus, W.D., Jr., McManus, L.R. and Durand, P.D., "Development of Headforms for Sizing Infantry Helmets", Technical Report 75-23-CEMEL, U.S. Army Natick Development Center, Natick, MA, June 1974.

[7] Prather, R.N., "Transient Deformation of Military Helmet and its Injury Potential", Technical Report EB-TR-74028, Edgewood Arsenal, Aberdeen Proving Ground. MD, July 1974.

[8] Letter to NDC from Edgewood Arsenal dated 22 January 1974, Transient Deformation Resulting from Impacting Helmets, (Kevlar).

[9] Fonesca, G., "Heat Transfer Properties of Military Protective Headgear" Technical Report 74-29-CE, U.S. Army Natick Laboratories, Natick, MA, January 1974.

TABLE V

Thermal Characteristics of Selected Helmets-After Fonseca[9]

| Helmets | "Still Air" | | | 3 Meters/Second | | |
	CLO	im/CLO	im	CLO	im/CLO	im
Aircrew AFH-1	1.72	0.38	0.65	0.48	1.8	0.88
Aircrew APH-5	1.45	0.32	0.47	0.51	1.4	0.72
Standard CVC	1.28	0.36	0.46	0.43	1.9	0.83
English Infantry	0.97	0.45	0.44	0.37	1.9	0.70
Football Helmet	1.16	0.32	0.37	0.47	1.6	0.78
Experimental Hayes-Stewart	1.11	0.35	0.39	0.45	1.9	0.87
Italian Infantry	1.03	0.43	0.44	0.42	2.0	0.84
Experimental Parachutist Liner	1.36	0.37	0.50	0.54	1.5	0.81

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from the open English infantry helmet to the nearly closed aircrew helmet. The corresponding extreme Clo values range from 0.97 to 1.72 in still air.

Two important aspects of Fonseca's study are the effects of ventilation holes in helmets and the effects of increasing the percentage of the head covered by a helmet. By removing differing amounts of material from a helmet to provide ventilation and then measuring the thermal properties of the modified helmets, Fonseca concluded that such holes did not increase the evaporative heat transfer from the head in a practically significant way. Also, by systematically removing strips of material from an experimental shell, evaporative heat transfer was increased little until nearly 30% of the helmet was removed.

The insulation provided by the helmets listed in Table V is undesirable and should be reduced to increase comfort. On the other hand, the head is deliberately insulated by the "Cap, insulating, helmet liner", which provides 2.5 Clo, 0.27 im/Clo, 0.68 im. When worn with the M-1 helmet the thermal properties are 2.5 Clo, 0.14 im/Clo and 0.35 im.

Another design parameter which was systematically studied was the standoff required for optimum ventilation. Custom shells were vacuum-formed from sheet plastic with varying stand-off distances and the insulation values were measured.[9] The conclusion of these studies and the transient deformation study indicated that one half inch (1.3 cm) standoff was adequate to provide both optimum ventilation and protection against transient deformation using the most promising ballistic material (Kevlar).

The determination of the standoff distance represented the first helmet design parameter. NARADCOM was now able to have working helmet molds made over which helmets could be designed. The sculptor was given a new set of probe readings for the "working helmet molds" which represented the headform probe readings symmetrized with one half inch (1.3 cm) added to each reading. Symmetry was accomplished by selecting the larger reading of the paired left and right probes. The "working helmet molds" essentially represented the inside of future designed helmets.

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5. EDGE—CUT CRITERIA AND HELMET DESIGN

An example of the close cooperation and management of this program was manifested by the coordination of the Human Engineering Laboratories' work with Natick Research and Development Center's efforts. As the working helmet models were being made by NARADCOM, HEL was completing their work on vision, audition, weapon, clothing and equipment compatibilities and how they affect the edge-cut of a helmet. Although most of these studies are reported separately[10,11,12,13] the compounded effect is reported in a Summary of Infantry Helmet Edge Cut Criteria dated Nov 73.[14]

NARADCOM, with the assistance of HEL personnel, literally inscribed the edge cut criteria on the "working helmet molds". The molds then had a line of demarkation above which a helmet could be designed having maximum vision, audition, weapon, clothing and equipment compatibility; and below which a helmet design would interfere with one or more of an infantryman's operations or mission. (see Fig. 4)

An important factor in the helmet edge-cut criteria was that most of the ear and temple areas could be covered by the helmet. This extremely important point meant that helmets could be designed which could cover more of the head and this coupled with the low one half inch (1.3 cm) standoff would lower the center of gravity of the helmet. The resulting helmet design would of itself automatically reduce casualties and increase stability.

[10]Jones, R., Corona, B., Ellis, P., Randall, R., and Scheetz, H.,"Perception of Symmetrically Distributed Weight on Head", Technical Note 4-72, U.S. Army Human Engineering Laboratory, Aberdeen Proving Ground, MD, April 1973.

[11]Randall, R. Bradley and Holland, Howard H., "The Effect of Helmet Form on Hearing Free-Field Thresholds", Technical Note 5-72, U.S. Army Human Engineering Laboratory, Aberdeen Proving Ground, MD, April 1972.

[12]Randall, R., and Holland, H., "The Effect of Helmet Forming on Hearing: Speech Intelligibility and Sound Localization", Technical Note 10-72, U.S. Army Human Engineering Laboratory, Aberdeen Proving Ground, MD, September 1972.

[13]Sheetz, H., Corona, B., Ellis, P., Jones, R., and Randall, R., "Method for Human Factors Evaluation of Ballistic Protective Helmets", Technical Memorandum 18-75, U.S. Army Human Engineering Laboratory, Aberdeen Proving Ground, MD, September 1973.

[14]Summary of Infantry Helmet Edge-Cut Criteria, Progress Report HLR-7, U.S. Army Human Engineering Laboratory, November 1973.

Figure 4. Working Helmet Mold with Edgecut Inscribed

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NARADCOM personnel designed several helmet models and had the sculptor fashion these designs over the "working helmet molds". Since the final helmet would be compression molded, care was taken to eliminate any undercuts in the helmet design as well as have sufficient draft to insure ease of molding. All models were designed to provide maximum head coverage consistant with the edge-cut criteria. A panel selected the final helmet design consistent with all of the criteria developed under the program for prototype fabrication (Fig. 5).

6. SUSPENSION SYSTEMS

A suspension system is defined as that component of a helmet which comes in contact with the head; it supports and secures the helmet on the head. When a chin strap is used, it is considered a part of the suspension system.

Suspension systems are generally of three basic designs: cradle type, padded type, or combinations there of.

A cradle suspension consists of a circumferential band affixed to the helmet usually at 4 to 6 points with an over the head portion that suspends the helmet a given distance from the head. A cradle suspension usually provides for circumferential and height adjustments.

Pacded suspension systems usually consist of expanded elastomers (foams) filling all or part of the void between the head and the helmet. If adjustment is provided it is often by means of the addition or elimination of fitting pads.

In the past, NARADCOM has expended considerable effort investigating and developing suspension systems. The efforts included a survey of foreign military helmets as well as American sports and industrial helmets. In 1968, eight different cradle suspensions were developed under contract for the LINCLOE helmet. In 1969, a variable selective fitting pad suspension was developed in-house for the Hayes-Stewart helmet. Because of the interest and recommendation of the NCO board at Ft. Benning, GA this concept was later evaluated in the M-1 helmet. During this period, the Riddel air/liquid suspension system (used in professional football helmets) was investigated for adaptation to the M-1. In an attempt to product improve the M-1 helmet (1971-72), several versions of the Welson-Davis cradle suspension were evaluated. In 1973, four separate contracts were awarded to industry by NARADCOM to develop new and novel suspension systems for the M-1 Helmet. These contracts resulted in 10 concepts, 8 cradle types and 2 padded types.

Figure 5. Prototype Helmet Design

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Evaluated with the suspension systems were various crown and nape pads and chin straps. The chin straps were 2, 3 and 4 point attachments; they were under the chin type as well as closed and open chin cups. It was a two point attaching chin strap with an open chin cup that proved highly acceptable to the troops and was adopted in 1973 as standard for the M-1 helmet.

It is the consensus of government and industry experts that the cradle type suspension is the most practical for use in an infantry helmet. This fact, coupled with the design parameters (e.g. one half inch standoff) for the one piece infantry helmet, led to the development of a cradle suspension for the new helmet. The development incorporated many of the desirable features and design criteria of past suspension systems work. Those characteristics that would yield greater comfort, stability and safety were designed into the suspension.

The suspension system developed for the helmet was a replaceable cradle type in three sizes that was attached to the helmet with screws and threaded A-washers. The construction was primarily nylon webbing with a self-compensating drawstring adjustment at the top. The drawstring used a velcro tab for rapid height adjustment. The suspension was dimensioned to preclude contact of the helmet with the head under all conditions. The headband utilized velcro pile to prevent the headband clips from coming in contact with the head. The headband clips were of a new design with a positive lock to preclude release under impact. The leather covering of the headband is not sewn at the top, and overlaps the top of the headband itself. The chinstrap, a two point open chin cup, utilized pivots at the attachment points in order to provide better comfort and incorporated a new style buckle for easier adjustment. In general, the suspension system was designed to provide increased stability by having a high tension in the circumferential straps and uniform tension in the over-the-head straps; increased safety by minimizing the amount of interior hardware; and increased comfort by a combination of features of the headband and chinstrap.

7. FABRICATION OF MOCK–UP HELMETS

The scheduled HEL human factors evaluation required NARADCOM to fabricate 36 prototype helmets faithful to the design, weight and esthetic qualities of the selected model. Time and cost did not permit the building of matched metal compression molds so a unique fabrication technique was conceived. Since laminated Kevlar was the most promising ballistic material, the thickness and weight of the helmet made from this material was calculated for a 38 oz/ft^2 (11.6 kg/m^2) areal density. (The areal density of the M-1). The sculptor made male vacuum forming molds for each size helmet conforming to the inside surfaces of the helmets; and female molds which represented the outside surfaces of the helmets (actually the male mold plus .350 inches (8.9 mm) thickness). ABS molded shells were obtained from each respective mold. The male shell was placed into the female shell separated by spacers to give the desired 0.350 in. (8.9 mm) thickness. The volume of the resulting space was determined by filling with water. Knowing the weight of the inside and outside shells and the volume in between, the exact weight of the corresponding Kevlar helmet was obtained by filling the space with an epoxy resin

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with the proper specific gravity. 18 helmets, 6 in each size, were made at this weight. The MN requirements permitted a lighter helmet with protection equivalent to the M-1, so 18 helmets were made using a resin of lower specific gravity which resulted in helmets weighing approximately 12 to 14 ounces less than the epoxy filled mock-ups. These were equivalent to 30 oz/ft^2 (9.2 kg/m^2), areal density Kevlar helmets. All helmets were painted with a camouflage pattern.

The nylon, six point cradle-suspension system described in the previous section was fabricated and inserted into the helmets.

The helmets (Fig. 5) were delivered to the Human Engineering Laboratories, Aberdeen, MD in April 1974 for a 3 month human factors evaluation of the ground troop personnel armor system which included both weights of helmets and two new armored vests.

8. HUMAN FACTORS EVALUATION OF HELMETS AND BODY ARMOR

The results of the HEL evaluations are included in the Executive Summary of the final report[15] which is reproduced on the following pages. Table VI is a list of items with which the helmet was evaluated. The conclusions indicate that from a human factors point of view the design of the helmet is functionally successful and highly acceptable.

Human Factors Evaluation of Two Proposed Infantry Fragmentation Protective Systems[15]

OBJECTIVE

The objective of this research by the US Army Human Engineering Laboratory (HEL) was to compare (from a human factors point of view) two proposed infantry fragmentation protective systems (helmet and vest) with each other and with the M-1 helmet and the Standard B nylon fragmentation protective vest.

DISCUSSION

The helmets of the proposed systems have an identical edge-cut shape, and share a common sizing system, varying only in weight and projected level of protection. The vests of the proposed systems are identical in sizing, configuration and articulation with only weight and projected level of protection varied. System I can be considered as a system that provides ballistic protection equivalent to the Standard System with an increase in area coverage of the head

[15] Corona, Bernard M., et. al., "Human Factors Evaluation of Two Proposed Army Infantry/Marine Fragmentation Protective Systems", Technical Memorandum 24-74, U.S. Army Human Engineering Laboratory, Aberdeen Proving Ground, MD, October 1974.

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TABLE VI

HELMET COMPATABILITY LIST (AFTER REF. 15)

A. Individual Weapons

1. M16 Rifle
2. Saws (Squad Automatic Weapon System Contenders) (3)
3. M79 Grenade Launcher
4. M72 Antitank Rocket Launcher (Law)
5. I-Law (Improved Law Configurations)
6. M-47 Dragon
7. M203 Flame Rocket Launcher

B. Crew — Served Weapons

1. M60 Machine Gun
2. M67 90mm Recoilless Rifle
3. M2 50-Cal. Machine Gun
4. M40 106 mm Recoilless Rifle
5. M29E1 81 mm Mortar

C. Communication System

1. AN/PRT — 4A & AN/PRR-9 Squad Radios
2. AN/PRC-77 Radio Set, Individual Man-Packet
3. H-189/U Handset
4. H-144 Handset — Headset

D. Night Vision Systems

1. AN/PVS-5 Individual Goggles
2. AN/PUS-4 Individual Weapon Sight
3. AN/TVS-5 Crew-Served Weapon Sight
4. AN/TAS-3 Dragon Night Sight
5. AN/PAS-7 Thermal Intensifier

E. Other Vision Devices

1. M17 Binoculars
2. AN/GVS-5 Monocular/Laser Range Finder
3. Anti-Laser Goggles (Various Laser Protective Goggles)

F. Other Worn Systems

1. M17 CB Protective Mask
2. Prototype CB Protective Masks (3)
3. LINCLOE Pack Frame

of 11.6 percent (average), and an increase in area coverage for the torso of 5 percent (average). System II can be considered as a system that provides increased ballistic protection at slightly less weight than the Standard System with increases in area coverage identical to System I.

1. Proposed System I (Equivalent Protection)

a. Helmet — Single-piece resin-reinforced Kevlar body (facsimile) with a modified M—1 suspension, two-point chin strap and provided in three sizes: small, medium and large, weighing 1.14 kg, 1.19 kg, and 1.25 kg, respectively.

b. Vest — Articulated Kevlar fabric, 6-ply, nominal 14 oz/yd^2 (475 g/m^2) with snapped pivot shoulders, Velcro front closure and elastic constant-coverage slide closure and provided in four sizes: small, medium, large and extra-large weighing 2.39 kg, 2.61 kg, 2.93 kg, and 3.15 kg, respectively.

2. Proposed System II (Increased Protection)

a. Helmet — Single-piece resin-reinforced Kevlar body (Facsimile) with a modified M—1 suspension, two-point chin strap and provided in three sizes: small, medium and large, weighing 1.46 kg, 1.52 kg, and 1.69 kg, respectively.

b. Vest — Articulated Kevlar fabric 11-ply, nominal 14 oz/yd^2, with snapped pivot shoulders, Velcro front closure and elastic constant-coverage side closure and provided in four sizes: small, medium, large and extra-large, weighing 3.47 kg, 3.83 kg, 4.16 kg, and 4.64 kg, respectively.

3. Standard System III (Equivalent Protection Standard)

a. Helmet — M-1 Hadfield steel body with ballistic nylon liner, a standard suspension, and the improved two-point chin strap. This helmet is made in only one size weighing 1.46 kg.

b. Vest — Standard B, nylon, single-piece, provided in four sizes: small, medium, large, and extra-large, weighing 3.52 kg, 3.97 kg, 4.82 kg, and 4.88 kg, respectively.

The systems were compared by means of eight procedures:

1. Items were classified as to physical characteristics and design features.

2. Anthropometric measurements were taken of men, then each system was assessed as to adequacy of fit for selected environmental clothing ensembles and assault load-carrying ensemble.

3. Measurements were made which show movement characteristics of each system on the body of the wearer.

4. Compatibility assessments were conducted using a variety of infantry-operated systems and equipment ranging from shoulder-launched rockets, communication equipment, and crew-served weapons, to night-vision sights and goggles.

5. Men wearing each system plus an assault load participated in exercises on the HEL mobility/portability course which simulate body movements and postures made in typical tactical situations.

6. Rifle and machine-gun firing behavior was examined with each system in conjunction with load-bearing equipment.

7. User acceptance was estimated from subjective comments of individuals and subjective comments of a consumer panel.

8. In addition to the above procedures which compared total systems, a separate and limited evaluation was performed on the acoustical characteristics of the proposed helmets.

CONCLUSIONS

Systems I and II — These two helmet vest systems can be considered a successful solution, ergonomically, for use by the infantrymen. Improvements accruing from sizing systems, for both helmet and vest, helmet balance, area coverage, body-system interaction, compatibility with selected infantry employed weapons, equipment systems, mobility and soldier acceptance far outweigh the limited number of negative findings.

System III — This system cannot be considered an acceptable solution, ergonomically, for use by the infantryman. The many problems occurring with this system — the lack of sizing for the helmet, outdated sizing for the vest, helmet instability, poor area coverage, and negative body-system interactions — result in an overall poor rating by the subjects.

RECOMMENDATIONS

Systems I and II — There is sufficient evidence to indicate that either of these two systems is superior across evaluation areas which warrant their consideration as a replacement for the M-1 Steel Helmet and Standard Nylon Fragmentation Protective Vest. From a human factors standpoint they appear to be equal choices. In the body of the report we point out the advantages and disadvantages of weight between these systems as revealed by our measures

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of human performance and user acceptance. The ultimate choice will be based on trade-off analyses which will include physiological stress, casualty reduction, cost effectiveness, logistics supply, and Infantry Community requirements. One factor in the helmet design and one factor in the vest design can be considered as human factor trade-offs which may be manipulated without impacting on major system design. The area for the helmet is the protective skirt, defined as that area of the helmet that projects below the lower edge of the crown band and is presently configured at the maximum lower limit in depth and the maximum lateral limit in width. The area for the vest is the collar. The collar covers a minimal area and is one-half the ply weight of the vest body. This single item (collar) causes a majority of helmet/vest interactions and should be considered for removal. Aside from the selection of component weight and the design factors mentioned above, the changes to the systems which are suggested in the body of this report will correct the problem areas identified.

9. LARGE SCALE FITTING TEST

The small fitting test run during the HEL evaluation on 36 subjects did not reveal any major sizing problems. However, before investing a large amount of time and money in obtaining armor items, a verification fitting test was performed in July 1974 at Ft. Devens, MA.[16] Over 400 subjects from the 10th Special Forces were measured, fitted and helmet standoff determined.

The method used to verify the sizing criteria of the helmets was to vacuum form clear plastic shells over the male molds used in the fabrication of the HEL test helmets. Thirteen probe holes were drilled at key locations and suspensions inserted into the shells.

The subject's heads were anthropometrically measured, their sizes determined according to the sizing criteria and then fitted to the corresponding sized helmet (see Table VII).

[16]McManus, L.R., Claus, W.D., Durand, P.E., and Kulinski, M., "Verification Fit Test of Three Size Infantry Helmet", Technical Report 75-79-CEMEL U.S. Army Natick Development Center, Natick, MA, January 1975.

TABLE VII

Helmet Sizing Criteria

Size	Head Dimension (mm)		
	Circumference	Length	Breadth
Small	555	193	151
Medium	576	200	159
Large	611	210	166

Instruction: A subject whose measurement is plus in any dimension will move to the next larger size.

With the helmet fitted properly, the standoff was determined at the 13 probe stations of the helmet shell. The test concluded that the tariff of sizes for the helmet system was 20%, 50% and 30% respectively for small, medium and large and that 95% of the probe readings were equal to or greater than the designed one half inch (1.3 cm) standoff for the helmet.

The 5% of the probe readings less than one half inch (1.3 cm) averaged .40 inches (1 cm). Consequently, the helmet developers modified or rather "fine tuned" the final master molds to compensate for this small disparity.

New master helmet models were made incorporating HEL recommended periphery changes and the Fit Test "fine tuning". The ear section of the helmet was flared directly into the frontal opening. These changes were made to facilitate the use of weapons and communication devices with the new helmet even though the test helmet was more compatible with these items than was the M-1 System. (see Fig. 6)

The master models represent the inside surfaces of the new helmets and were used by the mold maker to fabricate a set of production matched metal molds.

10. CONCLUSIONS

With the final set of master models, the helmet design program was complete. Matched metal molds were procured, and helmets were successfully manufactured for DT-II/OT-II testing (Fig. 7). The results of those field tests will be reported in a future document.

The objectives of the helmet program were met. The philosophy and plans of the helmet program were followed in detail and every feature of the helmet design was documented. The new helmet design in three sizes fit the 1st to the 99th percentile
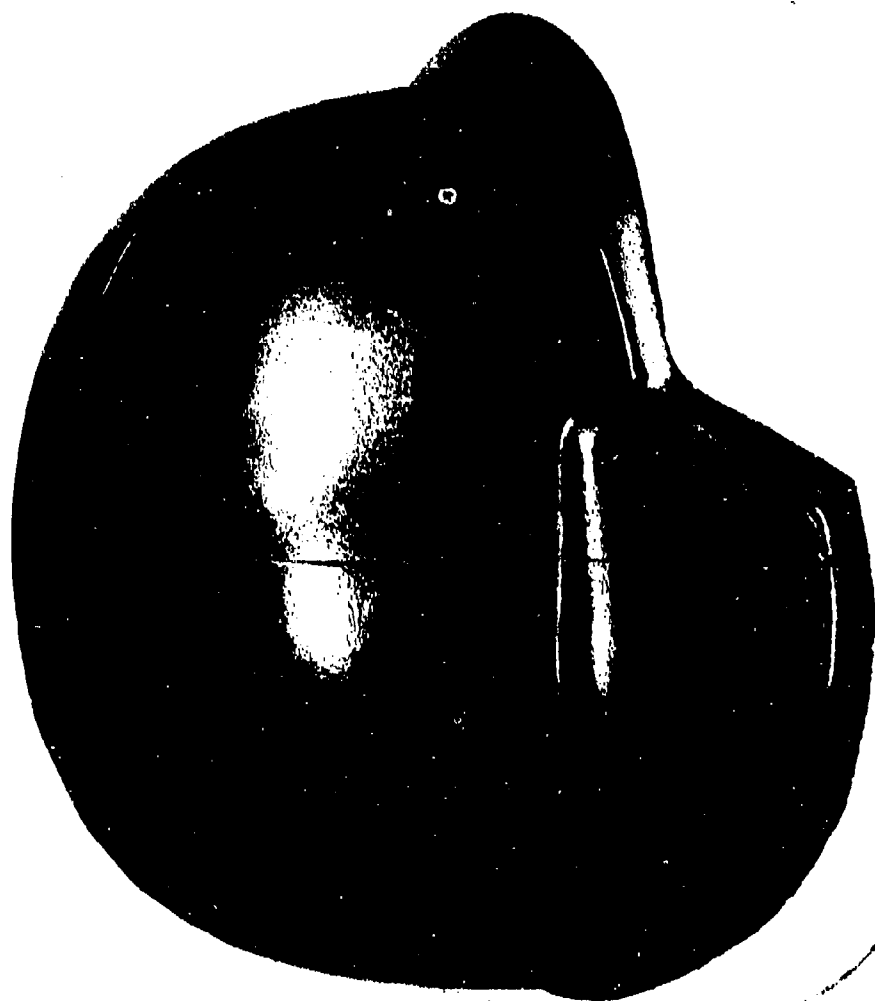
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Figure 6.   Master Model of Final Design

Figure 7. Compression Molded Helmet

of the U.S. Army population. The helmet was comfortable and stable, covered more of the head, and provided more ballistic protection than the M-1 steel shell and nylon liner.

Generalized shaped headforms representing the U.S. Army population were developed. Baseline helmet data and evaluation and measuring techniques were established which can be used in the development of any future helmet.

ACKNOWLEDGEMENTS

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2. McManus, L.R., "Protective Helmets of NATO and Other Countries", Technical Report 72-29-CE, US Army Natick Laboratories, Natick, MA, January 1973.

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Abstract -- The heat transfer properties of headgear have been determined in chamber studies using a physical model (copper manikin). The evaporative head transfer (im/clo) from a head in "still" air was constant above a standoff distance of 1.27 cm. for helmets with a constant head area coverage (67%). Reducing the head area coverage from 67% to 50% was necessary to increase the evaporative heat transfer for a helmet standoff distance of 1.27 cm. The effect of wind on the heat transfer properties of selected headgear with varying designs was to decrease the values of insulation (clo) by about 60% and increase those for the evaporative heat transfer (im/clo) by about 4 times the "still" air values.

10. Jones, R., Corona, B., Ellis, P., Randall, R., and Scheetz, H., "Perception of Symmetrically Distributed Weight on Head", Technical Note 4-72, U.S. Army Human Engineering Laboratory, Aberdeen Proving Ground, MD, April 1973.

Abstract — Thirty-eight enlisted men, 18 Ordnance and 20 Infantrymen, judged whether experimentally weighted helmets were heavier, lighter or the same weight as the referenced M-1 Helmet. The findings indicate a lower difference threshold of 2.0 pounds and an upper difference threshold of 3.85 pounds for the combined groups. The Ordnance groups lower difference threshold was 2.25 pounds, while the Infantry groups lower threshold was 1.8 pounds. The differences were statistically significant. It was concluded that complaints about the present helmet being "too heavy" are not based on particularly accurate perception of weight on the head and that Infantrymen are not as accurate in their judgments of weight on the head as the soldier with less field experience with the M-1 Helmet.

11. Randall, R. Bradley and Holland, Howard H., "The Effect of Helmet Form on Hearing Free-Field Thresholds", Technical Note 5-72, U.S. Army Human Engineering Laboratory, Aberdeen Proving Ground, MD, April 1972.

Abstract — Audiometric thresholds were determined for 12 subjects under three head conditions: bareheaded, while wearing an M-1 Helmet, and wearing an experimental helmet. The thresholds were measured for seven tones: 125, 350, 500, 1000, 2000, 4000, and 8000 Hz, at each of five angular orientations. Statistically significant differences were found for all main effects and interactions. The experimental helmet was not significantly different between head conditions. The differences

are of little practical significance, however, since they fall within the range of variation most people experience on a day-to-day basis.

12. Randall, R., and Holland, H., "The Effect of Helmet Forming on Hearing: Speech Intelligibility and Sound Localization", Technical Note 10-72, U.S. Army Human Engineering Laboratory, Aberdeen Proving Ground, MD, September 1972.

Abstract — This report presents the results of an investigation of the effects of a standard and of an experimental helmet on speech intelligibility and sound localization. Eight enlisted men with no hearing deficits were used as subjects. Intelligibility was tested with the American Standard Method for Measurement of Monosyllabic Word Intelligibility. Localization error was determined for three groups of noise bands one octave wide with center frequencies of 250, 2000 and 8000 Hz. There were no practical differences between the two helmets, nor between the bareheaded and helmeted conditions with either helmet.

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Abstract — Several experiments and surveys were conducted to learn more about the relationship between helmet weight, shape and suspension for ballistic protective helmets. Surveys were conducted to develop rating scales suitable for field testing. Experiments were conducted using the rating scales as the dependent variable. Design guidance and testing methodology are suggested for development and for human factors evaluation for future ballistic protective helmets.

14. Summary of Infantry Helmet Edge-Cut Criteria, Progress Report HLR-7, U.S. Army Human Engineering Laboratory, November 1973.

15. Corona, Bernard M., et. al., "Human Factors Evaluation of Two Proposed Army Infantry/Marine Fragmentation Protective Systems", Technical Memorandum 24-74, U.S. Army Human Engineering Laboratory, Aberdeen Proving Ground, MD, October 1974.

Abstract — A human factors engineering test of two proposed Army infantry/marine fragmentation protective systems (helmet and vest) was conducted by the U.S. Army Human Engineering Laboratory (HEL). The test systems were compared with each other and the current standard system. Comparisons made included physical characteristics, sizing system accommodation, compatibility with selected environmental clothing systems, and with selected infantry-employed weapons/equipment under static and dynamic situations. Thirty-three

enlisted personnel, MOS 11B (Light Weapons Infantryman), performed an infantry assault scenario on the HEL Mobility/Portability Course using each test system. Objective performance measures were overall time and discrete obstacle time. Subjective measures were rating scales and user panel discussions. These thirty-three infantrymen and an additional twenty-two infantry men (MOS 11B) participated in compatibility assessments of a wide range of infantry-employed weapons and equipment. The results yielded many points of contrast between the proposed systems and the current system. Significant differences were found in both the objective and subjective evaluations between the proposed systems and the standard system. The proposed systems can be considered successful solutions, ergonomically, for use by infantrymen. No significant differences were found between the two proposed systems.

16. McManus, L.R., Claus, W.D., Durand, P.E., and Kulinski, M., "Verification Fit Test of Three Size Infantry Helmet", Technical Report 75-79-CEMEL U.S. Army Natick Development Center, Natick, MA, January 1975.

Abstract — This report presents the statistical analysis of data generated by a fitting test of a 3 size infantry helmet system. The report includes analysis of anthropometric head data over the total population of 414 test subjects as well as with in the context of sizing criteria for the three helmet. In addition, the report presents an analysis of helmet stand-off from the head as compared to a designed minimum stand-off of one half inch. The tariff of sizes established by the study is 20%-50%-30% for the size small, medium and large respectively. Ninty-five percent of all probe readings meet the minimum stand-off of ½ inch.

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Abstract — A computer model to aid in the evaluation of body armor has been developed at the U.S. Army Materiel Systems Analysis Agency. The program, coded in Fortran II and IV, may be used as a tool for obtaining the potential casualty reduction of body armor. A program listing and a sample of input and output as well as flow charts are shown.

18. Young, Annie L., "Helmetran Computer Model", Technical Memorandum No. 171, U.S. Army Materiel Systems Analysis Agency, Aberdeen Proving Ground, MD, March 1973.

Abstract — A computer model used in the evaluation of helmets has been developed by the U.S. Army Materiel Systems Analysis Agency. The computer model, coded in Fortan II and IV, is described herein. Also included are program listing, flow chart and program input/output data.

19. Mascianica, Francis S., "Ballistic Technology of Lightweight Armor — 1973", AMMRC TR 73-47. Classified Confidential, U.S. Army Materials and Mechanics Research Center, Watertown, MA, November 1973.

Abstract (U) — This handbook is an updated compendium of ballistic information on the efficiency of various types of homogenous and composite armor materials impact by American, Soviet, and Communist China kinetic energy ammunition. An analysis is made of terminal ballistic data on armor-piercing, ball, and tungsten carbide cored ammunition ranging from 5.56 mm up to 122 mm in size as well as with fragment-simulating projectiles weighing up to 830 grains. Master ballistic curves are drawn as a function of armor thickness or areal density, obliquity, projectile velocity, and environmental parameters which are of significant importance when designing armor systems against a specific projectile threat. Projectile range-velocity characteristics are also documented. The ballistic analysis of various candidate armors represents the type of information required on a continuing basis by the Army Aviation Systems Command, Army Materiel Command, Combat Developments Command, armor designers, vulnerability analysts, and by other Department of Defense agencies. This document contains appropriate master ballistic performance graphs.

APPENDIX A

BALLISTIC MATERIALS

1. Ballistic Evaluation Methodology (by Thomas M. Keville, CE&MEL)

The ballistic limit or V_{50} has been employed since World War I as the principal technique to rank the protective capabilities of candidate materials for personnel armor applications. The V_{50} is by definition the velocity at which there is a .50 probability of a projectile completely penetrating a material. For two armor materials of the same areal density, the one with the higher V_{50} is considered the more protective material.

Although this is a traditionally recognized and accepted method of assessing differences between armor materials, it is of limited value in determining the effectiveness of a material in a tactical situation against immediate and future threats. Our real interest is in the velocity of the projectile after penetration of the armor. This has led to the determination of the residual velocity/striking velocity relationship at velocities higher than the ballistic limit. Now materials can be compared over an entire range of striking velocities. Frequently, however, the V_s/V_r curves across. A material which provided lower residual velocities at the lower striking velocities, sometimes yields higher residuals as the striking velocity is increased. Hence, the choice of materials is not clear and additional data is needed by the decision maker.

To fully characterize the ballistic protective capabilities of a material against fragmenting munitions, it would be desirable to fire actual fragments at the test samples from a wide range of obliquities. However, the process is expensive, time consuming and the distribution of the fragment size and striking orientation make it difficult to obtain consistent and reproducible data. This problem has been simplified by the correlation of the results of actual fragment firings with various shapes of fragment simulators.

Using simulators, V_s/V_r data representative of actual fragment impacts are generated. Presently, 2, 4, 16 and 64 grain masses at 0 and 45° obliquity are fired.

The ballistic data are input to a computer program to determine the regression coefficients that provide the best fit to the "Johnson Equation". This equation is used in the casualty reduction programs to predict the residual velocity of a projectile when the regression coefficients, the striking velocity, the obliquity angle, and the fragment area to mass ratio are known.

The two computer programs which are used to determine the casualty reduction potential of armor materials were developed by the Army Material Systems Analysis

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Activity. They are referred to as ARMORTRAN[17] and HELMETRAN.[18] The models determine the expected number of casualties through simulation of a shell bursting within range of vulnerable targets.

The program locates a target at a point relative to the burst in terms of range and angle from the nose of the shell. The range fixes the presented area of the target; the angle determines which group of fragments are likely to reach the target. Next, the probability of a hit in each of six body parts is calculated. Given a hit, the probability of sustaining a wound in an unarmored area is determined directly from the casualty criteria for each anatomical part. The criteria considers the mass and velocity of the striking fragments. The wounding probability in the protected or armored areas are determined in the same manner except that the residual velocity as calculated from the Johnson equation is used in the casualty criteria. By summing, the total probability of a soldier in that location becoming a casualty from the explosion of the munition is established. By repeating this process for all potential identical targets, the expected number of casualties is determined. The results of this analysis will show the difference in ability of two materials and/or designs to reduce casualties against the simulated threats.

In summary, the older and less expensive ballistic limit, V_{50}, will continue to be used for screening of candidate armor materials. However, the ultimate selection of any material for personnel armor applications will be made only after full consideration of the material's casualty reduction potential.

[17]Young, Annie L. and Kelly, Mary Ella, "Armortran: A Computer Model for Evaluating Body Armor Systems," Technical Memorandum No. 126, U.S. Army Materiel Systems Analysis Agency, Aberdeen Proving Ground, MD, January 1972.

[18]Young, Annie L. "Helmetran Computer Model," Technical Memorandum No. 171, U.S. Army Materiel System Analysis Agency, Aberdeen Proving Ground, MD, March 1973.

2. Material Evaluations (by Roy C. Laible, CE&MEL)

Continuous evaluation of potential materials for helmet and body armor applications is a major activity within CE&MEL. Ballistic evaluations have been going on for many years under many programs.[19]

Materials such as titanium, Hadfield Steel, ABS, PPO, Nylon, XP and polycarbonate have all been considered for use in a rigid helmet. Of these materials, Hadfield steel was accepted into the system early in the 1940's and the main change since then has been the substitution in 1958 of a nylon helmet liner for the cotton one previously used. This helmet system gives excellent protection against fragments of moderate size and velocities emanating from grenades, rockets and mortar shells. It provides hand gun protection but was never intended to provide protection against rifle fire and does not do so.

The all organic material helmets such as Lexan, ABS and nylon were considered mainly in connection with the LINCLOE system for the preparation of lighter weight Army Items. At these lighter weights, the organic materials provided too little ballistic protection.

The principal serious contender as a substitute for the Hadfield steel shell in the past was a titanium alloy. But it, too, did not yield improved casualty reduction values.

More recently, the primary contenders for a one-piece, laminated helmet are two fibrous materials, fiberglass and a new high strength organic fiber named Kevlar. Kevlar is thought to be the condensation polymer of paraphenylene diamine and terephthalic acid. It is, therefore, a fairly good analog to nylon with repetitive amide groups but with the aromatic rings substituted for the methylene groups characteristic of nylon. The fiber has a strength double that of any organic fiber previously seen, a modulus as high as glass and a heat resistance which would allow it to be heated to the melting point of ordinary nylon while still retaining a good portion of its original strength. The Kevlar was tested in unlaminated form against many kinds of missiles and casualty reduction analyses performed. The advantages of this new material over currently available materials were obvious. The material was then pre-pegged with phenolic modified polyvinyl butyral

[19] Mascianica, Francis S. "Ballistic Technology of Lightweight Armor 1973", AMMRC TR 73-47 Classified Confidential. U.S. Army Materials and Mechanics Research Center, Watertown, MA, November 1973.

and laminated into flat panels. Many ballistic evaluations and casualty reduction analysis were conducted on these flat laminates, the results of which confirmed the superior performance of Kevlar. In a parallel effort prepregged Kevlar was formed into complex shapes and finally into helmets. Limited ballistic tests were conducted on the helmets themselves to confirm the good results obtained with the flat laminates. The results showed that Kevlar laminates show every indication of meeting the MN with its required improvement over the M-1 helmet.

Glass fabric was pre-pregged with polyester resin and prepared into flat laminates. The interest in glass stems from its relatively low cost. Evaluation of the ballistic qualities of the glass laminates showed that they also have a potential for providing a considerable improvement in protection over that offered by the M-1. However, this potential for improvement is less than that of Kevlar.

Comparative mechanical tests were also conducted on Kevlar and fiberglass laminates in an effort to determine their relative durability in field use. A summary of the results of these studies follows:

a. The interlaminar shear strength of 38 oz/ft^2 (1.16 g/cm^2) Kevlar laminates averages 3500 psi (24 MPa) as contrasted with 1400 psi (9.7 MPa) for glass laminates of same areal density.

b. The tensile strength of Kevlar is 64,000 psi (440 MPa) while the glass laminate averages only 38,000 psi (260 MPa).

c. In bending experiments the absolute force to bend a 38 oz/ft^2 (1.16 g/cm^2) glass laminate is 100 pounds (45 kg) or less for a one inch strip as contrasted with 150 pounds (68 kg) for a Kevlar laminate of exactly the same areal density and strip width. However, the greater thickness of the Kevlar laminate compared to that of the glass at the same areal density is important in this practical comparison. In engineering terms, the glass laminate is calculated to have the higher bending modulus (3,000,000 vs. 1,400,000 psi or 21,000 vs. 9,600 MPa) and maximum stress (26,900 vs. 16,000 psi or 185 vs. 110 MPa).

d. Multiple bending (cyclic) causes yielding of the Kevlar and of the glass. The difference is that after the Kevlar yields in the first cycle it can sustain additional cycles (1000) without catastrophic fracture. This is not true of the glass which has essentially reached total failure after 20-30 cycles.

e. Tests were conducted in the field at HEL to determine the relative durability of glass and Kevlar helmets under extremely difficult service conditions (digging with helmet, dropping, etc.). The helmets after such treatment showed greater damage to the

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glass helmets than to the Kevlar ones, which is consistent with differences indicated by the laboratory tests described in paragraph c above.

The ballistic data on the fiberglass and Kevlar laminates are contained in classified reports.[20],[21]

[20] Keville, Thomas M., Denommee, Maurice R. and Laible, Roy C., "Evaluation of Kevlar 29 Laminates as a Material for Infantry Helmets", Technical Report 75-26-CEMEL. Classified Confidential. U.S. Army Natick Laboratories, Natick, MA, October 1974.

[21] Denomee, Maurice R., Keville, Thomas M., Jr., and Laible, Roy C., "Comparative Ballistic Performance of Fiberglass and Kevlar Laminates", Technical Report 75-119-CEMEL. Classified Confidential. U.S. Army Natick Development Center, Natick, MA, June 1975.