Phase I

in the

DEVELOPMENT OF CRITERIA FOR INDUSTRIAL AND FIREFIGHTERS' HEAD PROTECTIVE DEVICES

Work Performed By
Dayton T. Brown, Inc.
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Results are presented of a research project to develop criteria for a performance standard, a testing standard, and a users' standard for industrial and firefighters' head protective devices. Adequate industrial and firefighter head protection necessitates the use of four distinct levels of protection, the use of protective devices depending on the occupational hazard. A human head injury index, the Head Injury Criterion, is applied as an impact performance evaluation technique, and the test methods, equipment and procedures necessary for accurate measurement are developed. Recommendation is made for further research in developing protective equipment and evaluation techniques.

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FOREWORD

This research project was conducted by Dayton T. Brown, Inc., under contract HSM-99-72-86 for the Division of Laboratories and Criteria Development, National Institute for Occupational Safety and Health (NIOSH), Department of Health, Education, and Welfare. Technical monitoring of the work and editing of the report was provided by Jeff I. Kamin of the Engineering Branch.

This report has been reviewed by NIOSH and has been approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of NIOSH, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

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Introduction

This report contains the findings of a project designed to insure that the American worker is provided with a means of head protection which will substantially reduce the probability of serious head injury in environments of known high risk.

Towards this end, on the basis of the criteria contained in this document and subsequent experimental work a series of standards for industrial and firefighters' head protective devices will be developed. These will constitute: (a) a performance standard which lists the attributes and levels of performance for four classes of industrial head protective devices, (b) a testing standard, which describes test methods, procedures, and equipment for each attribute to be tested, and (c) a user standard which describes how industrial and firefighter's head protective devices are to be properly selected, used, and maintained.

Though accident prevention is the most certain method of preventing accidental head injury, with the use of the levels of head protection developed by this study, both the frequency and severity of head injury to the industrial worker and firefighter may be reduced.

Current Regulation of Head Protection

The need for adequate forms of head protection is presently recognized by the U.S. Department of Labor. The regulation of head protective devices as noted in the Code of Federal Regulations, Title 29, Chapter XVII, is as follows:

(a) Part 1915 – Safety & Health Regulations: Ship Repairing.
- 1915.83 – Head, Foot and Body Protection.

(b) Part 1916 – Safety & Health Regulations: Shipbuilding.
- 1916.24 – Painting.
- 1916.83 – Head, Foot and Body Protection.

(c) Part 1917 – Safety & Health Regulations: Shipbreaking.
- 1917.83 – Head, Foot and Body Protection.

(d) Part 1918 – Safety & Health Regulations: Longshoring.
- 1918.105 – Head Protection.

(e) Part 1926 – Safety & Health Regulations: Construction.
- 1926.100 – Head Protection.
- 1926.300 – General Requirements.
- 1926.551 – Helicopters.
- 1926.650 – General Protective Requirements.
- 1926.800 – Tunnels and Shafts.
- 1926.951 – Tools and Protective Equipment.

(f) Part 1910 – Occupational Safety and Health Standards, Subpart I, Personal Protective Equipment.
- 1910.132 – General Requirements.
- 1910.135 – Occupational Head Protection.

(g) Part 1910 – Occupational Safety and Health Standards, Subpart R, Special Industries.
- 1910.261 – Pulp, Paper, and Paperboard Mills.
- 1910.262 – Textiles.
- 1910.265 – Sawmills.
- 1910.266 – Pulpwood Logging.

Evaluation of the Needs of Industrial Head Protection

The Occupational Head Injury Accident

The Frequency and Severity of Head Injury

The National Safety Council reports [1]* that in 1971, there were 160,000 occupational head, face, and neck (excluding eye) injuries which accounted for 7 percent of all injuries and 8 percent of workmen's compensation paid.

To serve as an aid in the development of standards for industrial and firefighters' head protective devices, calculations of injury frequency rates and injury severity rates have been made for all industries, with respect to head injury.

The State of New York was chosen for the analysis. New York has a population of approximately 18 million and a wide range of industries. In addition, information necessary to correlate accident statistics with labor statistics, by industry classification was available.

In the United States, most individual states tabulate accident cases as needed to implement workmen's compensation programs. The methods used vary from state to state and cross checking or accumulation of data is often impossible.

Accident data for 2,564 head injuries ($6,931,568 compensation) from the State of New York for 1970 [2] was tabulated by electronic data processing methods as follows:

- Industry by extent of disability
- Industry by number of cases and compensation awarded
- Occupation - Number of cases and compensation awarded
- Accident agency by type of accident (number of cases)
- Accident agency by type of accident (compensation awarded)

These data, from the files of compensated cases closed during 1970, were used in the calculation of Head Injury Frequency Rate (HIFR) and Head Injury Severity Rate (HISR). HIFR and HISR follow the method as set forth in ANSI Z16.1–1967 [3] for Disabling Injury Frequency Rate and Disabling Injury Severity Rate. The number of head injuries and total days charged per head injury were substituted for the total number of injuries and total days charged, respectively.

The Head Injury Frequency Rate and Head Injury Severity Rate have been therefore calculated as:

- $$\text{Head Injury Frequency Rate} = \frac{\text{Number of Head Injuries} \times 1{,}000{,}000}{\text{Employee Hours of Exposure}}$$
- $$\text{Head Injury Severity Rate} = \frac{\text{Total Days Charged} \times 1{,}000{,}000}{\text{Employee Hours of Exposure}}$$

Total days charged were computed by determining the dollars earned per employee per day from the Bureau of the Census "taxable payrolls" for the first quarter of 1970 and assuming this constant for the year. By dividing the dollars compensation awarded to a particular industry by the dollars earned per employee per day, a "Total Days Charged" was found.

The Head Injury Frequency and Severity Rates for the 64 industries studied is presented in Table 2.

The accident data used for calculation of these rates was checked against national head injury figures. The New York State data show total compensated cases closed as 117,100 cases. Therefore, 2.2 percent of New York State accidents are head injuries of the following types:

- Brain injuries (916 cases)
- Skull and scalp injuries (809 cases)
- Ear injuries (357 cases)
- Head injuries not otherwise classified (482)

These cases accounted for 2.5 percent of the total compensation for the State. The percent of injury compared with the percent of compensation ratio is equivalent for the National Safety Council (7 percent 8 percent) and the New York State (exclud-

*Numbers in brackets designate references.

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ing face and neck) of 2.2 percent 2.5 percent. In New York there were 11,907 head, face, and neck injuries (excluding eyes) which represent 9 percent of the total cases. This compares favorably with the 13 state National Safety Council average of 7 percent.

The 2,564 head injury cases were reported from 64 industries and were tabulated by Standard Industrial Classification Manual Codes (SIC) [4] and are shown in Table 1.

To obtain the value of employee hours of exposure needed for HIFR and HISR calculation, an assumed average of 2,000 hours worked per year was multiplied by the number of employees in that particular industry. Employment values were taken from Bureau of the Census figures [5].

Table 1. Head injuries, compensated cases closed, New York, 1970

SIC code	Industry	Number employed	Number of head injuries	Dollars compensation
07	Agricultural services, forestry, fisheries (Agricultural services and hunting)	9,003	12	66,365
10	Mining, Metal Mining	1,818	1	2,612
14	Non-metallic minerals, except fuels	3,601	1	57
15	Contract Construction, General building contractors	58,062	80	279,826
16	Heavy construction contractors	29,583	54	109,076
17	Special trade contractors	147,630	178	666,177
20	Manufacturing Food and kindred products	106,815	95	351,299
22	Textile mill products	50,625	22	35,059
23	Apparel and other textile products	277,339	46	144,325
24	Lumber and wood products	14,611	17	176,459
25	Furniture and fixtures	33,101	18	59,085
26	Paper and allied products	59,637	32	118,881
27	Printing and publishing	177,347	39	92,972
28	Chemicals and allied products	62,009	21	14,157
29	Petroleum and coal products	2,573	4	4,160
30	Rubber and plastics products, n.e.c.	33,487	11	4,360
31	Leather and leather products	40,261	10	13,606
32	Stone, clay and glass products	38,532	27	91,014
33	Primary metal industries	70,277	54	184,833
34	Fabricated metal products	95,319	74	178,320
35	Machinery, except electrical	153,070	59	211,133
36	Electrical equipment and supplies	211,843	54	170,703
37	Transportation equipment	87,441	73	70,903
38	Instruments and related products	92,746	22	45,086
39	Miscellaneous manufacturing industries	83,587	21	61,255
40	Transportation and other public utilities, Railroad transportation	33,500	3	—
41	Local and interurban passenger transit	95,128	104	363,543
42	Trucking and warehousing	82,230	113	306,815

Table 1. Head injuries, compensated cases closed, New York, 1970 — Cont'd.

SIC code	Industry	Number employed	Number of head injuries	Dollars compensation
44	Water transportation	33,337	15	53,843
45	Transportation by air	57,397	107	32,123
46	Pipe line transportation	189	1	4,485
47	Transportation services	29,580	30	55,800
48	Communication	151,546	25	122,933
49	Electric, gas and sanitary service	55,517	16	36,250
50	Wholesale trade	496,740	105	367,835
52	Retail trade, Building materials and farm equipment	25,131	12	59,227
53	General merchandise	201,170	68	67,300
54	Food stores	166,975	62	161,466
55	Automotive dealers and service stations	88,644	31	63,708
56	Apparel and accessory stores	101,598	23	12,440
57	Furniture and home furnishing stores	41,761	16	63,732
58	Eating and drinking places	229,607	86	238,160
59	Miscellaneous retail stores	105,332	36	152,696
60	Finance, insurance and real estate; banking	175,038	22	48,389
61	Credit agencies other than banks	24,209	1	19,440
62	Security, commodity brokers and services	99,344	5	3,565
63	Insurance carriers	125,951	12	12,645
64	Insurance agents, brokers and service	34,824	1	1,058
65	Real Estate	124,321	48	216,907
67	Holding and other investment companies	10,882	1	350
70	Services Hotels, and other lodging places	73,691	42	92,512
72	Personal services	94,176	34	46,116
73	Miscellaneous business services	290,493	54	200,166
75	Auto repair, services and garages	35,013	15	15,321
76	Miscellaneous repair services	18,875	16	12,105
78	Motion pictures	30,423	5	2,966
79	Amusement and recreation services, n.e.c.	49,193	23	15,225
80	Medical and other health services	296,949	142	190,453
81	Miscellaneous services, legal services	130,841	10	2,719
82	Educational services	137,273	71	137,553
86	Nonprofit membership organizations	138,827	46	149,348
93	Government; Local	831,900	103	—

Table 2. Head injury frequency rate and head injury severity rate, New York

SIC code	Head injury frequency rate	Head injury severity rate	SIC code	Head injury frequency rate	Head injury severity rate
07	0.6664	163.5	47	0.5071	28.2
10	0.2750	19.2	48	0.0825	11.1
14	0.1389	0.2	49	0.1441	7.8
15	0.6889	66.5	50	0.1057	9.9
16	0.9127	44.0	52	0.2387	46.9
17	0.6029	59.4	53	0.1690	9.8
20	0.4447	54.3	54	0.1857	27.3
22	0.2173	13.6	55	0.1749	13.9
23	0.0829	11.1	56	0.1132	3.2
24	0.5818	241.2	57	0.1916	29.2
25	0.2719	33.5	58	0.1873	35.6
26	0.2683	33.6	59	0.1709	31.5
27	0.1010	7.3	60	0.0628	4.3
28	0.1693	3.4	61	0.0207	13.7
29	0.7773	20.9	62	0.0252	0.4
30	0.1642	2.5	63	0.0476	1.5
31	0.1242	8.2	64	0.0144	0.5
32	0.3504	31.5	65	0.1930	41.1
33	0.3842	38.0	67	0.0459	0.4
34	0.3882	30.3	70	0.2850	34.1
35	0.1927	20.3	72	0.1805	12.5
36	0.1275	11.9	73	0.0929	11.9
37	0.4174	10.2	75	0.2142	8.7
38	0.1186	5.8	76	0.4238	10.9
39	0.1256	15.0	78	0.0822	1.6
40	0.0448	—	79	0.2338	6.8
41	0.5466	70.9	80	0.2391	13.6
42	0.6871	60.7	81	0.0382	0.3
44	0.2250	25.2	82	0.2586	18.8
45	0.9321	6.0	86	0.1657	23.2
46	2.6455	204.6	93	0.0619	—

National average values for HIFR and HISR may be found by averaging the 1970 and 1971 National Safety Council disabling injury frequency and severity rates and taking 3 percent of this as the ratio of head (excluding face, neck, and eyes) injuries to total bodily injuries. This yields a 2-year national average HIFR of 0.27 and HISR of 19.0.

Industries found to have a HIFR and HISR greater than the 2-year national averages are considered to deserve priority analysis of head injury hazards. In order for these industries to reduce both frequency and severity rate, it will be necessary to have employers adhere to more stringent safety policies by:

- Reducing head injury hazards
- Increasing the use of adequate head protective devices

The 17 New York industries which fit into this category are listed in ascending SIC code order as follows:

- Agricultural services and hunting
- Metal mining
- General building contractors
- Heavy construction contractors
- Special trade contractors
- Food and kindred product manufacturing
- Lumber and wood product manufacturing
- Furniture and fixture manufacturing
- Petroleum and coal product manufacturing

- Stone, clay and glass product manufacturing
- Primary metal industries
- Electrical equipment manufacturing
- Local and interurban passenger transit
- Trucking and warehousing
- Pipeline transportation
- Transportation services
- Hotels and other lodging places

Economics of Head Protection

The New York State accident sample showed that head injuries accounted for $6.9 million of the State's workmen's compensation payment. We have earmarked all industry in that State which has demonstrated a HIFR and HISR greater than the national averages.

We may demonstrate the reduction in head injury costs through the implementation of more rigorous head protection programs and thus project the cost effectiveness of industrial headgear.

From the data presented in Table 1, it can be seen that the total compensation awarded to the 17 previously cited industries is $3,021,892.

It is widely accepted [6] that uninsured costs (lost production, accident investigation, accident-report writing, lowered employee morale, etc.) may cost from a low of one times the insured cost to a high of six times the insured costs of accidents. The actual percentages are based upon the individual employer's circumstances.

Studies of motorcycle accidents have shown [7] that the introduction of adequate head protection in a hazardous environment is likely to cause a 30 percent reduction in injuries.

In any attempt to control a hazardous environment by means of adequate head protection there will remain a percentage of unavoidable accidents. The New York State samples showed that 445 head injuries were the result of vehicular accidents and 388 cases were classified as resulting from "Other Agencies." This represents 32.5 percent of the accident cases.

Industrial head protection, unless specifically designed to mitigate the effects of a vehicular head impact, will not offer total protection.

In the same regard, head injuries from undefined events may not be controlled by head protective devices whose needs have been predetermined by the known conditions of the environment. Under these circumstances we may expect approximately 30 percent of industrial head injuries to be unavoidable.

In summary then, after implementing a strong head protection we may expect:

(a) 30 percent of all accidents to be unavoidable

(b) 30 percent reduction of head injuries.

(c) 40 percent of head injuries to be of reduced severity

In terms of actual injuries avoided:

Compensation costs	-	$ 6,900,000
Uninsured costs (100 percent)	-	$ 6,900,000
Total costs	-	$13,800,000
Unavoidable injury	-	$ 4,140,000
Avoidable injury	-	$ 9,660,000
Avoided injury	-	$ 2,900,000

Because approximately 900,000 employees are in the 17-industry sample, any helmet which costs the employer:

$$\frac{\$2,900,000}{900,000} = \$3.20/\text{employee}$$

will be cost effective.

Most forms of head protection, to be discussed subsequently may be expected to last 2½/3 years. Therefore, if the head protection cost is written off in a 2-year period a $6.40 helmet would be cost effective.

An average retail price of $4-5 per helmet, will be cost effective in most circumstances.

Type of Industrial Accident and Severity of Head Injury

The quantity and quality of accident statistics from State to State vary greatly. This situation may be alleviated in the future with the analysis of information contained in the current Occupational Safety and Health Administration of the U.S. Department of Labor (Forms 100 and 101).

The one characteristic of accident statistics which is both useful to the analysis of the needs of industrial and firefighters' head protective devices and is found in most accident report tabulations is the descriptive category "Type of accident."

From the frequency and severity of accidents of any particular type, it is possible to estimate the basic requirements of industrial headgear.

Table 3, shows a ranking, in terms of compensation awarded, from the New York State accident sample. The accident types listed in the table are the most common. Others either occurred too infrequently or could not be controlled by means of a head protective device.

In Table 3 the compensation/injury has been calculated by dividing the total compensation

Table 3. Types of accidents versus cost of injury

Type of accident	Number of injuries	Compensation/ injury
Slip or overexertion	5	$7,769
Caught in or between	22	4,930
Fall to different level	320	4,226
Struck by	1,107	2,755
Fall on same level	306	2,406
Exposure to extremes of temperature	29	849
Struck against	329	783

awarded for any one type of accident by the number of occurrences of head injury.

To allow any conclusions to be drawn from these data, attention must be focused on the most prominent types of accidents. Of the 2,118 head injuries shown in Table 3, "slip or overexertion" accounted for 0.2 percent of the injuries "caught in or between" for 1 percent, and "exposure to extreme temperatures" for 1.4 percent of the injuries.

In not considering these we are left with only those accident types as shown in Figure 1. It would seem that each of these accident types will have individual characteristics and will require different levels of head protection.

The "struck against" accident is seen to produce the least severe type of injury. This is, however, a significant injury type. Because so many of these injuries are minor, many are not reported as lost time accidents. The cost to the employer of a great many superficial wounds can be substantial.

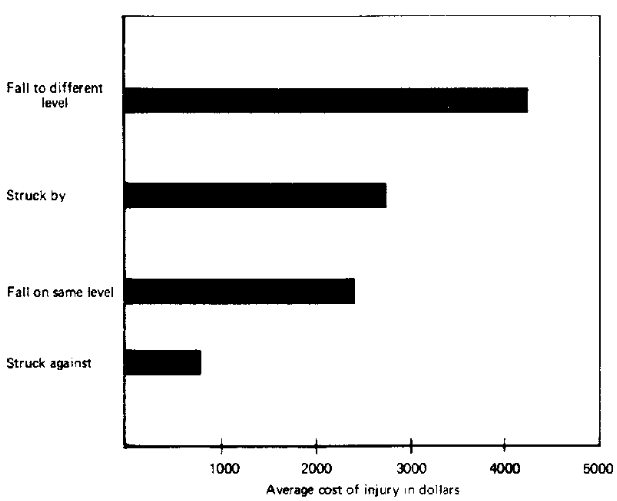


Fig. 1. Type of accident-producing head injury

It should be noted that a means of head protection from the "fall to different level," "struck by," and "fall on same level" accident types, because of their more severe nature, would at the same time offer protection from the "struck against" accident. It is thus concluded that industrial protective headgear (excluding firefighters') should be capable of controlling these types of accidents. These then lay the basis for the major classes of industrial head protection. These are shown in Table 4.

Table 4. Distribution of major classes of headgear

Accident type	Level of Protection Maximum duty	Medium duty	Light duty
Fall to different level	X		
Struck by	X	X	
Fall on same level	X	X	X
Struck against	X	X	X

Other Industrial Head Injury Accident Parameters

Area of the Head

We have shown that the "struck by" type of accident is the most common of the serious head injury accidents. One would expect, therefore, that the top of the head would be the most vulnerable to falling objects.

Lynch [8] in a study of industrial head protection in New Zealand, found that approximately one half of all head impacts occurred at the top of the head and one half around the periphery. Interestingly, from our accident sample, the "struck by" accident caused 1,107 injuries and the sum total of the "fall to different level," "fall on same level" and "struck against" accidents was 955.

This is not to say that all accidents where one is struck by falling objects will occur at the top of the head nor that whenever one falls or strikes his head an injury will occur on the sides. However, protection from these accidents should follow this pattern.

In a study of 150 accident reports involving head impacts [9] where the recipient of the blow was wearing an industrial helmet of the type used in the United States, it was found that an equal distribution of impacts occurred at all head areas. Rather than being contradictory to what has previously been said, these 150 accident reports graphically demonstrate that the present level of head protection is limited to areas at the top of the head. The industrial helmet, depending upon the environment in which it is used, needs varying degrees of top of head and lateral protection from impact.

Electrical Hazards

Industrial head protective devices of the high voltage electrical insulation type have been instrumental in reducing the number of fatalities in the electric utilities industry attributed to burn and electric shock through contact with the head.

The STOP SHOCK campaign of the Edison Electric Institute, starting around 1961, led to the development of a test for electrical insulation characteristics of industrial headgear. This effectively controlled the electrical hazard.

Figure 2 shows a plot of the number of fatalities resulting from electrical contact with the head for the period 1949 to 1963 [10]. It should be noted that 1961 was the year that the insulating headgear was made mandatory in the electrical light and power industry.

In 1967, the New Jersey Power and Light Company reported that since the adoption of hard hats in 1954, no deaths or serious injuries have occurred [11]. The employment for this utility is approximately 1,700.

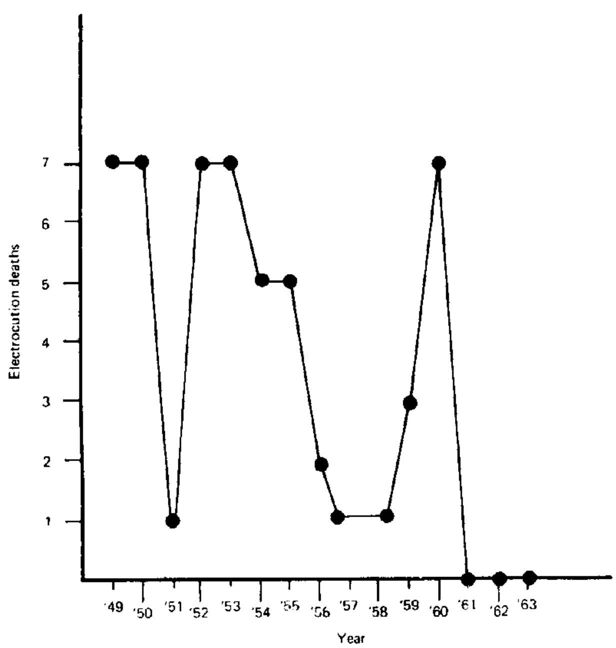


Fig. 2. Electrocution deaths by contact with the head

In recent years, the materials used in the construction of industrial headgear have changed. Most have shells made of a thermoplastic material. Many such materials inherently possess electrical insulating qualities. This situation has resulted in many helmet manufacturers producing one design of helmet and by means of different labeling, designating separate models for general industrial use and for those whose environments contain the electrical hazard.

A review of accident data from the State of Ohio in 1970 [12] shows that bodily injuries resulting from contact with electric current occur in many different industry classifications. These data are shown in Table 5.

Table 5. Bodily injuries resulting from contact with electric current, Ohio, 1970

Industry	Cases
Agriculture	3
Automobile manufacturing	8
Chemicals	5
Communications	2
Concrete products	1
Construction	48
Electrical equipment	7
Electric utilities	7
Food	5
Foundry	3
Glass	2
Iron and steel production	8
Machinery	18
Meat packing	1
Mining, coal	5
Miscellaneous manufacturing	3
Non-ferrous metal production	2
Petroleum	2
Printing and Publishing	1
Pulp and paper	2
Quarry	2
Rubber	1
Service	10
Sheet metal	3
Steel	6
Transit and transportation	3
Wholesale and retail	2
Wood products	1

Because of the distribution of the electrical hazard problem and the fact that an electrical insulation requirement would not place an undue burden on present industrial helmet technology, all industrial headgear should possess electrical insulating qualities. Those particular industries in which an environment hostile to thermoplastics is present may be considered a specialty case.

Head Injury Types

Degree of Head Injury

Head injuries are often categorized into three groups.

- Soft tissue (scalp) injuries
- Skull fractures
- Brain injuries

These types may be expanded upon and categorized as follows [13]

- Minor - contusions, abrasions, or superficial lacerations
  - mild concussions with no loss of consciousness
- Moderate - deep or disfiguring lacerations (non-dangerous)
  - extensive lacerations without dangerous hemorrhage
  - concussion with unconsciousness 5 to 30 minutes
  - skull fracture without concussion or other intracranial injury
- Dangerous - lacerations with dangerous hemorrhage (survival not assured)
  - skull fracture with concussion as evidenced by loss of consciousness up to 2 hours
  - concussion as evidence by loss of consciousness from 30 minutes to 2 hours without reference to possible intracranial injury
  - depressed fractures of the skull
  - evidence of critical intracranial damage

We may define these injuries as follows:

- *Contusion* - A contusion occurs when a blunt force is applied to the scalp of sufficient magnitude to extravasate blood into the surrounding tissue under the intact skin. The characteristic black, yellow, and blue discoloration occurs as blood is broken down and removed from the area [14].
- *Abrasion* - An abrasion is caused by a blunt object sliding over a body area with sufficient force to denude the superficial layers of the skin [14].
- *Lacerations* - A laceration may be either of two types, a puncture wound or a longer, incised wound. A puncture wound occurs when a sharp object applies enough force to the skin to penetrate it. When a sliding force is added to the penetration by a sharp object, a tearing or slicing produces a long opening in the skin [14].
- *Concussion* - Concussion is that immediate post traumatic conscious state; not associated with microscopic lesions of the brain, frequently reversible but potentially fatal; and associated in the human with amnesia [15].
- *Consciousness* - General wakefulness and responsiveness of the mind to impressions made by the senses.
- *Skull Fracture* - The breakage of the bones of the skull resulting from the application of an external force.

Head Injury in the Industrial Environment

Accident statistics from the State of Wisconsin [16] allow a closer look at how the various types of head injury relate to the type of accident.

Table 6 shows type of injury versus type of accident for some 290 accident cases.

It should be noted that in this data, skull fractures were of the moderate-to-dangerous type and concussions of the moderate type.

These data suggest that:

(a) Moderate to severe skull fractures may be controlled by protecting the head from falls to different levels and objects striking the head.

(b) Moderate brain concussions may be controlled by protecting from objects striking the head, from falls on the same level and from striking against objects.

(c) Scalp bruises and lacerations may be controlled by protecting from being struck by objects and striking against objects.

Head Injury Criteria

The ultimate goal in evaluating the safety characteristics of a helmet is to assure that human head impact tolerance is not exceeded as a result of an

Table 6. Type of head injury as related to type of accident

Type of Accident	Skull fracture (a)		Brain concussion (b)		Scalp bruises and lacerations (c)	
	No.	percent	No.	percent	No.	percent
All types	31	100	181	100	78	100
Fall to different level	10	32.3	19	10.5	3	3.8
Struck by	10	32.3	47	26.0	30	38.5
Fall on same level	4	12.9	38	20.9	7	9.0
Struck against	0	0	31	17.1	29	37.2
Other or unspecified	7	22.6	57	31.5	9	11.5

accident. Thus, it is necessary to define human head injury tolerance. Various measures of head impact tolerance have appeared over the years, the most recent of which is the Head Injury Criteria as adopted by the U.S. Department of Transportation [32].

HEAD INJURY CRITERION

Considerable research was conducted by the National Highway Traffic Safety Administration of the Department of Transportation into the development of the Head Injury Criterion in order that it would "set limits on the acceleration exposure of the head that reflect the available biomechanical data in terms that can be satisfactorily measured by a test dummy" [33].

The Head Injury Criterion, abbreviated HIC, represents a tolerance limit assigned to the maximum permissible acceleration exposure the head may experience without serious internal injury.

The Head Injury Criterion may be expressed mathematically as:

$$\left[\frac{\int_{t_1}^{t_2} a\,dt}{t_2 - t_1}\right]^{2.5} (t_2 - t_1) \leq 1000$$

Where: a = Instantaneous acceleration at the head center of gravity.

t1 = An arbitrary time in the pulse.

t2 = For a given t1, a time in the pulse which maximizes the HIC.

This mathematical expression was derived from the tolerance limit line as shown in Figure 5:

$$(\bar{A})^{2.5} \quad (T) = 1000$$

Where: $\bar{A}$ equals the average acceleration of the head during impact, the area under an acceleration-time history of the head at impact, divided by the time duration of impact, or:

$$\text{Average acceleration} = \frac{\int_{t_1}^{t_2} a\,dt}{t_2 - t_1}$$

and T is the time duration of impact.

The data from which the tolerance line has been derived comes from two basic sources, the Wayne State University skull fracture data and the whole body acceleration data as summarized by Eiband [27].

THE NEED FOR A HEAD INJURY CRITERION

The factors of human injury tolerance which must be considered in the performance of an industrial helmet are as follows.

Skull fracture. In many cases, skull fractures themselves are not a major cause of injury. They often serve as indicators of the actual severity of the head injury. For this reason, fracture threshold has been widely used in cadaver impact studies as a means of gaging serious trauma.

The exceptions [17] are:

(a) When a fracture crosses a major artery or vein and gives rise to hematoma.

(b) When the fracture line enters an adnasal sinus or the mastoid cells providing an entry for infection.

(c) When a basal linear fracture traumatizes or severs a cranial nerve or major artery.

(d) When a depressed fracture causes the cranial cavity to decrease in size and the blow causes the brain to swell and demand more intracranial space.

There are two major types of skull fracture, open and closed. The open fracture will have a break in both the scalp and the underlying bone, and the closed fracture will have a break in the bone with no break in the overlying skin.

Subdividing these general types there are many subgroups such as:

- *Simple linear fracture* — occurring as a result of the application of a blunt force which cracks the bone. The crack often takes the form of a single line running for a short distance from the area of contact.
- *Comminuted fracture* — resulting in an area of the bone breaking into many small pieces.
- *Depressed fracture* — occurs when an object of small surface area strikes the skull and causes a localized indentation and breaks the depressed bony area into several pieces.

Human tolerance to skull fracture. A pressure of 800-1,000 psi is sufficient to cause the skull to fracture [18]. It has also been reported [19] that the cadaver head with scalp intact requires 400 to 600 in - lb of energy to fracture.

Insofar as the area of the head is concerned, the head is strongest with respect to fracture in the rear, side, and front in that order [20]. It is expected that the top of the skull is at least as strong as the sides [21].

The fracture tolerance of the head decreases with a decreasing radius of the impacting object [22].

Brain injury. In general, there are three major types of brain injury:

- Cerebral laceration
- Cerebral contusion
- Cerebral concussion

Cerebral laceration, the tearing of the brain substance is the most severe type of brain injury and may be caused by direct contact of an impacting object with the brain or by violent motions of the brain relative to the skull.

Cerebral contusion is a bruising of the brain without a break in the continuity of the surface of the deeper tissues [14].

The brain contusion injury may occur in both the coup (point of impact) and contrecoup (directly opposite) locations of the skull/brain interface. The contusion injury is characterized, by the rupturing of small blood vessels at the coup and contrecoup points. Blood is then extravasated into the sursounding brain tissues. In the brain contusion injury, the contrecoup injury is more severe than the coup [23, 24].

It has been shown that rotations of the head will cause shearing of the membranes between the skull and the brain [25].

Cerebral concussion is often classified as the least severe form of brain injury because it is often reversible. There are many theories concerning the mechanism of cerebral concussion. The conditions which exist when concussion is produced are [26]:

- Shear stresses always occur in the brain stem region.
- Compression stresses occur in some areas or throughout the entire brain.
- Pressure gradients generally occur throughout the brain. Although pressure gradients may be minimal throughout the brain but are always present in the brain stem region.
- The brain, or at least a portion of it, has been linearly accelerated in all tests in which concussion has been produced to date.
- Electrical transients occur which may be due to compressive stresses.

It is felt that a primary cause of cerebral concussion is the interruption of neural impulses in the reticular formation (located within the spinal cord at the base of skull). These interruptions are caused by stretching of the reticular formation [14]. It may be expected that this stretching will occur as a result of rotation of the brain mass about the brain stem in any of the three principal axes of head rotation (figure 3) caused by an impact to the head.

Human tolerance to brain injury. The effects of cerebral laceration and cerebral contusion have been well documented in the medical literature but human tolerance values for these brain injuries are not available. Cerebral concussion tolerance data are available and may be used as an injury criterion.

Hodgson [27] points out three reasons why concussion tolerance is a useful design parameter:

- It can be produced in laboratory animals under controlled investigations of mechanism and/or mitigation.
- By definition, concussion is often reversible and therefore may be considered as a conservative tolerance limit.
- Linear fractures comprise 80 percent of all skull fractures and 80 percent of all linear fracture cases have had associated concussion. In essence, this states that acceleration data from cadaver impact studies of threshold linear fractures may be used as concussion tolerances.

Until the present time, the most widely accepted

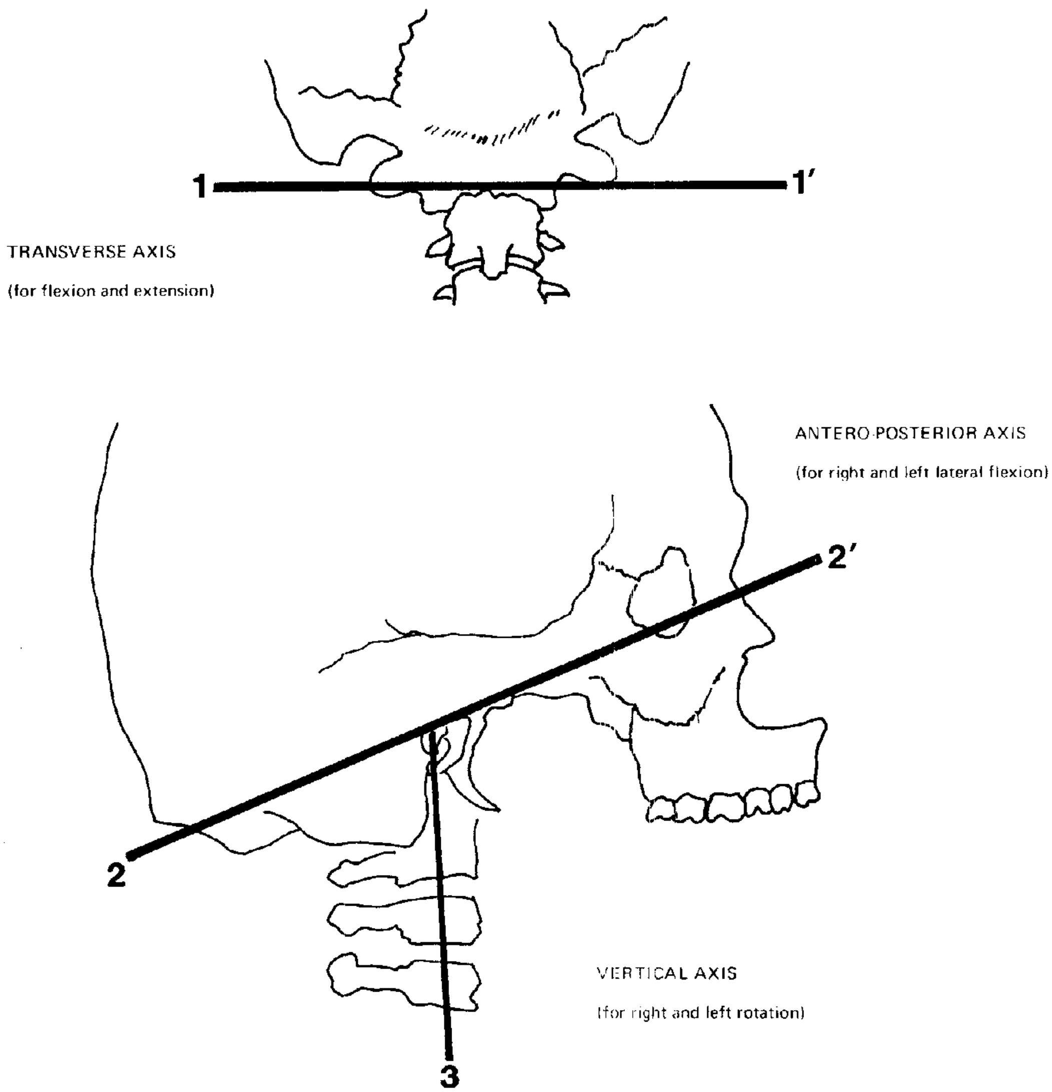


Fig. 3. Axes of movement of skull on vertebral column

cerebral concussion tolerance data has been the Wayne State University cerebral concussion tolerance curve [28], Figure 4.

The ordinate of the curve represents a measure of head linear acceleration, the effective acceleration. Effective acceleration has been defined as the average acceleration or the area under the acceleration-time impact response curve divided by the time duration of impact.

The Wayne State University curve represents the results of cadaver head impacts on to hard, flat surfaces.

The acceleration-time exposure seen by the head as a result of an impact with an object may be compared with the curve and if the data point lies above the tolerance line, a concussion is assumed to have occurred.

Gadd, seeking a useful tolerance criteria for testing purposes combined the Wayne State University and Eiband data and formulated a Severity Index. The Severity Index was derived from a plot of the Wayne State University and Eiband data on log-log coordinates.

The resultant line had the equation:

$$(\bar{A})^{2.5}(T) = 1{,}000$$

In Gadd's words: "The inverse of the slope of

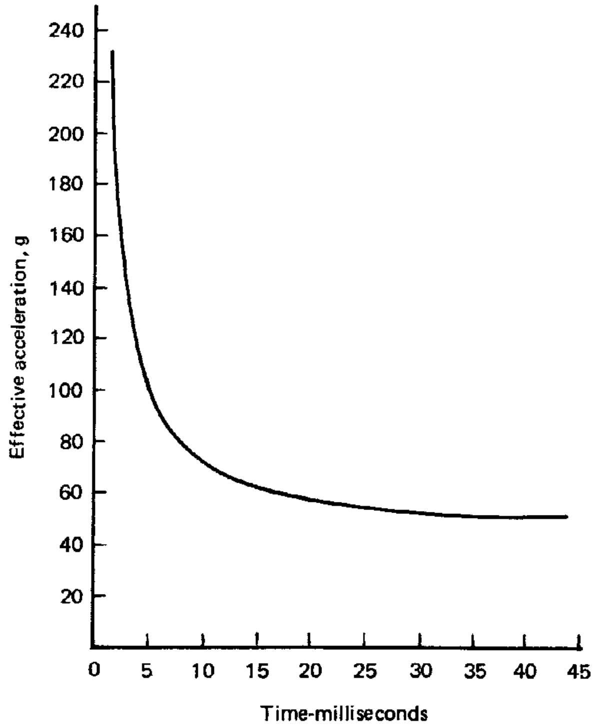


Fig. 4. Wayne State University cerebral concussion tolerance curve

such a straight line threshold corresponds numerically with a simple exponential weighting factor, from which it follows that injury threshold can be defined as a single number" [30].

From this, was produced the Severity Index formula [31]:

$$SI = \int a^{2.5} dt$$

Where: SI = Severity Index
a = Acceleration (instantaneous)
2.5 = Weighting factor for head impacts
t = time

When: SI = 1,000 it is assumed that the head injury tolerance threshold has been reached.

Although the SI has been used for over 10 years, it has recently been under considerable criticism regarding its injury assessment accuracy and reproducibility. It has since been replaced by the Department of Transportation with the Head Injury Criterion.

One essential NHTSA criticism of the Gadd Severity Index is that the Gadd SI "implicitly assumes that the injurious effect of acceleration exposures are additives" [33].

It is pointed out by the NHTSA that an analysis of air bag impacts conducted at Hollman Air Force Base [34] using human volunteers which showed that in several cases the volunteers were not injured and yet the Gadd SI exceeded 1,000.

When the Wayne State University, Eiband (whole body acceleration), and the Hollman studies are then plotted on log-log coordinates, Figure 5, it is seen that all fall at or near the injury threshold line.

The characteristics of the Head Injury Criterion [35] may be summarized as follows:

- It follows a formulation on which *actual* human tolerance is based.
- It assures that an exposure to acceleration does not contain any time intervals that have average accelerations which are above the tolerance line

$$(\bar{A})^{2.5} (T) = 1,000$$

- It implicitly separates an impact impulse and a rebound impulse unless they are extremely close together.
- It does not scale injury in terms of severity but rather represents a boundary between unacceptable and acceptable acceleration-time exposures.
- Since average acceleration is used, the HIC has a tendency of smoothing closely spaced recurring peaks and troughs rather than highlighting them.

A treatment of a mathematical rationale for a Head Injury Criterion suggests that there may be inadequacies in the analysis due to a lack of biomechanical research [36].

Other Human Tolerance Considerations

Head rotational acceleration. As pointed out earlier, severe brain angular motions are known to produce brain injury. Recent investigations on the effects of head rotational accelerations on brain injury [37, 38] have shown that these angular motions are closely related to the cerebral concussion phenomena. However, at this time, there are no quantitative human tolerance data available.

Head rotational acceleration injury studies require the use of living subjects and have therefore been restricted to tests on rhesus and squirrel monkeys. Attempts have been made to scale these data to humans [39], but no conclusive evidence is available.

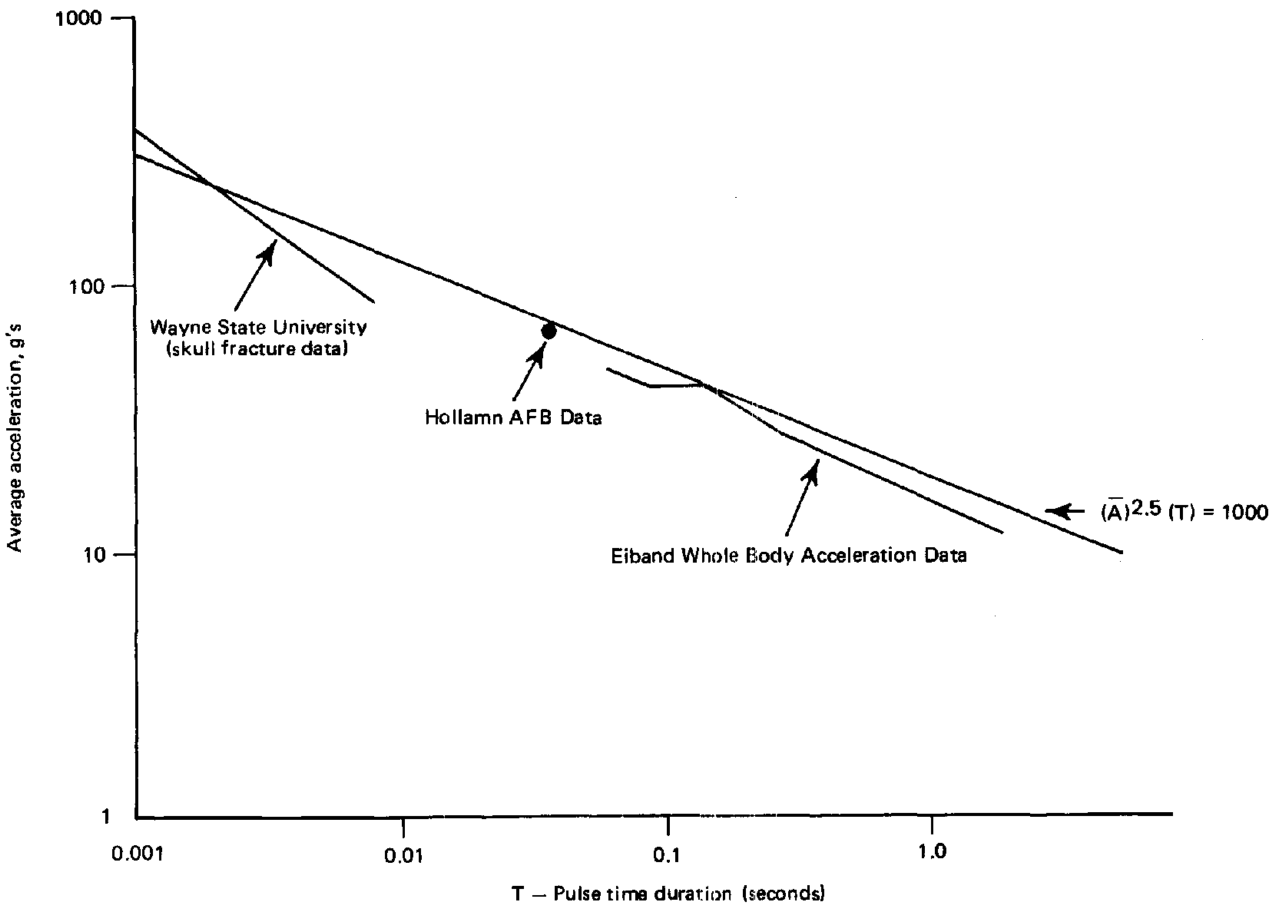


Fig. 5. Summary of human tolerance data for head impacts

A method of measurement of head rotational accelerations has been established [40] although no substantial human tolerance data from volunteers has been compiled.

The application of this information to human injury has, therefore, been limited. The existence of head rotational accelerations must be appreciated, and their occurrence controlled through adequate headgear design.

Cervical injury. It has been shown that industrial workers and firefighters are exposed to hazards of falling objects. If a falling object were to strike a man standing upright at the top of his head (a condition which does occur in reality), the effects would be quite different from a blow on the side of the head where the head may swing freely on the neck.

If the man struck by the falling object were not wearing head protection, he would undoubtedly receive a head injury. If, on the other hand, the man was wearing head protection, the forces transmitted through his helmet would have to be limited to protection of the weakest link in the body system. The cervical spine may be the weakest link.

Cervical spine injury resulting from top of head blows may be classified as extension-compression and flexion-compression injuries [41].

This type of injury is found in automobile accidents and may also be a result of [42]:

- A direct blow on the head when the individual is standing or sitting.
- A fall on the head such as diving into shallow water or hitting a submerged object.

It has been reported that the values for maximum allowable transmitted force through a helmet as used in present standards for industrial head protection have been the maximum allowable force to the cervical vertebrae [43, 44]. However, published research demonstrating human tolerance to dynamic cervical compression is not available.

Studies of vertebral tolerance [45] show the average ultimate static compressive strength of the cervical vertebrae to be 830 pounds and that of the lumbar vertebrae to be 1,220 pounds for ages 20–59. Patrick [46] has stated an approximate dynamic tolerance of 2,000 pounds for the lumbar vertebrae. If this static/dynamic ratio is applied to the cervical vertebrae, we find that the cervical dynamic tolerance is in the order of 1,360 pounds.

Anthropometry of the Head

For the purposes of establishing a standardized testing surface for industrial headgear, a set of headforms must be defined.

Industrial and firefighters' headgear presently sold in the United States must meet the requirements of the ANSI Z89.1 and Z89.2 standards. The impact absorption and penetration resistance tests are conducted with the helmet mounted on an "A.M.L. Size Medium" headform, Photograph 7. The AML headforms were originally fabricated as a result of work performed at the U.S. Army Aero Medical Laboratory in May of 1944 [47]. This study summarized anthropometric data for a head circumference sizing system. Four sizes, small, medium, large, and extra large were specified, the size medium being chosen for the ANSI Z89 Standards. In 1960, the WADD TR 60-631 Head Circumference Sizing System [48] was published. This system established head anthropometry for a six-size circumferential system. Differences between the WADD dimensions and the AML dimensions are accounted for by the authors of the WADD system who state that the AML sizing system "was based on measurements made on an Air Force population known to be significantly different from that measured in 1950."

The latest available head anthropometry data generated in the United States has been the U.S. Army Natick Laboratories [49] for the male population and the U.S. Air Force Aero Medical Research Laboratory (AMRL) [50] for the female population.

Table 7 shows a comparison of the AML sizes with the Natick data. It is seen that the size medium approximates a 40th percentile male in the later study. Values for head circumference, head length, head breadth, and head height are shown.

These quantities are defined as follows:

- Head circumference — The maximum circumference of the head measured above, but not including the brow ridges (bony protrusions above the eye sockets).
- Head length — The maximum length of the head from the gabella (the most forward point in the midline between the brow ridge) to the back of the head.
- Head breadth — The maximum breadth of the head in a plane perpendicular to the midsagittal plane (plane dividing the body into equal right and left sections).
- Head height — The vertical distance between the tragion, a point located at the upper edge of the ear hole, and the highest point on the head.

Table 8 shows a comparison of head sizes for 5th, 50th and 95th percentile male (Natick) and female (AMRL). From these data, it is seen that there are small differences between the male and female. These differences pose no problem in headform dimensioning.

In 1966, the ANSI Z90.1-1966 [51] standard adopted a headform for which basic dimensions were chosen from the WADD data for a size 4 headform. The headform designated was modified from the original data so that its contours were smoothed in order to minimize testing variables.

The latest series of standard headform dimensions were designated by the Department of Transportation for use in motorcycle helmet testing [52]. These dimensions are shown in Figure 6 for headform sizes A, B, C, and D.

Human Factors Considerations

In order for a head protective device to offer the protection needed to overcome occupational hazards, it must be comfortable to the wearer. Comfort is necessary because:

(1) It is essential that the helmet be worn to be effective, and therefore any actions which would tend to discourage use must be avoided.

(2) When protective qualities weigh too heavily, there may exist a point where the man is so heavily taxed by factors of weight, size, etc. that his own defensive mechanisms may be impaired and thus occupational hazards are amplified.

Once a worker dons his helmet, the two become an operating combination interacting to bring about a condition of sufficient protection from the environ-

Table 7. A.M.L. - Natick head size comparison

Dimension	Small		Medium		Large		Extra Large	
	A.M.L. size mm	Percentile (Natick)	A.M.L. size mm	Percentile	A.M.L. size mm	Percentile	A.M.L. size mm	Percentile
1. Circumference	533	30	557	40	578	85	599	99
2. Head Length	184	5-10	194	45	201	80	210	98
3. Head Breadth	143	5	150	35	156	70	161	90
4. Head Height	126	20	130	40	132	50	138	75-80

Table 8. Male - female head size comparison

Dimension	Percentiles					
	5th		50th		95th	
	Male	Female	Male	Female	Male	Female
Head circumference	53.52	52.25	56.08	54.82	58.82	57.59
Head length	18.25	17.27	19.47	18.41	20.67	19.52
Head breadth	14.34	13.54	15.25	14.50	16.26	15.52
Head height	11.91	11.56	13.23	12.67	14.52	14.07

(Dimensions in centimeters)

ment in which comfort and human acceptance are limiting factors. Human factors can weigh so heavily that it can logically be seen that the maximum in head protection comfort is equivalent to no protection at all. Almost without exception, when the factors of comfort are maximized, they detract from the helmet's protective capabilities.

Comfort

Human factors studies in the specific area of comfort are scarce, to say the least, and yet comfort is basic in the process of providing the worker with protection. The study of helmet comfort contains both physiological and psychological factors, the most dominant considerations are weight, size, fit, thermal characteristics, skin reaction to helmet materials, restrictions of sensory process, and aesthetic qualities.

Helmet Weight

By means of a mail survey technique, an assessment has been made of the most frequent comfort complaints of industrial head protective devices. Approximately 90 percent of the respondents complain that industrial helmet weight is excessive. Considering that most industrial helmets manufactured to meet present standards weigh essentially one pound, it would appear as if these complaints are unwarranted. From data gathered, it is evident that the complaints are not so much unwarranted as misdirected. Weight must be subdivided, and factors such as size and fit must be examined.

Incorporating Titchener's [53] description of the three kinesthetic sensations, the perception of weight on the head and the contribution of weight to discomfort are:

- Fatigue of muscles that move the head.
- Pressure exerted on joints.
- Strain induced in tendons (effort).

To these we may add:

- Restriction of blood vessels by excess pressure at points of head/helmet contact.

The effects of helmet weight will be a function of how well balanced a helmet is and for how long a period of time it is worn [54].

From the adaptation level theory [55], it is known that the longer a helmet is worn, the more the wearer becomes accustomed to its weight.

Size of Helmet

To date, the relationship between the helmet size and the comfort it provides the wearer has not been firmly established. Generally speaking, it can be stated that the optimum helmet design is one which fits closely to the head, is not excessively hot, and does not restrict sensory input. That is, the mass moment of inertia should be kept as low as possible while maintaining human comfort and compatibility.

In addition to moment of inertia considerations, the effects of an altered head center of gravity resulting from the attachment of a helmet must be examined. Industrial headgear symmetry will as-

Fig. 6 (a) Headform size A (from [52])

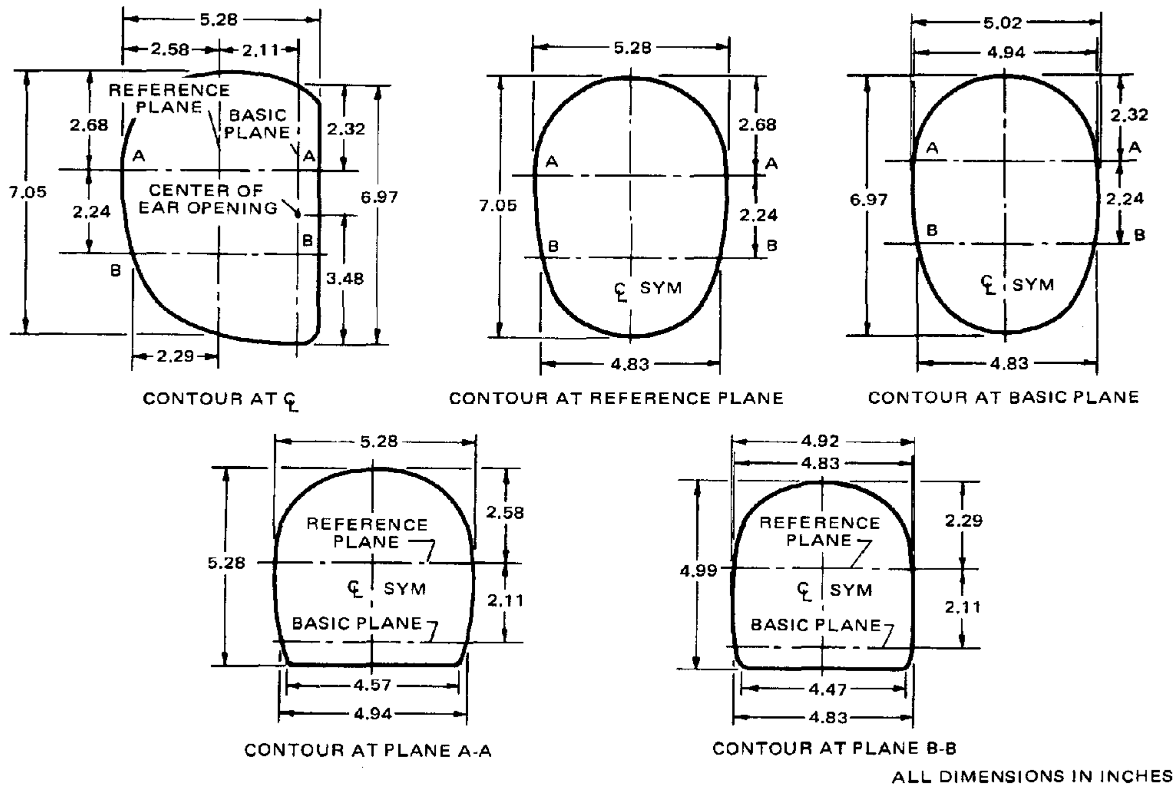


Fig. 6 (b) Headform size B (from [52])

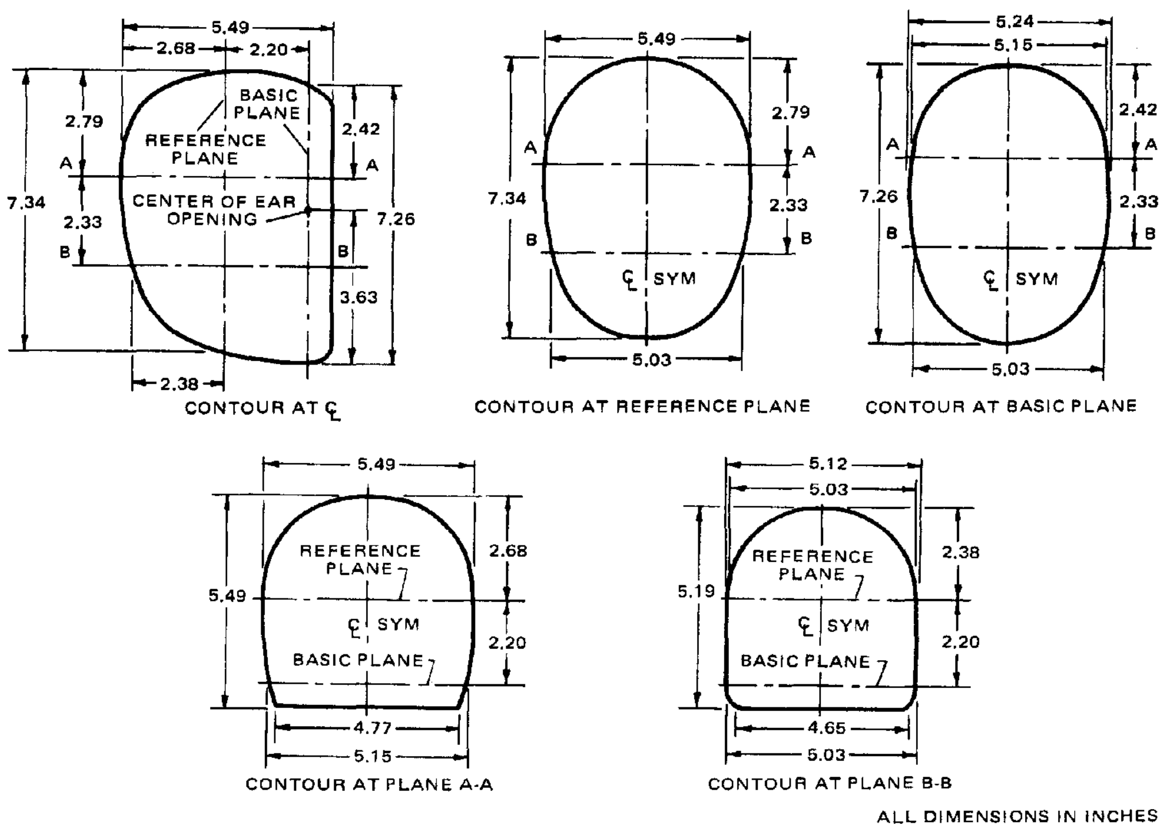


Fig. 6 (c) Headform size C (from [52])

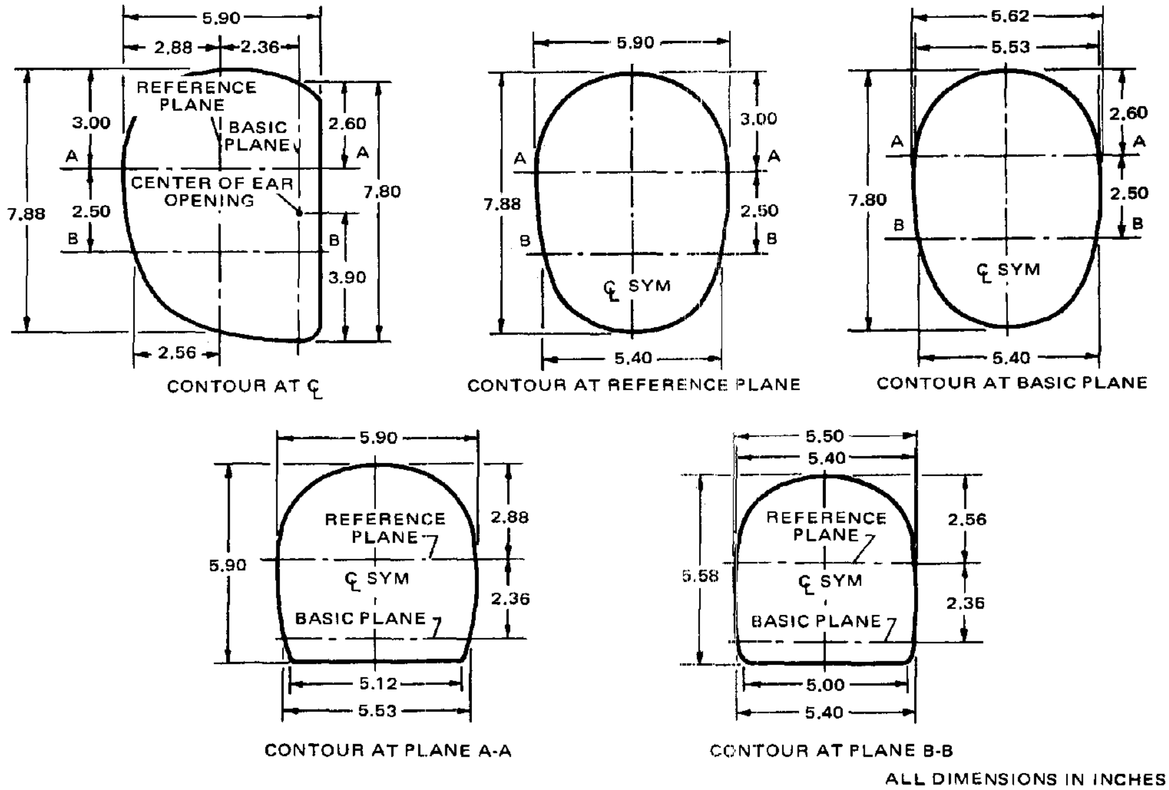
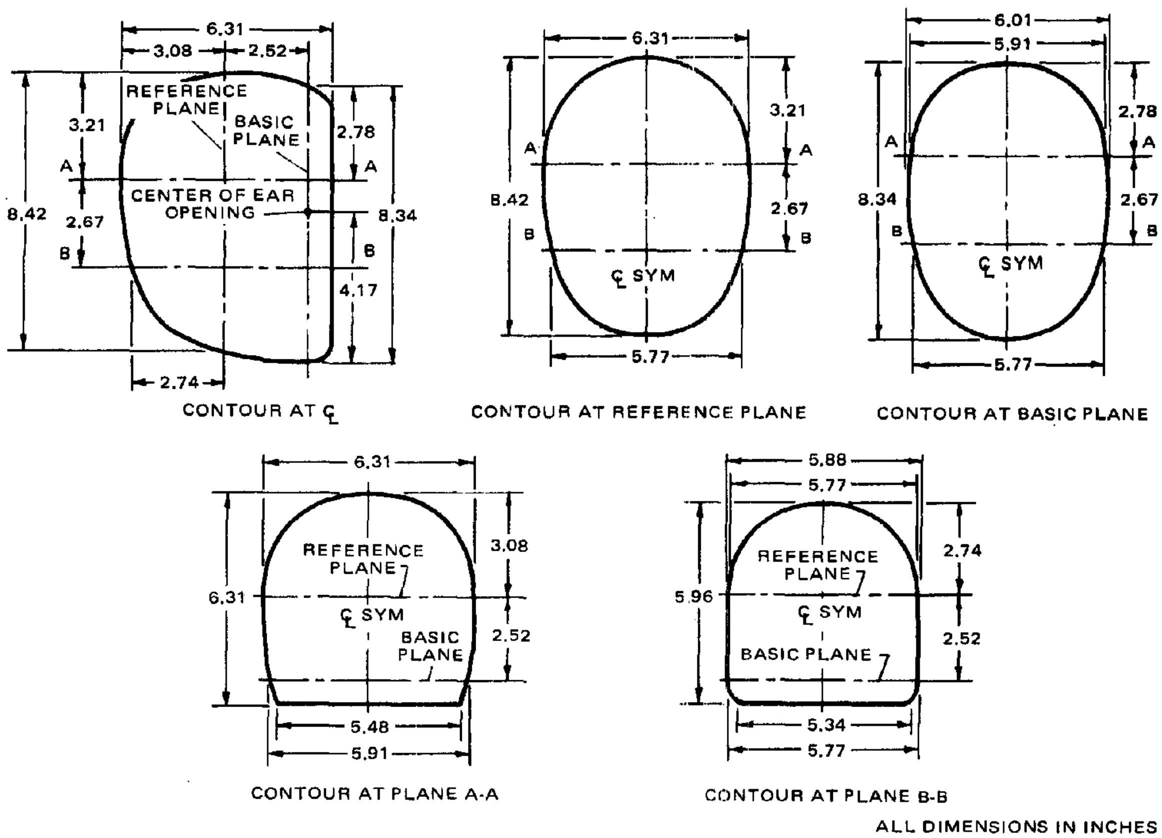


Fig. 6(d) Headform size D (from [52])



sure right or left center of gravity location at or near the mid-sagittal plane. However, most industrial headgear offering protection primarily to the top of the head, will effectively raise the head center of gravity. The increased moment experienced at the occipital condyles (head/neck junction) when the head vertical axis changes orientation will result in increased loading of the muscles that move the head which will increase muscular fatigue and discomfort.

Helmet Fit

From a review of the available literature, there are strong indications that helmet fit plays an important part in helmet comfort. It was established that, in many cases, fit was found to be a primary cause of discomfort [56]. It has also been found [57] that the ability of the helmet to form itself around the head (load distribution) is an important fit and comfort consideration.

These factors suggest that it is quite possible that many of the complaints of excess helmet weight may be more accurately attributed to fit characteristics rather than the weight per se. The fit problems found most frequently in present industrial head protection devices are due to:

(a) Rigid or semirigid suspension components which do not form themselves to the head when worn.

(b) Helmets with distinct methods of suspension adjustments are not properly adjusted by the wearer.

(c) Many helmets, especially the low quality ones, lose adjustment easily.

McKenzie [56] has found that "when fit characteristics are analyzed, it will become apparent that the elimination of the current cradle type suspension is the key toward developing a comfortable headgear."

When considering the need for a closely fitting headgear, the thermal characteristics of the headgear become important considerations.

Thermal Characteristics

From surveys on industrial head protection it is evident that the second most prevalent comfort complaint is attributed to excess heat. While head/helmet clearance may provide ventilation, there exists the undesirable attribute of greenhouse effect. The inclusion of a close-fitting compressible liner may well serve to act as a heat insulator.

Some helmets with closely fitting liners are known to be hot in warm weather [58] while there have been reports [59] that industrial helmets of present design help keep the head cool when in a hot environment. Because of lack of more substantial data in this area, it would seem desirable to retain the present head/helmet clearance configuration.

From military experience [60], it is known that many complaints of excess helmet heat may better be attributed to psychological rather than physiological factors. For this reason, it is recommended that most helmets have a glossy, light colored finish.

Skin Reaction to Helmet Material

It is desirable that the materials used in the construction of helmets not react adversely with the skin and the helmet should be resistant to normal substances applied to the skin and hair.

In general, a helmet must be resistant to:

- sweat, hair oil, and grooming aids
- dust, pollutants
- fungus and rot

Restriction of Sensory Processes

In order to assure that the industrial helmet provides adequate head protection, it is essential that the senses of sight and hearing are not restricted by the employment of the protective device. In the continuous process of mentally monitoring his working environment, the worker's sensory inputs of potentially hazardous industrial conditions are the most important safeguards against industrial accidents. At present, the industrial helmet offers virtually unrestricted use of sight and hearing. It is, therefore, important that such features do not become infringed upon. In order to prevent the possibility that new designs might tend to restrict the sensory inputs, it is essential that the standards for head protective devices specify minimum sensory restriction.

It should be noted that little is known about the psychological effects of sensory deprivation on the industrial worker. Curtis and Zuckerman [61] have shown that adverse reaction can be expected from total sensory deprivation, but the effects of partial sensory deprivation as a result of protective headgear design have not been fully investigated.

Aesthetic Qualities

There is no available data in the literature on the effect of wearer reaction to helmet style on the incidence or severity of head injuries. It is reasonable to assume that style factors will be controlled by consumer selection of marketed helmets. There exists some concern that women are less likely to wear industrial head protection than men due to helmet style. However, from questionnaires received from employers, there appears to be no distinguishable problem in this area.

Requirements of Industrial and Firefighters' Head Protection

Industrial and firefighters' head protective devices must be designed to provide:

(1) *impact protection* - by limiting the magnitude concentration of impact forces.

(2) *penetration resistance* - by being shatter resistant, smooth and rigid.

(3) *retention* - by having sufficient securing strap strength.

(4) *protection from the environment* - by being resistant to weather and fire and by being electrically insulating.

(5) *comfort* - as required by the intended use.

Industrial Headgear Requirements

The discussion beginning on page 47 of this report details the development of criteria for the performance requirements of industrial headgear. For purposes of systematically listing the needs of industrial headgear the essential performance requirements are outlined here.

IMPACT PROTECTION

As previously discussed, the distribution of classes of head protection by severity of head injury accident type shows the following:

Class	Most severe hazard
Class 1	Fall to different level
Class 2	Struck by objects
Class 3	Fall on same level

We may consider each of these circumstances individually.

A. *Falls to Different Levels* - The fall to different level accident may be viewed as a random occurrence which will be dependent upon the work area, the worker's protective equipment (safety harness, shoes, etc.), his physical condition, his acclimation to heights, and his mental attitude.

Some common types of falls to different levels are:

- falls from roofs
- falls from skeleton constructions
- falls from scaffolds
- falls down stairs
- falls off ladders
- falls from platforms
- falls from motor vehicles

The accident data studied revealed no mean or common fall height which would enable laboratory accident simulation. In addition, there appears to be no relationship between the degree of injury and height of fall [61] which precludes comparison of injuries from fall on same level and fall to different level accidents for computations of mean fall height.

When the body falls in a position such that the head is free to move on the neck, we may consider the head as a rigid body. Under these circumstances, a one story (10 feet) fall will result in the head impacting with 110 foot-pounds of energy (assuming an 11-pound head). At present, the only class of industrial headgear designed to operate at such high energy levels are those built to New Zealand Standard 2264-1970 [62]. In the New Zealand specification, helmets must pass an impact test comprised of dropping an 11-pound mass a distance of 10 feet onto a rigidly mounted headform. Under these circumstances, a force, measured at the base of the headform, is not to exceed 5,000 pounds.

B. *Struck by Objects* - A worker receives a head injury most frequently from objects striking his head. An analysis of 150 Turtle Club ([9] accident reports has shown such objects may weigh an average of 17.8 pounds and may possess 300 ft - lb of energy at the time of impact.

As stated earlier, the commonly encountered accident where the worker is struck by falling objects presents a unique problem to top of head impacts. In this configuration, the head is not freely movable and may be considered as semirigidly mounted to the neck.

Industrial helmets manufactured in the U.S. are impact tested by being mounted on a headform which in turn is mounted to a force measuring device and then having an 8-pound steel sphere dropped a distance of 5 feet onto the apex of the helmet.

The discussion beginning on page 47 of this report shows that when the force measuring device used in the impact test system of the ANSI Z89 standard reads its maximum allowable, (1,000 pounds) an acceleration measured at the center of gravity of an instrumented drop mass (of approximately the weight of the head) will be 80g.

When industrial helmets are mounted to an instrumented headform and dropped onto a rigidly mounted spherically shaped anvil at the helmet apex from a distance of 72 to 75 inches, they remain operational. With improved design it is expected that helmets subjected to such a test will pass an 80g failure criterion.

To provide protection from falling objects which strike the head, an industrial helmet should be impact tested by being mounted to an instrumented headform and dropped a distance of 72 inches onto a hemispherically shaped steel anvil. Headform accelerations should not exceed 80g when such an impact occurs.

C. *Falls on Same Level* - Accidents where one falls on the same level are frequently of the slip and fall and trip and fall types. The blows applied to the head are of the fall to different level type, but of a lesser magnitude.

Protection from falls of this nature requires that a helmet must sustain an impact of being dropped from a height of 36 inches onto a rigid flat steel anvil.

Penetration Resistance

The testing of the penetration resistance capabilities of a helmet:

- assures the integrity of the outer surface of the headgear
- demonstrates the helmet's ability to ward off sharp objects
- requires that the helmet spread concentrated forces over a larger area

Investigatory tests have shown that helmets designed to protect from falls to different levels and to ward off falling objects may be tested for penetration resistance by dropping a 1 Kg (2.2 pounds) plumb bob a distance of 3 meters (118 inches) onto the outer surface of the helmet. Helmets used for protection against falls on the same levels should resist the penetration of the same plumb bob when dropped a distance of 1.25 meters (47 inches) onto the helmet's outer surface.

Retention

The forces generated in the fall to different level accident require that a chin strap used to retain a helmet on the head should remain intact when subjected to a chin loading of 100 pounds. Helmets used for the purpose of warding off objects and protecting from falls on the same level should withstand 25-pound chin forces.

Protection from the Environment

Helmets designed for general industrial use:

- should remain operable within a temperature range of 14°F to 122°F and should be resistant to storage temperatures. of 160°F.
- should not absorb more than 5 percent water by weight when subjected to 24-hour water immersion.
- should not burn at a rate greater than 3 inches per minute.
- should withstand voltages of 30,000 volts, AC.

Comfort

Helmets designed to protect from falls to different levels should not weigh more than 18 ounces, those designed to ward off falling objects should not weigh more than 16 ounces, and 13 ounces should be the maximum allowable for helmets used to protect from falls on same levels.

Special Requirements for Firefighters' Headgear

Impact Attenuation and Penetration Resistance

Head injuries sustained by the 18,000 man New York City Fire Department during 1971 [63] have been studied. These data are shown in Table 9.

The data illustrate that firemen are most likely to receive impacts from falling objects such as weakened ceilings and falling debris.

From the above and from surveys of safety personnel in the New York City, Los Angeles, Boston and Chicago fire departments, the special requirements of firefighter's headgear have been determined.

Insofar as impact protection is concerned, firefighters' helmets should be tested by being mounted on an instrumented headform and dropped a distance of:

- 72 inches onto a hemispherically shaped anvil at the apex.
- 36 inches onto a flat anvil in other areas of the head.

Penetration resistance should be of the type as noted for industrial headgear for the struck by and fall on same level protection, that is, a 1 Kg plumb bob dropped a distance of:

- 3 meters onto the helmet apex.
- 1.25 meters onto other areas of the helmet.

Retention

Firefighters' headgear as presently manufactured incorporate a wide brim for deflecting water.

Table 9. New York City Fire Department head injuries, 1971

Total number of head injuries = 58; total days lost = 712
Total number employed = 13,000; 42 hours/week
Head injury frequency rate = 2.12
Head injury severity rate = 27.4
Average days charged per head injury = 12.92

Extent of head injury by accident agency						
Accident agency	Concussion	Contusion	Loss of consciousness	Laceration	N.E.C.	Total
Falling objects	1	6	-	1	7	15
Falling ceilings	2	18	2	3	8	33
Hostile Missles	-	3	-	1	2	6
Explosion	1	-	-	-	-	1
Direct Lateral Blow	-	-	-	-	1	1
Bump into	-	-	-	-	1	1
N.E.C.	-	-	-	1	1	2
Total	4	27	2	6	20	59*

N.E.C. = Not otherwise classified
*One report of a double agency

Falling objects are likely to strike such a large area and forcibly remove the helmet from the fireman's head. It is essential that the chin strap of a fireman's helmet withstand a 100-pound chin force.

PROTECTION FROM THE ENVIRONMENT

A. *Heat* - From an analysis of firefighting heat environments [64], we find that heat conditions are likely to exist in the range of 20-7000°C.

In order to assure adequate performance, firemen's helmets must be tested at temperatures of 14°F (−10°C) to 300°F (150°C). Temperatures at this level are sufficient to protect from most situations. Temperatures "in the furnace" would require specialized radiation reflecting protective apparel.

B. *Fire Resistance* - The necessity of the firefighter's helmet to resist fire is self-explanatory. These helmets must be made of materials which exhibit self-extinguishing characteristics.

C. *Electrical Protection* - Although the incidence of electrical shock and burn injuries in firefighting activities is low, firefighters are often exposed to electrical hazards. Fires in urban areas may take the men into areas on or around electrically powered rail transportation systems. In residential and industrial fires, it is our understanding that electrical supply lines are often not disconnected prior to commencement of firefighting activities. This is clearly an electrical hazard. The low incidence may be explained by the usage of other rubber insulating gear worn by firefighters.

These circumstances dictate that firefighter's headgear should withstand the 30,000-volt requirement of industrial headgear.

D. *Water Absorption* - Firefighter's headgear must be made of materials which will not absorb an excessive amount of water. Five percent water absorption (by weight) after a 24-hour water bath is an agreeable upper limit.

E. *Weight* - Firefighter's headgear are worn for relatively short durations. Under these circumstances, a maximum helmet weight of 30 ounces is acceptable.

Methods of Head Protection

In the discussion thus far, the head injury environment has been described and the levels and types of head protection necessary to overcome a hazard have been outlined. It is the purpose of this section to explain the methods by which a head protective device offers protection, to describe how present industrial helmets in the United States are constructed and to note how head protective devices are manufactured and what are the manufacturing capabilities of the head protection industry in the United States.

Characteristics of Helmets

Protecting the head from injury is essentially a packaging problem. When the head is placed in a hostile environment, it may be shielded by being encased in a protective structure.

Nature has designed the head in a sophisticated fashion so that the scalp, skull, and cerebrospinal fluid surround and shield the brain from injury.

As an example, it is known [65] that the dry human skull will fracture with the absorption of 25 inch-pound of energy whereas with the scalp and brain intact 400-600 inch-pound is necessary for fracture, when dropped on a hard flat surface.

When it is expected that forces will be exerted on the head which exceed the protective capabilities of the anatomical structure it is necessary that we provide additional protection.

THE IMPACT

When an object strikes the head (or when the head strikes an object) forces exerted on the head will:

(a) compress the scalp

(b) deform the skull

(c) move the skull with respect to the brain

Each of these three actions is likely to cause injury if the impact is of sufficient magnitude.

The present level of understanding of biomechanics requires that in designing for impact protection we consider the head as a rigid body. As such, we may fashion a protective structure around the head which will mitigate the effects of the impact.

In describing the impact situation it should be noted that the situations of a moving object striking an immovable head and a moving head striking an immovable object are mechanically equivalent, assuming the moving mass, be it the head or the object have the same weight.

The consideration of the impact condition where a moving body strikes an immovable object is a simpler case than the object striking a movable object and is less likely to induce error in experimentation. We will consider the impending object as striking normal to the immovable surface. These situations are shown in Figure 7.

In the collision between the head and an object, if the relative velocity between the two is brought to zero without injury to the head, impact protection will have been achieved.

If the unprotected head is taken as colliding with a rigid surface, the head will be brought to rest relative to the surface by its own deformation. To eliminate deformation of the head, some other medium which provides a stopping distance must be added. This stopping or crush distance may be supplied by a helmet.

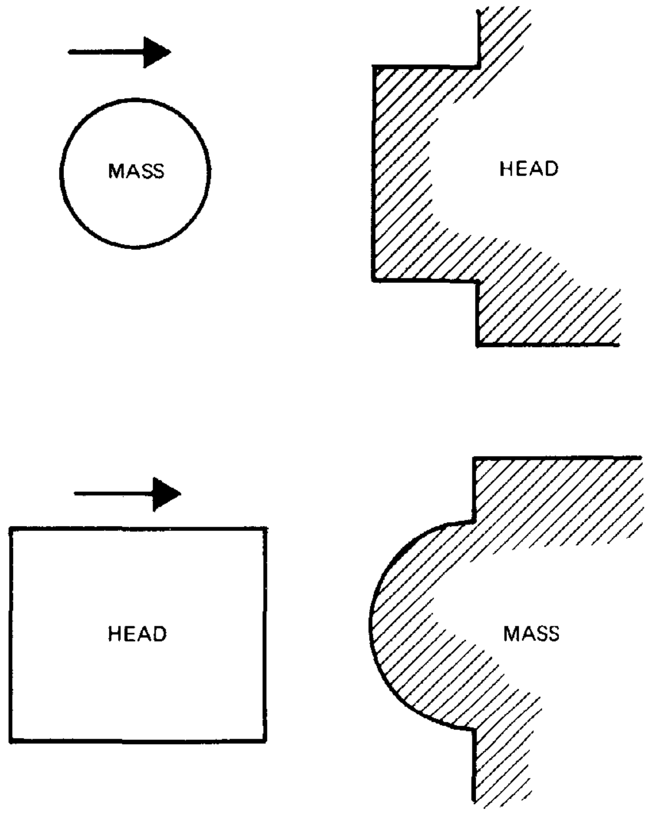


Fig. 7. Head impact schematic

In this case, the head is brought to rest by forces applied to it by the helmet. Due to the compression of the helmet these forces are exerted even after the head comes to rest and the head is accelerated in a direction opposite to its original motion.

The measurement of the deceleration and rebound of the head would permit the graphical representation of the impact as shown in Figure 8. Such an acceleration - time exposure must then be critically analyzed for its injury producing potential. The ability of a material to decelerate the head without injury will depend on the physical properties of the material. The methods of head protection which are used to effectively provide a sub-critical acceleration - time exposure are:

- protective padding/semi-rigid shell.
- suspension/semi-rigid shell.
- padding & suspension/semi-rigid shell.

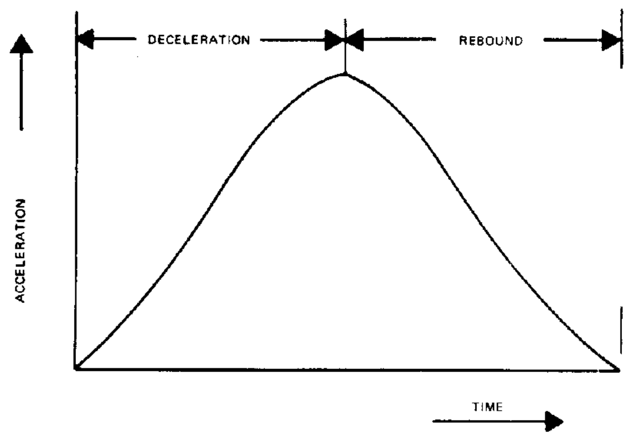
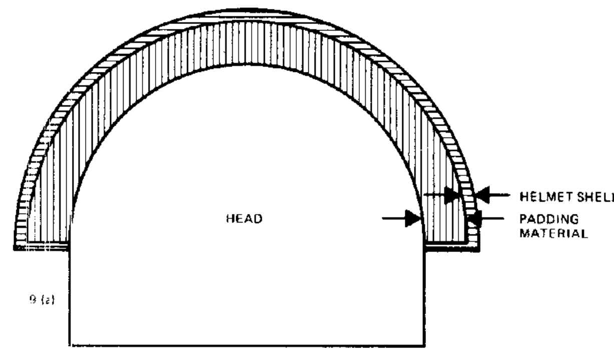


Fig. 8. Head impact acceleration response



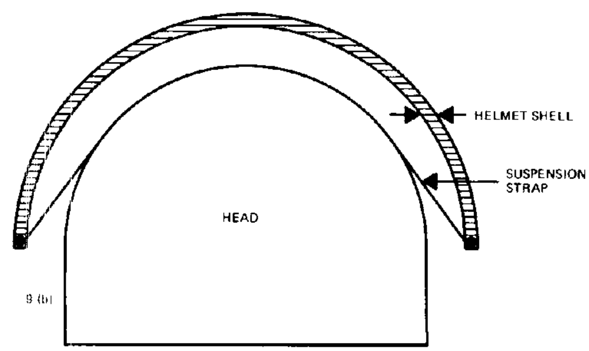


Fig. 9. Protective padding and suspension systems

In all cases, a semi-rigid shell is used to distribute concentrated loading.

In the first case, stopping distance is provided by padding material and in the second method the head is maintained a distance from the semi-rigid shell by means of a suspension or harness. These are depicted in Figures 9(a) and 9(b), respectively. The third case may be considered as a hybrid and will possess properties of both protective padding and the suspension system.

A. *Protective Padding* - Protective padding, which may be of a resilient or non-resilient nature, in its normal configuration is bonded to the inner surface of a helmet shell (semi-rigid outer surface).

Although a thorough treatment of the design of protective headgear and the dynamic behavior of their composite materials is beyond the scope of this report, a series of illustrative examples of material and helmet response is in order.

For purposes of experimentation, protective padding materials were mounted to a helmet impact testing apparatus in much the same manner as would be experienced in the testing of the helmet itself. The test apparatus, as shown in Figure 10, is the standard rigid anvil apparatus as specified in ANSI Z90.1–1971 [66].

The system is comprised of a drop carriage, to which is mounted a magnesium test headform. The headform has a piezoelectric accelerometer mounted at its center of gravity which, when appropriate signal conditioning equipment is used, provides accurate recording of the acceleration — time history of the impact onto the rigid steel anvil. A detailed discussion of this equipment is given in the subsequent section on Test Requirements, page 66.

Samples of protective padding materials were prepared by cutting the materials into 4″ x 4″ squares and attaching to their surfaces sheets of 4″ x 4″ x ⅛″ polycarbonate plastic, as depicted in Figure 11.

The samples were then attached to the forehead part of the test headform and dropped from various heights onto a hemispherically shaped rigid steel anvil of 1.9-inch radius.

The materials studied were:

(a) expanded polystyrene foam, 9 lb/ft^3 density, 1-inch thickness

(b) ethafoam (polyethylene), 9 lb/ft^3 density, 1-inch thickness

Figure 12(a) and 12(b) show the impact results in terms of:

- peak acceleration (g) versus drop height
- Head Injury Criterion and Gadd Severity

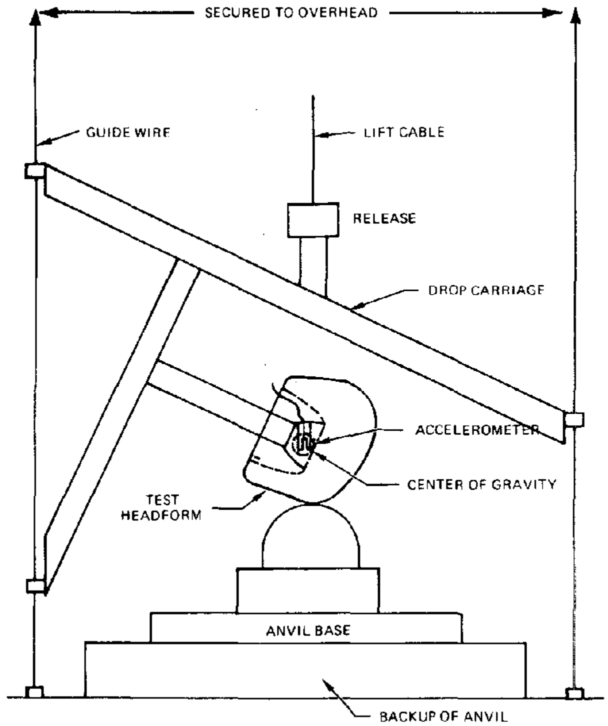


Fig. 10. Impact test apparatus

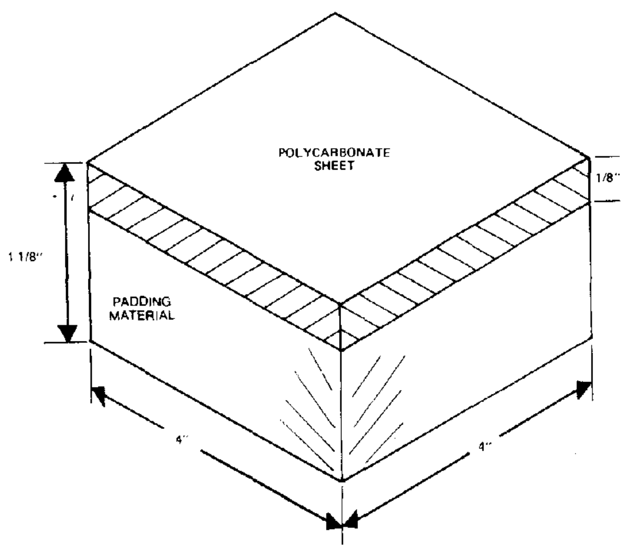


Fig. 11. Material sample for impact evaluation

Index versus drop height, respectively.

From the graphs it is evident that for greater drop heights, the expanded polystyrene produces lower acceleration and injury index values than

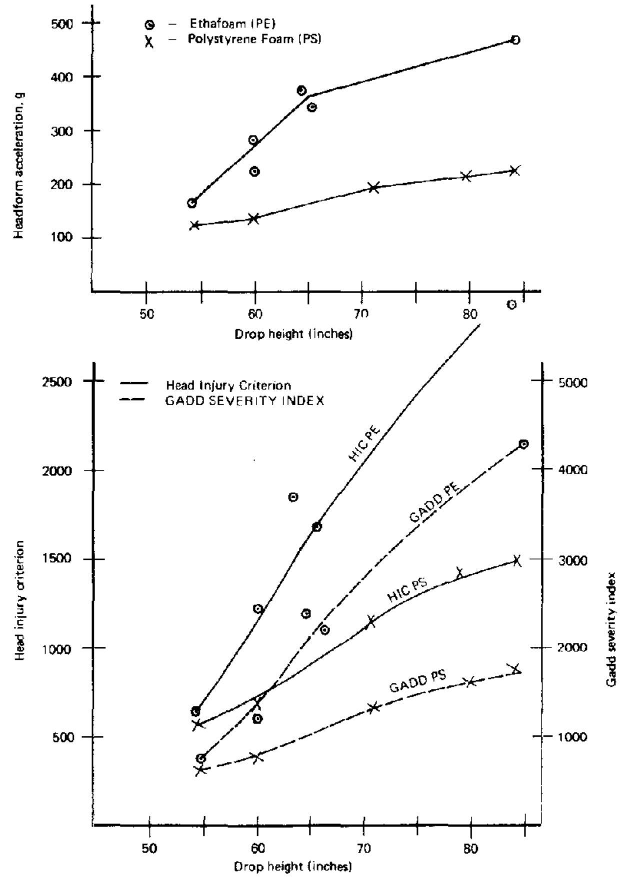


Fig. 12. Impact performance of padding material samples

the ethafoam. This may not be construed to be an indictment of any class of materials because the material selection process will involve many other factors which must be determined experimentally for the application.

When designing a protective headgear, the engineer must view the following factors as variables in the selection of his helmet materials:

- density, thickness and stiffness of the outer shell.
- density and thickness of padding material.
- curvature of anvil.
- local curvature of headform.
- size and shape of helmet.
- resistance of construction materials to expected environmental conditions.

To these must be added the required range of operating impact energies, the required acceleration — time output, the over-all weight of the helmet, its expected selling price, ease of manufacture and safety factors for production — line variation.

Examination of Figures 13(a) and 13(b) shows the variation in pulse shape for the expanded polystyrene for drops at the 54 inch and 72 inch levels, respectively.

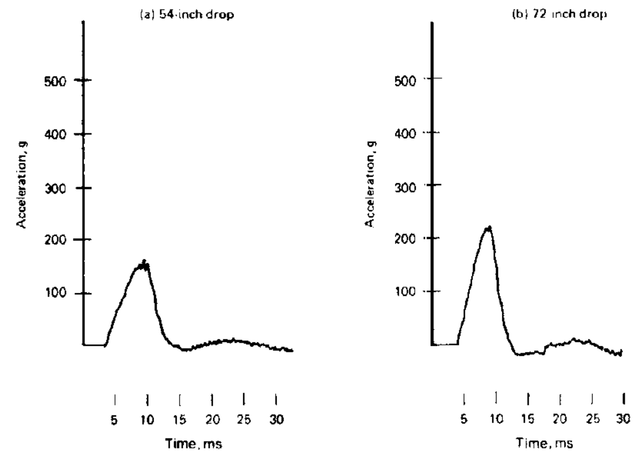


Fig. 13. Acceleration response, polystyrene foam

It should be noted that no protective padding material will compress to its fullest. Most padding materials will behave in a spring-like manner where the acceleration (force) will increase with increased deformation. This will continue until the material "bottoms" and can be no longer compressed. At this point accelerations will have greatly exceeded human tolerance limits.

An example of this characteristic is seen in the acceleration pulses of Figures 14(a) and 14(b) for the drops with the ethafoam padding at the 54-inch and 84-inch levels, respectively.

Suspension System

In the suspension type helmet, straps encircle the head and are attached to the helmet shell maintaining crush distance between the head and the shell. This configuration is extensively used in present industrial headgear sold in the United States.

The system makes use of the deformation characteristics of the helmet shell and the tensile properties of the webbing material.

As in the case of protective padding, head acceleration is the measurable quantity. The suspension rests on and distributes load over the head, and, therefore, the area of the suspension in con-

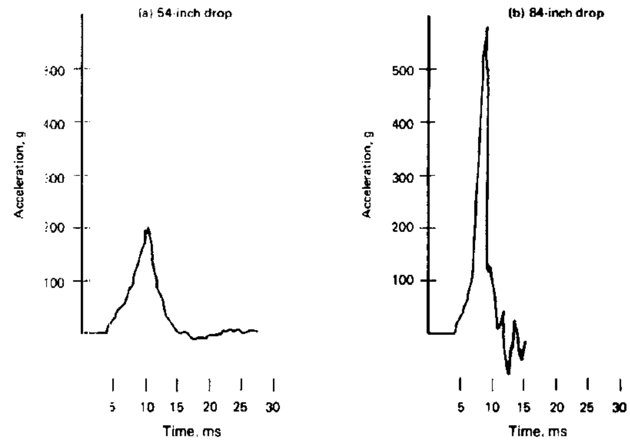


Fig. 14. Acceleration response, ethafoam

tact with the head must be sufficiently large to minimize the risk of skull fracture during impact loading.

There are two general types of suspension systems:

Crown Straps - (Figure 15) crown straps are normally made of either nylon webbing or of one-piece plastic construction. These straps are rigidly anchored to the helmet shell at four, six, or eight points, depending upon the number of straps used. Attached to (or in the case of molded plastic, integral with) the crown straps is a headband which encircles the head. At the forehead part of the headband is a sweatband, and at the rear on some models is a nape strap which assists in retaining the helmet on the head when the wearer is in the bending-over forward position.

The type of suspension system thus used will provide unidirectional impact energy absorption and in this case will afford protection from blows to the top of the head only.

The use of crown straps requires that a minimum distance exist between the top of the head and helmet shell. The ANSI Z89 standards require a minimum of 1¼ inches be maintained regardless of wearer adjustment.

Attachment of the straps to the shell is normally provided by through - the - shell rivets or, in the case of electrically insulating headgear, by hook type anchors seated in grooves or indentations in the shell.

Depending upon design, anchorages projecting into the shell cavity may pose a hazard to the wearer by being non-deformable. These will become high forge concentration points when

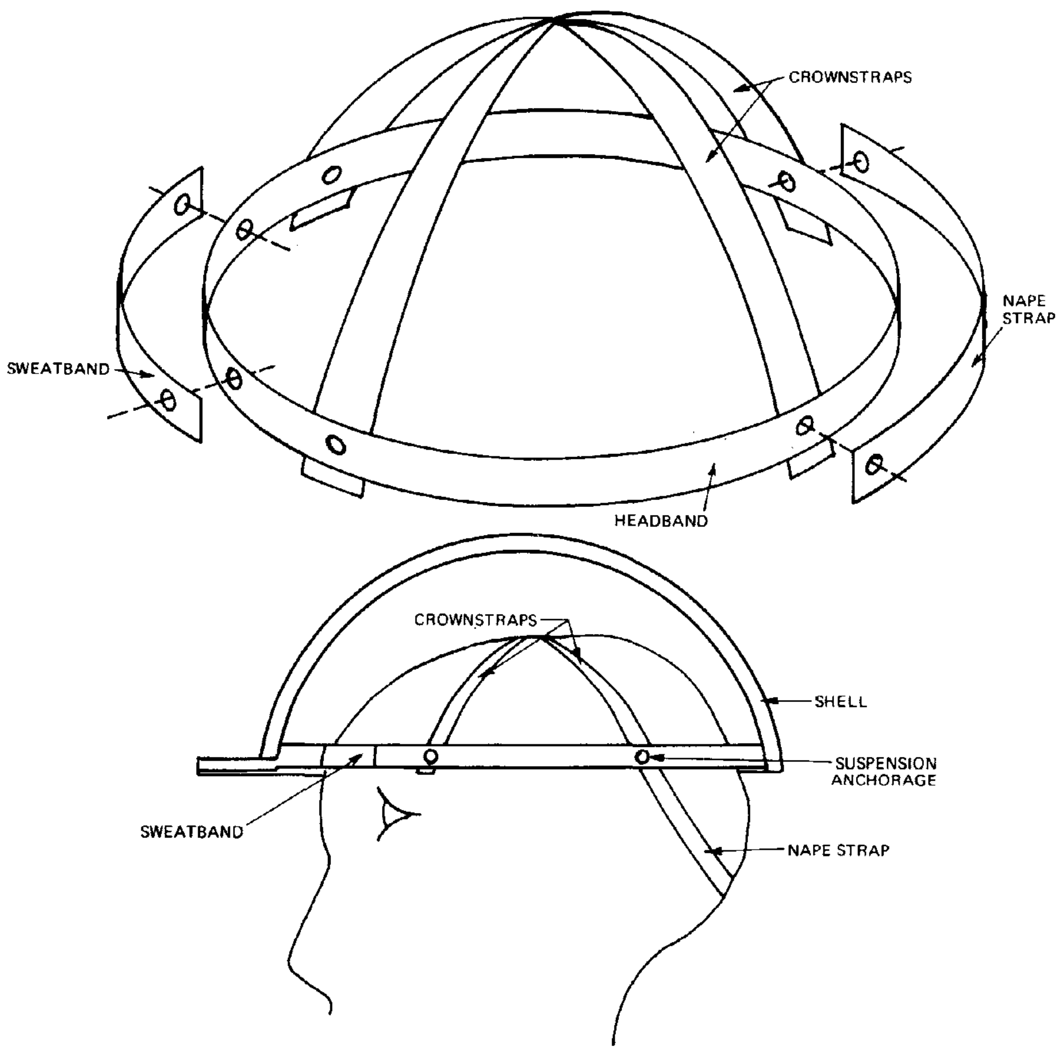


Fig. 15. Helmet suspension system

a blow is delivered on or around their location.

In general, when a blow is delivered to the apex of the shell/suspension helmet, the force of impact is efficiently attenuated by the system.

As an example of the interaction between the shell and suspension, consider Figures 16(a) and 16(b). Figure 16(a) shows the headform response when a helmet of aluminum shell and four-point nylon webbing suspension is dropped a distance of 40 inches onto a flat rigid anvil. Figure 16(b) shows the response for the same type helmet with rigid steel straps installed in place of the original webbing material.

It is seen that the suspension effectively reduces both peak acceleration and onset rate (g/sec.) and spreads out the impact over a longer period.

The suspension helmet will function well until the head/shell distance approaches zero and the total remaining force of impact is transferred directly to the head.

Such a case may be seen in Figure 17 where a helmet of polycarbonate shell and nylon suspension was dropped a distance of 90 inches onto a rigid hemispherical anvil at the apex.

Merits and Weaknesses of Padding and Suspension Methods

The inherent characteristics of both impact protection systems may be summarized as follows:

(a) *Direction of Impact* — padding material pos-

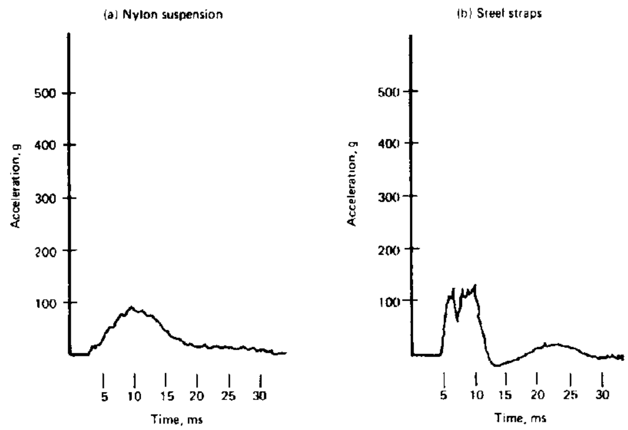


Fig. 16. Shell suspension response

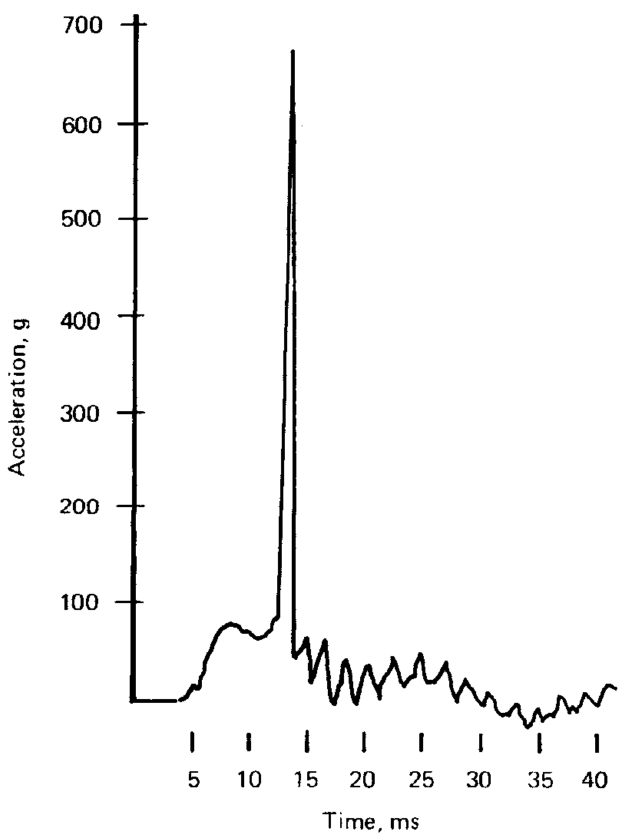


Fig. 17. Helmet bottoming response

sesses the ability to protect from blows to many head areas. To offer the same protection, suspension type helmets would need an elaborate system of straps and anchorages to maintain head/helmet clearance in all directions.

(b) *Protection Ability* — impacts to the apex of helmets with padding and with suspension have shown that the suspension helmet offers superior energy absorption characteristics. In areas other than at the apex, however, present industrial headgear offer virtually no protection whereas the padding type helmets are capable of absorbing high energy blows in all directions.

(c) *Comfort Factors*

(1) Heat - suspension type helmets are more suited to high temperature working conditions as the head/helmet clearance allows ventilation. The padding helmet which fits closely to the head will tend to be uncomfortably hot.
Conversely, in cold environments the padding helmet is more suitable.

(2) Fit — Both the suspension and padding helmet, to fit well, must conform to the contours of the head. In padding type helmets this may be accomplished by a soft foam covering over the padding material. For suspension helmets, the nylon webbing material conforms well to the head dimensions whereas the molded plastic suspensions are not pliable and tend to produce poorer fit.

(3) Weight — If designed properly, the padding type helmet will not be appreciably heavier than the suspension type, because of the very low density of padding materials.
However, because of the large head/helmet apex clearance in the suspension helmets, these will tend to have a high center of mass and therefore will feel "top heavy" when worn.

(d) *Ease of Maintenance* — The suspension helmet is by far the more easily maintained of the two. By removing the suspension from the shell, both may be cleaned or disinfected or, if needed, a new suspension may be installed.
Most padding materials are not easily cleanable, and may be damaged if cleaning is attempted. Thus, soiled padding must be able to be removed and easily replaced with new material or the padding must be covered with a material which is resistant to contaminants.

The Hybrid

In many applications such as protective headgear for sports and helmets for law enforcement officers, the relative merits of both protective padding and suspension have been combined to offer the best possible protection.

Present Types of Head Protection

In the United States there are two basic levels of industrial head protective devices:

- The industrial helmet and the fire helmet.
- The bump cap.

The Industrial Helmet

The standard industrial protective helmet, often referred to as a hard hat or industrial helmet, is governed by the following types and classes according to ANSI Z89.1–1969 and ANSI Z89.2–1971:

Type 1 - Helmet, full brim
Type 2 - Helmet, brimless, with peak
Class A - Limited Voltage Protection
Class B - Maximum Voltage Protection
Class C - No Voltage Protection
Class D - Limited Voltage Protection, Fire Fighter's Service, Type 1 only.

The most prevalent construction details of these head protective services are:

1. A hard *shell,* some smooth, others with reinforcing ridges of various designs. The most common shell materials are polyethylene, polycarbonate, ABS (Acrylontrile-Butadiene-Styrene), polycarbonate/ABS blend, aluminum, fiberglass, and resin-impregnated textiles.
2. *A suspension* which encircles the head usually of plastic construction and adjustable to a variety of sizes. The suspension provides inpact protection from top of head blows.
3. *A sweatband* which contacts the workers head at least at the forehead area. It is usually of a leatherette construction.

Accessories for these helmets include:

1. A *chin strap* of fabric covered elastic which attaches to the shell or suspension.
2. A *nape strap* usually of plastic material, sometimes containing a plastic foam pad. It extends from the rear of the suspension and encircles the occipital region of the head for retention purposes.

Firefighters' helmets are governed by the Z89.1 specification, however, these are often thought of as being classified separately because of their different construction. The shell materials for firefighters' headgear are found to be made of leather, fiberglass, thermoplastic and aluminum.

The shells have large, contoured brims which are designed to shed falling water. Chin straps found on these helmets may be of the elastic type or of leather construction. The suspension may be of the type found on industrial helmets but in some cases a cotton skull cap is used in its place.

The Bump Cap

The bump cap is a small light helmet whose function is to serve as protection from bumps, cuts, and scrapes. Presently, no standard or specification exists for this type of headgear.

The bump cap consists of:

1. A light, smooth plastic *shell* of cap design which has a peak but no brim. Some designs incorporate a rolled edge. Other designs contain 2 to 4 inches of perforations for ventilation on the sides of the cap.
2. A positioning *suspension* which secures the shell to the headband, usually of plastic construction and not designed to absorb impact forces.
3. An adjustable *headband* with size ranges marked. The headband is usually made of plastic material and covered by a leatherette *sweatband.*

Manufacturing Capabilities

The purpose of this section is to outline the capability of industry within the United States and in foreign countries to manufacture the types of head protective devices needed.

Present U.S. Production

In 1971, some 30 manufacturers and distributors in the United States sold over 15,000,000 industrial and firefighter's head protective devices, including bump caps.

Table 10 lists 26 helmet models which appeared on the 16 February 1972 Qualified Products List of Construction Workers' Helmets (Federal Specification GGG-H-142) [67].

Helmets having thermoplastic shells, the most abundant type, are manufactured using injection molded techniques. There are an estimated 30 molds in use in the United States, each costing approximately $20,000 (mold only, does not include molding machine).

Fiberglass shell helmets are normally of flocking and resin construction and manufactured by common molding techniques. Helmets of aluminum shell construction are produced by metal stamping methods. Helmets of resin impregnated textiles are normally fabricated by application of phenolic resin to several layers of textile matting.

Table 10. Helmet models appearing on 16 February 1972 Qualified Products list of construction workers' helmets

Manufacturer	Model
Type I (full brim hat)	
Apex-Fibre Glass Products	Apex 1F-1
E. D. Bullard Co.	Models 70-503DM, DL
E. D. Bullard Co.	Models 70-803DM, DL
The Fibre Metal Products Co.	Superglas
Mine Safety Appliance Co.	Type "K" "Skullgards"
Mine Safety Appliance Co.	M.S.A. Glass Fiber Hat
Mine Safety Appliance Co.	M.S.A. Topgard
Mine Safety Appliance Co.	M.S.A. V Gard
Willson Products Div.	Style No. 3STH
Willson Products Div.	Model 8STH
Type II (cap with peak)	
American Optical Corp.	X 16A
Apex Fibre-Glass Products	Apex 1F-2
E. D. Bullard Co.	Models 70-502DM, DL
E. D. Bullard Co.	Model ES502
E. D. Bullard Co.	Model 70-802-D
Cam-Hi Safety, Inc.	CH-69 Raintrough
The Fibre-Metal Products Co.	Superglas
The Fibre-Metal Products Co.	Superelectric E-2 Cap
Jackson Products	SC-3
Jackson Products	SC-10
Mine Safety Appliance Co.	Type "B" "Skullgards"
Mine Safety Appliance Co.	M.S.A. Glass Fiber Hat
Mine Safety Appliance Co.	M.S.A. Type B Skullgard
Mine Safety Appliance Co.	M.S.A. V Gard
Welsh Mfg. Co.	Polycap
Welsh Mfg. Co.	CAPAT
Willson Products Div.	Willson Products No. 5 STC
Willson Products Div.	Style No. 9 STC

Firemen's helmets of leather construction are made from sewn together segments of horse leather, contoured and finished by hand.

Internal suspensions of the plastic type are injection molded. Other types and materials of suspension components are manufactured and assembled by various automated and manual production methods.

With the exception of the leather firefighter's helmet, modern mass production techniques have been applied to the manufacture of industrial protective headgear.

This accounts for the relatively low retail price of industrial headgear. Industrial helmets conforming to ANSI Z89 standards, depending upon design and materials, will cost the consumer approximately \$3-6 each.

Foreign Production

Most industrialized nations of the world manufacture and use industrial head protective devices. Most nations have their own specifications, however, many western European countries adhere to ISO standards.

Although actual total production figures have been difficult to obtain, the following estimates have been obtained for three representative countries:

- West Germany — 3,000,000 units per year
- Australia — 300,000 units per year
- Japan — 6,000,000 units per year

Required Modification for Improved Head Protective Devices

The production of head protective devices to meet the needs of the industrial and firefighting environment as developed in this study will require modification of existing designs and/or totally new headgear. The need for standardized identification markings and consumer information appearing on each head protective device will, by itself, necessitate modification of all existing industrial helmet shell molds and dies. As has been previously stated, the impact protection afforded by industrial headgear should be extended to include the front, rear, and sides of the head as well as the top. Modification of the present shell/suspension design will be needed in order to effect this change. Manufacturers may be expected to incorporate various types of protective padding and suspension arrangements depending upon the chosen design, materials, and manufacturing methods.

It is expected that all requirements set forth herein are within the state of the art technology. The apex impact requirement (72-inch impact drop — 80g maximum head acceleration) of CLASS 1, CLASS 2, CLASS 4 headgear may pose some problem to designers.

Matrix

The needs of industrial and firefighters' head protective devices may be tabulated with respect to devices presently available, devices which may be produced with present technology, and current standards which apply to the need.

As such this represents a matrix or guideline by which recommended standards may be developed. The matrix is presented as Table 11 and considers the following need categories:

Table 11.

(a) Impact protection, fall to different level hazard

(b) Impact protection, struck by object hazard

(c) Impact protection, fall on same level hazard

(d) Penetration resistance, fall to different level hazard

(e) Penetration resistance, struck by object hazard

(f) Penetration resistance, fall on same level hazard

(g) Retention, fall to different level hazard

(h) Retention, struck by object hazard

(i) Retention, fall on same level hazard

(j) Operating temperatures

(k) Electrical resistance

(l) Flammability

(m) Moisture resistance

(n) Weight

(o) Identification markings

Table 11. (a), (b) and (c) - MATRIX

IMPACT PROTECTION

Need category	(a)	(b)	(c)
Description	Control of fall to different level, characterized by high energy impact at all head locations.	Control of objects striking the head. Hazard characterized by low to high energy impacts with top of head most vulnerable.	Control of fall on same level and bump into hazards, all head locations.
Performance required	Magnitude of impact not definable, impact energy level must be maximum possible within state of the art. Head acceleration must be maintained within Head Injury Criterion (HIC) limits.	Magnitude of impact not definable. Apex impact energy level must be maximum possible within state of the art. Head acceleration must be kept as low as possible to minimize possible neck injury.	Fall on same level may be simulated by modified head to floor height drop. Head acceleration must be maintained within HIC limits.
Available helmets	New Zealand heavy duty industrial helmets.	Best performing U.S. industrial helmets with possible modification.	Impact attenuation well within capability of helmets with protective padding.

Table 11. (a), (b) and (c) - MATRIX — Cont'd.

IMPACT PROTECTION

Need category	(a)	(b)	(c)
Test requirements	(1) Accurate measurement of head acceleration in simulated head impact. (2) Test headforms with simulated human response and standard dimensions. (3) Data reduction equipment for peak "g" and/or Head Injury Criterion evaluation.		
Applicable standards	(1) Suitable impact drop fixture — ANSI Z90.1–1971. (2) Simulated human head response desirable, but no available suitable headform sizes — FMVSS No. 218. (3) Head Injury Criterion — FMVSS No. 208.		
User considerations	Impact performance must not be degraded by normal user cleaning and adjustment.		

Table 11. (d), (e) and (f) - MATRIX

PENETRATION RESISTANCE

Need category	(d)	(e)	(f)
Description	Must parallel fall to different level impact hazard.	Must parallel object striking head impact hazard.	Must parallel fall on same level impact hazard.
Performance required	Magnitude of penetration must be sufficient to demonstrate integrity of helmet shell. Penetrating object must not come in contact with the head.		
Available helmets	Most rigid shell U.S. industrial helmets offer sufficient protection.		
Test requirements	(1) Plumb bob used as penetrating object. (2) Rigidly mounted test headform. (3) Head contact sensing apparatus.		
Applicable standards	(1) Suitable plumb bob — ANSI Z89.1 and Z89.2 — modified. (2) Standard headforms — FMVSS No. 218.		
User considerations	Penetration resisting ability must not be degraded by normal user cleaning and adjustment.		

Table 11. (g), (h) and (i) - MATRIX

RETENTION ABILITY

Need category	(g)	(h)	(i)
Description	Must parallel fall to different level impact hazard.	Must parallel object striking head impact hazard.	Must parallel fall on same level impact hazard.
Performance required	Must be sufficient to retain helmet on head under normal impact conditions.		
Available helmets	New Zealand heavy duty industrial helmets.	Within capability of chin straps but not currently available except those as E. D. Bullard fire helmet.	Within capabilities of chin straps but not currently available.
Test requirements	It is desirable that head/helmet slippage be tested, however, simulated head not available, therefore, a test of chin strap strength must be used.		
Applicable standards	Test method as in NZS–2264–1970 and ANSI Z90.1–1971.		
User considerations	Chin straps must be comfortable when worn and must be compatible with other personal protective equipment.		

Table 11. (j), (k) and (l) - MATRIX

	OPERATING TEMPERATURES	ELECTRICAL RESISTANCE	FLAMMABILITY
Need category	(j)	(k)	(l)
Description	Industrial helmets must withstand normal working temperatures and storage temperatures. Fire helmets must withstand very high short duration temperatures.	Electrical hazard most frequent in building and utility trades, however, hazards occur in many industries.	Low burning rate desirable for industrial applications, fire helmets must be self-extinguishing.
Performance required	Industrial helmets must pass mechanical tests when conditioned at 14°F and 122°F, and withstand storage of 160°F. Fire helmets must also withstand test after short duration exposure to 300°F.	Helmet should demonstrate not more than 9 ma leakage at 20,000 V, AC and should not breakdown below 30,000 volts.	Burn rate maximum of 3 inches per minute for industrial helmets. Fire helmets must demonstrate self-extinguishing.
Available helmets	Most helmet materials suitable for 14°F to 122°F. Fiberglass and special material suited to 300°F exposure.	All ANSI Z89.2 helmets.	Most helmet materials are suitable.
Test requirements	Conditioning environment of: 14°F, 122°F, 300°F	Source of 30,000 V, AC and current measuring instrumentation and method of application to helmet.	Application of flame and timing and measuring instruments.
Applicable standards	ANSI Z89– 14°F to 122°F	ANSI Z89.2–1971	ASTMD635
User considerations	160°F storage temperature normally used for military application.	Most thermoplastics will withstand such voltages, thus, helmets cost not expected to drastically increase.	

Table 11. (m), (n) and (o) - MATRIX

	MOISTURE RESISTANCE	WEIGHT	IDENTIFICATION MARKINGS
Need category	(m)	(n)	(o)
Description	Must be sufficient to resist net weather and perspiration exposure.	Industrial headgear must be as light as possible. Fire helmets may be heavier due to intermittent wear.	Class of helmet must be readily apparent to user and compliance officer, important user information must be permanently present on helmet.

Table 11. (m), (n) and (o) - MATRIX — Cont'd.

	MOISTURE RESISTANCE	WEIGHT	IDENTIFICATION MARKINGS
Need category	(m)	(n)	(o)
Performance required	Water immersion at 77°F for 12 hours, should not increase weight more than 5%.	Maximum Duty - 18 oz Medium duty - 16 oz Light duty - 12 oz Firefighter - 30 oz	Class designation, manufacturer model, month and year manufactured, recommended cleaning agent.
Available helmets	Most industrial headgear are suitable.	NZ helmets suited to maximum duty modified Z89 suitable. For medium duty, firefighter and light duty not available.	None available.
Test requirements	Water bath apparatus	—	—
Applicable standards	ANSI Z90.1–1971	—	—
User considerations	—	—	Must be clear and legible in apparent location.

Evaluation of Current Standards

The ANSI Z89.1 and Z89.2 currently govern industrial and firefighters' helmets sold in the United States. The performance requirements of these standards are summarized in Table 12.

Background of the ANSI Standards

The existing ANSI Z89 Class A, B, C, and D headgear have evolved from previous standards and represent a compilation of many different requirements which have been found to be necessary through the years. Fragments of research and test methods developed over the past 50 years form the basis of these standards. Consequently, much of the reasoning which led to the production of the performance levels has been lost. Many of the researchers responsible for the derivation of the methods and procedures of the old standards are deceased, and the files and test reports surrounding their work have been lost or destroyed. We may trace the development of the ANSI standards which is shown in Figure 18. The complete titles of these standards are:

- Z2.1–1921 American Standard Code for the Protection of Heads, Eyes and Respiratory Organs.
- Z2.1–1938 American Standard Code for the Protection of Heads, Eyes and Respiratory Organs.
- Federal Specification GGG–H–142.
- Z2.1–1959 American Standard Safety Code for Head, Eye and Respiratory Protection.
- AP–1–1961 Specifications for Electrical Workers Insulating Safety Headgear, Edison Electric Institute.

Table 12. Industrial and firefighters' helmets present performance requirements

—CLASS—	A	B	C	D
DESCRIPTION	General use limited voltage	High voltage protection	General use metallic, no voltage protection	Firefighter service
Material to be	Water resistant, slow burning	Water resistant, slow burning	Water resistant, slow burning	Fire resistant
Insulation resistance	2,200 volts 60 cps 1 minute 3 ma max leakage	20,000 volts 60 cps 1 minute 3 ma max leakage	Not Applicable	2,200 volts 60 cps 1 minute 3 ma max leakage
Flammability	3 in/min	3 in/min	Not Applicable	Self extinguishing
Water absorption (by wt.)	5% max.	0.5% max.	5% max.	5% max.
Impact energy	40 ft-lb	40 ft-lb.	40 ft-lb	40 ft-lb
Impace force (avg.) attenuation (max.)	850 lbs. 1,000 lbs.	850 lbs. 1,000 lbs.	850 lbs. 1,000 lbs.	850 lbs. 1,000 lbs.
Weight (oz. max.)	15	15.5	15	30
Penetration resistance	3/8″ max.	3/8″ max.	7/16″ max.	3/8″ max.
Standard	Z89.1–1969	Z89.2–1971	Z89.1–1969	Z89.1–1969

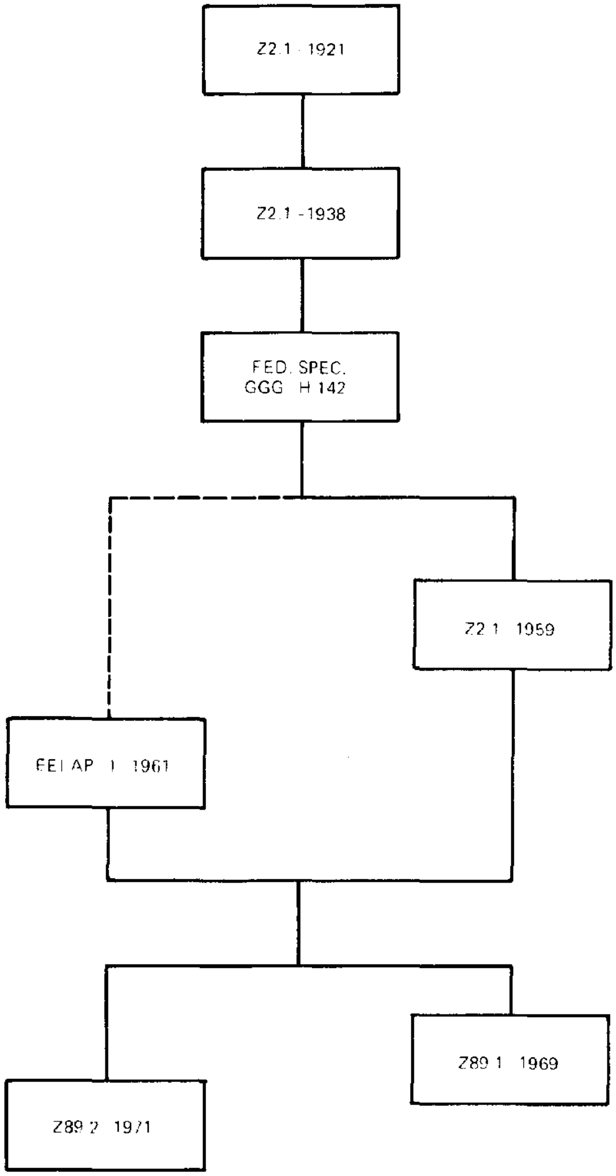


Fig. 18. Development of the ANSI Industrial Helmet Standards

- Z89.1–1969 American National Standard Safety Requirements for Industrial Head Protection.
- Z89.2–1971 American National Standard Safety Requirements for Industrial Protective Helmets for Electrical Workers, Class B.

Of particular interest in the progression of these standards is the development of the performance requirements. The bulk of the Z89.1–1969 standard appeared in the Z2.1–1959. Thus, we may focus our attention at the 1938–1959 standard evolution.

Impact Protection

Prior to the 1959 standard, the impact test was conducted by adjusting the helmet's crown straps to allow 1¼-inch crown clearance, a sheet of white paper backed up by carbon paper was then lined inside the shell. The helmet was then mounted on a wooden hat block and an 8-pound steel sphere was dropped a distance of 5 feet onto the center of the crown of the helmet. "The transfer of marks from the block or straps to the crown, or vice versa, shall indicate failure to withstand the impact from this same blow without breaking or forcing the hat down over the head" [68].

In July 1949, the New York Naval Shipyard reported [69] the results of a program to investigate possible improvements in this procedure.

In their words, "it was considered desirable to develop a method whereby the magnitude of the force transmitted by the impact to the hat block could be evaluated quantitatively." Their work resulted in the construction of an impact test apparatus consisting of a hat block mounted on a simply supported beam to which strain gages were attached. The strain gage output was amplified and displayed on a cathode ray oscilloscope, providing a record of the force transmitted through the helmet.

In August 1951, the Material Laboratory [70] engaged in a project to develop a simplified impact test evaluation method for brand approval and inspection test purposes.

It was noted that the carbon mark transfer method was ". . . found, in general, unsatisfactory and in many cases completely inadequate in evaluating drop ball impact performance." The developed strain gage method was not considered a viable solution because ". . . of the relatively intricate procedure involved in recording and calibrating the transient force-time curves."

Their final effort produced an apparatus whereby the force transmitted through a helmet under test was measured by means of a mechanical indentation gage. This system called the "Brinell Impression Method" consisted of having a hat block apply force by means of a hardened steel ball to which an aluminum bar whose Brinell Hardness has been predetermined. The diameter of the resulting impression in the aluminum bar, when read with a micrometer microscope, represents a measure of the transmitted force.

The diameter of the impression could be evaluated by the following Brinell hardness formula:

$$F = 2.2 \times H \times \frac{\pi D}{2} \times (D - D^2 - d^2)$$

where:

F = transmitted force in pounds.

H = average Brinell hardness number of the impression bar

D = diameter of impression ball, mm

d = diameter of impression, mm

This test method was adopted in Federal Specification GGG–H–142 and later Z2.1–1959 and exists in the ANSI Z89 standards almost exactly as developed by the Material Laboratory. The Brinell penetrator assembly as specified in ANSI Z89 is shown in Figure 19.

The developers of the Brinell impression method, as a result of impacts on 69 helmets demonstrating an average transmitted force of 1,090 pounds, recommended that a performance standard using this method should limit allowable transmitted forces to a maximum of 1,000 pounds average force of the samples tested and a maximum individual force of 1,500 pounds. Although the actual progression is not known, it is noted that Federal Specification

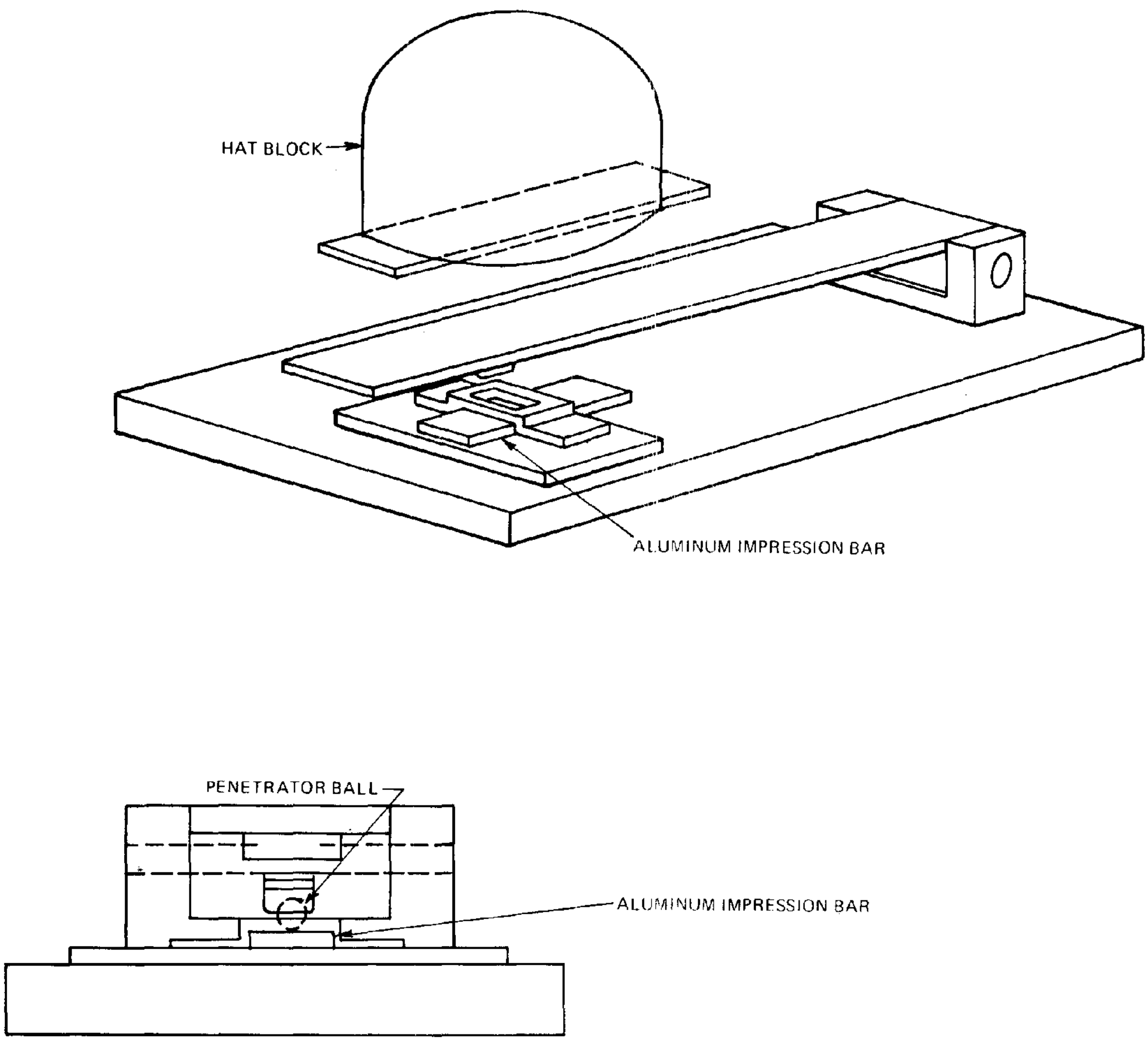


Fig. 19. Brinell penetrator impact assembly

GGG–H–142 required a maximum average force of 850 pounds with no limitations on peak individual forces. Z2.1–1959 adopted this same requirement.

The ANSI Z89 standards now limit transmitted forces of 850 pounds maximum average and 1,000 pounds maximum individual.

It should be noted that in the Z2.1–1959 standard a Class C headgear for limited impact protection and having no electrical protection was specified. This helmet, specifically intended to refer to the metallic helmet, was subjected to an impact of a 3-foot drop of the 8-pound steel sphere. This deviation from the 5-foot drop height was later omitted from the ANSI Z89 specifications.

Two other impact test developments are noteworthy:

(a) Headforms — Originally, a single wooden headform of unknown dimension was used for the carbon mark transfer method. With the development of the Brinell Impression method [71], a set of six wooden hat blocks of the type used for shaping the crowns of felt hats of different head sizes were employed. Subsequently, a set of four wooden headforms were produced from AML head size standards page 18, on Anthropometry of the Head, and used for impact evaluation. The present ANSI specifications require the use of the AML size medium headform for all impact tests. Presently, the short supply of wood headforms has led to the use of an aluminum headform as marketed by the Industrial Safety Equipment Association, ISEA.

(b) Crown Clearance — Understandably in the impact test, a variation in helmet crown clearance adjustment could yield vastly differing test results. To overcome this problem, the authors of the ANSI Z89 specifications eliminated the Z2.1–1959 requirement for adjusting crown clearance to 1½ inches and mandated that all industrial headgear when suspension is in its most relaxed position should have no less than 1¼ inch crown clearance.

Penetration and Low Voltage Insulation Resistance

The currently specified ANSI Z89 Penetration Resistance Test and Low Voltage (2200V) Insulation Resistance Test were in effect at the time of the Material Laboratory impact test investigations [69]. In addition, the current performance requirements for water absorption were also governing protective hats.

High Voltage Insulation Resistance Test

Concern over the number of fatalities to electrical workers due to contact of the head with sources of electric current led the Accident Prevention Committee of the Edison Electric Institute to develop a specification for high voltage electrically insulating headgear (EEI AP-1-1961). This requirement has been adopted in ANSI Z89.2–1961). This requirement has been adopted in ANSIZ89.2–1971 for Class B headgear.

Inadequacies of the Z89 Test Methods

The specific attributes of the Z89 test methods will be treated in detail in the section on Test Requirements, page 66. The following, however, is an overview of some of the more obvious inadequacies of the Z89 tests.

Impact Test

The drop ball impact using the Brinell Penetrator Assembly was, as previously stated, developed as a simplified impact test for inspection test evaluations. At that time, the mechanical test offered simplicity, ease of evaluation, low testing cost and, at that time, more reproducible results than more sophisticated force measuring devices.

It is apparent that certain factors, which at one time were considered insignificant, are causing a relatively large scatter in impact test results. These are summarized as follows:

(1) Degree of homogeneity of impression bars.
(2) Accuracy of impression bar hardness measurement.
(3) Elastic deformation of impression bar at the point of impact.
(4) "Mushrooming" at the edges of the impression bar giving rise to inaccurate measurements.
(5) Variation in drop ball impact point.

In addition, the Z89 impact test apparatus does not provide for impacts at areas other than at the apex of the helmet.

Penetration Tests

This portion of the standard should be revised to reflect the state of the art of helmet testing. The present method requires that penetration of the helmet shall not exceed ⅜ inch (measured along the side of the point of the plumb bob) when a one-pound plumb bob is dropped from a height of 10 feet into the apex of the helmet. The test is conducted at room ambient temperature and the results reported as the average result of the three helmets tested.

The existing method of measurement is inaccurate and does not account for the existence of transient deformation of the helmet shell. The test should be conducted at high and low temperatures as well as at room ambient in order to assess the variation of helmet material mechanical properties with temperature. In addition, the helmets should be tested on the sides, in addition to the penetration tests at the apex.

Electrical Insulation Test

The electrical insulation test, while essentially adequate for evaluation purposes fails to:

(1) specify instrumentation accuracy;

(2) explicitly define breakdown voltage.

Review of Standards

The specifications for industrial head protection in countries other than the United States have followed the basic concepts of the ANSI test methods. In particular, the standards of Canada, Great Britain, and Australia closely parallel the Z89 standards.

Tables 13, 14, 15 and 16 summarize the standard designations, performance requirements, test methods and user information of the U.S., Canadian, Australian, British, and New Zealand standards.

The most radical departure of this trend is seen in the newly developed New Zealand specifications (NZS 2264:1970) for maximum protection industrial head protection. It is readily apparent that none but the New Zealand standard has realized the need for providing helmet retention.

Of significance is the departure from the Brinell impact evaluation method in the Light Duty British Standard (BS 4033: 1966) and the New Zealand standard which have sought to more accurately measure impact performance. The only other major departure from the norm is the edge stiffness test of the Australian standard which somewhat resembles the now defunct edge stiffness test of the Z2.1–1959 U.S. standard.

Table 13. Review of standards, designations

Standard	Title	Organization	Date
ANSI Z89.1–1969	Safety requirements for Industrial head protection	American National Standards Institute	December 17, 1969
ANSI Z89.2—1971	Safety requirements for industrial protective helmets for electrical workers, Class B	American National Standards Institute	April 14, 1971
Federal Specification GGG-H-142G	Federal specification helmet, construction workers	General Services Administration	August 26, 1969
Federal Specification GGG-H-177a Amendment	Federal specification helmet, electrical workers	General Services Administration	July 24, 1968
CSA Standard Z94.1–1966	Industrial protective headwear	Canadian Standards Association	September, 1968
Australian Standard Z10–1967	Industrial safety helmets	Standards Association of Australia	June 1, 1967
British Standard 4033:1966	Specification for industrial scalp protectors (light duty)	British Standards Institution	June 30, 1966
British Standard 2095:1958	Industrial safety helmets (light duty)	British Standards Institution	January 31, 1958
British Standard 2826:1957	Industrial safety helmets (heavy duty)	British Standards Institution	March 20, 1957 (Amend. 2, 2/26/70)
New Zealand Standard 2264:1970	Specification for industrial safety helmets, maximum protection	Standards Association of New Zealand	June, 1970

Table 14. Performance requirements of standards

Standard	Impact	Penetration	Retention	Electrical	Water absorption	Weight	Edge stiffness
ANSI Z89.1–1969	850 lbs max. ave 1000 lbs max on individual	Class A & D - ⅜″ max. Class C - $\frac{7}{16}$″ max.	N/R	Class A & D: 2200 V, 3ma max. Class C: N/R	5.0%	Class A & C: 15 oz. Class D: 30 oz.	N/R
ANSI Z89.2–1971	850 lbs max ave 1000 lbs max on individual	⅜″ max.	N/R	Class B: 30,000 V max. 20,000 V, 9ma	B: 0.5% A & D: N/R	15.5 oz.	N/R
Fed. Spec. GGG-H-177a 1964	850 lbs max ave 1000 lbs max on individual	⅜″ max. (helmet not forced down over headform, nor straps pulled out or broken when tested)	N/R	9ma max. 30,000 V max.	0.5% max.	15½ oz.	N/R
Fed. Spec. GGG-H-142G 1969	850 lbs max ave 1000 lbs max on individual	⅜″ max. (helmet not forced down over headform, nor straps pulled out or broken)	N/R	3ma max.	5% max.	15 oz.	N/R
CSA Standard Z94.1–1966	850 lbs max ave 1000 lbs max on individual	⅜″ max. (and no headform contact)	N/R	Class A & D: 2200 V, 3ma max. Class C: N/R Class B: 20,000 V, 9ma 30,000 V max.	B: 0.5% wt max. A, C & D: 5% max.	Class A, B & C 15 oz.	N/R
Australian A10–1967	850 lbs max ave 1000 lbs max on individual	⅜″ max.	N/R	3ma max. (2,000 V 1 min.)	N/R	16 oz.	0.5″ max. @ 20 lb
BS4033: 1966	3000 lbs front & rear (No breakage or cracks)	No contact (No breakage or cracks)	N/R	N/R	N/R	N/R	N/R
BS2095: 1958	Apex 850 lbs max ave 1000 lbs. max on individual (No harness breakage)	⅜″ max. penetration depth (No harness breakage)	N/R	(Optional) 3ma max. leakage current	N/R	N/R	N/R
BS2826: 1957	Apex 850 lbs max ave 1000 lbs max on individual (No harness breakage)	⅜″ max. penetration depth	N/R	(Optional) 3ma max. leakage current	N/R	N/R (recommended) 18 oz. max.	N/R

Table 14. Performance requirements of standards — Cont'd.

Standard	Impact	Penetration	Retention	Electrical	Water absorption	Weight	Edge stiffness
NZS2264: 1970	Above test line max = 4400 lb	1/16" headform deformation	Chin strap 1" max. elongation	(Optional) 3ma max. or 9ma max. leakage current	N/R	(recommended) 18 oz. max.	N/R

Table 15. Test methods of standards

Standard	Impact	Penetration	Retention	Electrical resistance	Edge stiffness
Z89.1–1969	Brinell 5 ft. x 8 lb. = 40 ft.-lb.	Plumb Bob 1 lb. x 10 ft. = 10 ft.-lb.	N/R	2,200 V, 1 Minute	N/R
Z89.2–1971	Brinell 5 ft. x 8 lb. = 40 ft.-lb.	Plumb Bob 1 lb. x 10 ft. = 10 ft.-lb.	N/R	20,000 V, 3 Minutes Increase to 30,000 V (1000 V/sec.)	N/R
Fed. Spec. GGG-H-177a	Brinell 5 ft. x 8 lb. = 40 ft.-lb.	Plumb Bob 1 lb. x 10 ft. = 10 ft.-lb.	N/R	20,000 V, 3 Minutes Increased to 30,000 V at 1000 V/sec. for 3 sec.	N/R
Fed. Spec. GGG-H-142G	Brinell 5 ft. x 8 lb. = 40 ft.-lb.	Plumb Bob 1 lb. x 10 ft. = 10 ft.-lb.	N/R	2,200 V, 1 Minute	N/R
CSA Standard Z94.1–1966	Brinell 5 ft. x 8 lb. = 40 ft.-lb.	Plumb Bob 1 lb. x 10 ft. = 10 ft.-lb.	N/R	A, D 2,200 V, 1 Minute B 20,000 V, 3 Minutes increase 1000 V/sec. to 30,000 V, 3 seconds	N/R
Australian Z10–1967	Brinell 5 ft. x 8 lb. = 40 ft.-lb.	Plumb Bob 1 lb. x 10 ft. = 10 ft.-lb.	N/R	Gradually increase to 2000 V, 1 Minute	20 Pounds
BS4033:1966	10 ft.-lb. Force Gauge	Plumb Bob 1 lb. x 2 ft. = 2 ft.-lb.	N/R	N/R	N/R
BS2095:1958	Brinell 3.5 ft. x 8 lb. = 28 ft.-lb.	Plumb Bob 1 lb. x 7 ft. = 7 ft.-lb.	N/R	2,000 V RMS	
BS2826:1957	Brinell 5 ft. x 8 lb. = 40 ft.-lb.	Plumb Bob 1 lb. x 10 ft. = 10 ft.-lb.	N/R	2,000 V RMS	
NZS2264:1970	Load Cell 10 ft. x 11 lb. = 110 ft.-lb.	Plumb Bob 2.2 lb. x 9.8 ft. = 21.7 ft.-lb.	100 lbs.	(Optional) 2,000 V RMS or 20,000 RMS	N/R

Table 16. User information in standards

Standard	Cleaning	Painting	Inspection	Limits of protection	Precautions
Z89.1–1969	140°F water scrub and rinse	Caution noted consult mfgr.	Yes	Yes	Yes
Z89.2–1971	140°F water scrub and rinse	N/R	Yes	Yes	Yes
GGG–H–177a	N/R	N/R	N/R	N/R	N/R
GGG–H–142G	N/R	N/R	N/R	N/R	N/R
GGG–H–142G	N/R	N/R	N/R	N/R	N/R
CSA Standard Z94.1–1966	140°F water scrub, rinse 140°F max.	Caution noted consult mfgr.	Yes	Yes	Yes
Australian Z10–1967	N/R	N/R	N/R	N/R	N/R
BS4033:1966	N/R	N/R	N/R	Yes	Yes
BS2095:1958	N/R	N/R	N/R	Yes	Yes
BS2826:1957	N/R	N/R	N/R	Yes	Yes
NZS2264:1970	N/R	N/R	N/R	Yes	Yes

Criteria for Recommended Standards

Performance Criteria

It has been determined that the overall problem of providing adequate head protection for industrial workers and firefighters may best be accomplished by four levels of head protection:

(1) Maximum Duty — for use by industrial workers in extremely hazardous environments where work on elevated surfaces risks the precipitation of falls and where there is considerable risk of being struck by falling or flying objects.

(2) Medium Duty — for use by industrial workers in moderately hazardous environments where there is considerable risk of being struck by falling objects and where imperfect working surfaces create a risk of slips and falls.

(3) Light Duty — for use by industrial workers in low hazard areas where working surfaces create a risk of slips and falls and where objects in the work area create a significant bump-into hazard.

(4) Firefighter's Headgear — for use by individuals engaged in firefighting activities where there is considerable risk of being struck by falling debris and where walking surfaces are such that a slip and fall hazard is prevalent. In addition, firefighter's headgear must be highly resistant to fire and heat.

The following sections develop the attributes and levels of performance for these classes.

General Requirements

Materials

Industrial protective headgear for general use will be subjected to varying degrees of user abuse and environmental exposure. For this reason all industrial and firefighter's headgear must demonstrate:

(a) Durability of materials — Durability is a qualitative requirement which must be designed into the headgear, and which may be evaluated by the user. A manufacturer who does not produce a helmet which will stand up to the abuses of the wearer will find difficulty in marketing it.

(b) Resistance to sunlight — No helmet should be severely attacked or have its performance degraded by ultraviolet radiation. Although all materials will show some degradation with age, most helmet materials appear to be unaffected by exposure to the elements [72]. This, of course, does not guarantee performance of future designs, and a test method is desirable. However, the most reliable weathering information must come from actual exposure which is not well suited to laboratory test. Present methods of artificial U.V. conditioning such as the weatherometer, will not permit uniform and realistic exposure of a helmet. Until better definition of the U.V. condition is made, the requirement must be left to the integrity of the manufacturer.

(c) Compatibility with the wearer — All materials which come in contact with the wearer's head must not cause skin irritation or disease and must not be affected by perspiration, body oils or normal hair preparations. In addition, the structure of the helmet must not possess inherent risks to the wearer. That is, all edges of the helmet must be smooth, and there must be no rigid internal projections which may cause injury to the wearer in the event of an impact.

(d) Resistance to common cleaners — All helmets must withstand soap and water cleanings by the user. This should extend to common household detergents and, of course, any cleaners recommended by the manufacturers.

Helmet Assembly

All industrial and firefighters' helmets must protect all areas of the upper part of the wearer's head. This area may be described as lying above the reference plane of the head. The reference plane is an immaginary plane which lies a specified distance above and parallel to the basic plane. The basic plane passes through the centers of the external ear openings and the lower edges of the eye sockets, as shown in Figure 20. The distance between the reference and basic planes will be pro-

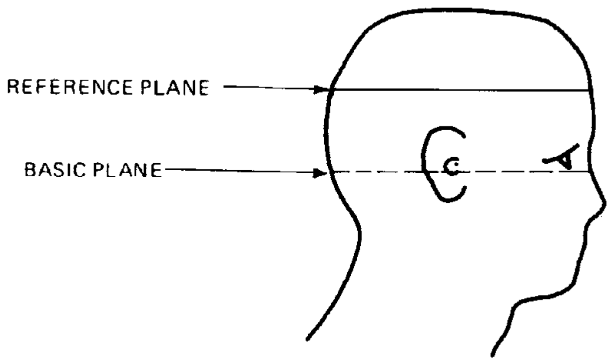


Fig. 20. Extent of protection

portional to head size and therefore must be designated on appropriate positioning headforms.

It is not intended that all protective headgear should *limit* protection to the upper area of the head. It is desirable that as much of the head as possible be protected, however, headgear for general industrial and firefighting use must be compatible with existing forms of eye, ear and respiratory personal protective equipment. Thus, any *required* area of protection should be limited so that it does not conflict with the space requirements of other protective gear.

Helmets designed for increased area of protection must not interfere with wearer's vision. To accomplish this, no less than 120° peripheral vision to each side of the mid-sagittal plane must be maintained from the basic plane to the brow opening of the helmet Figure 21.

In order to meet the needs of industrial and firefighter's head protection all helmets must provide:

(a) Outer shell — The outer shell of a helmet must be hard and non-brittle to resist penetrating objects and to spread impact loading. The shell must be as smooth as possible to minimize head rotation and ward off glancing impacts. In the area above the reference plane, the shell must be of uniform strength and thus have no holes or gaps, and must be of nominally uniform thickness.

For eye protection and ease of placement each helmet must have a peak extending, as part of the shell, over the eyes. The peak must be a minimum of one inch in width and to reduce the possibility of head rotation from falling object impact, should be no greater than two inches in width. The peak should extend to at least the biocular diameter (distance between the outer corners of the eyes) which is approximately two inches to each side of the mid-sagittal plane for the 50th percentile male [48].

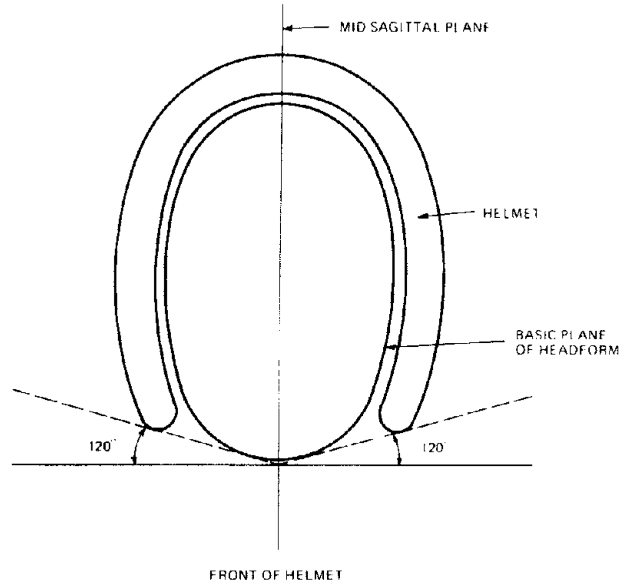


Fig. 21. Required peripheral vision

In some applications it may be desirable for the helmet to have a brim which extends the full circumference of the helmet for deflecting water. In this case brims on industrial helmets should be no greater than two inches in width.

For firefighters' use, brim dimensions and contours will be as selected by the user. Some firefighting departments have gone to great lengths to accurately describe brim contour requirements [73]. Many fire departments are currently investigating the use of one piece protective suits and helmets with integral eye protection. In these cases no peak or brim need be required.

(b) Force attenuating medium — It is imperative that the force attenuating medium used in the helmet be it protective, padding or a suspension system, have the following characteristics:
  - be moisture and perspiration resistant
  - be easily cleanable (exposed padding and straps)
  - cements used for the installation of protective padding must be weather and perspiration resistant

(c) Retention system — The helmet must have a chin strap or some other means of retaining the helmet on the head with equivalent strength. Straps used must be a minimum of ¾ inch in width to eliminate concentrated loading and to maximize comfort.

(d) Identification markings — For purposes of identification, each helmet must have a clearly visible marking depicting the class of protection. In order to optimize visibility a seal on the forehead part of the shell, such as that shown in Figure 22, should be molded as part of the shell. These marking are:

- Maximum duty - Class 1 -①
- Medium duty - Class 2 -②
- Light duty - Class 3 -③
- Firefighter - Class 4 -④

In addition, on the underside of the peak or brim, the following information must appear:

- Class of headgear
- Manufacturer's name
- Model designation
- Month and year of manufacture
- Recommended cleaning agent

This information must be permanently molded, stamped, branded, engraved or etched into the shell material. In this manner, the user will have this important information readily available. This will also aid the employer by assuring him that the helmet used is correct for the application. This will also assist him when it is determined that replacement of the entire helmet or parts of it is necessary.

Fig. 22. Identification markings

Performance Requirements

Impact Attenuation

In keeping within the basic impact protection needs of industrial and firefighters' headgear, we may develop the impact performance requirements of the various levels of protection:

Output: Human Tolerance

For purposes of assessing the helmet's ability to mitigate the effects of a blow to the head, we must evaluate a helmet's impact performance in terms of available human tolerance data.

A. Lateral Impact — In the section on Anthropometry of the Head, page 18, it was shown that severe injury to the front, rear, and sides of the head may be reduced by controlling cerebral concussion. Subsequently, it was shown that the Head Injury Criterion has been accepted as a means of assessing head impact response, such that the concussion injury threshold is not reached. Thus, the Head Injury Criterion must be used as a failure index for all helmet impacts except those occurring at the helmet apex.

B. Apex Impact — As stated previously, the biomechanical response of the human to an impact to the top of a protected head is not well defined. Many researchers have assumed that such impacts must be governed by the brain concussion injury tolerance. This has not been demonstrated. On the other hand, many have voiced concern that top of head impacts may accelerate the head downwards with such magnitude that cervical fracture will result.

Because of this lack of definitive data, it is considered essential that the present Z89 apex impact failure levels, which have not shown a large incidence of cervical or concussion injury be maintained. It is understood that this represents a conservative injury estimate, however, such a safety factor can only be expected to save the lives of more workers.

Head Injury Criterion evaluation requires the measurement of head acceleration. The present Brinell penetrator assembly does not allow this. The use of an instrumented headform as an impact test device is required. As such, it is beneficial to conduct all impact evaluations on one fixture, so a correlation is necessary between the Brinell method, and the instrumented headform method. The correlation is necessary because the Brinell method is known not to accurately measure impact force.

The developers of the Brinell Impression apparatus [70] state: "In the Brinell Impression method, the measurement of transmitted force, made by means of a mechanical indentation gage, represents, in effect, an "integrated" or summation value."

As shown in Photographs 1 and 2, the Brinell Impression apparatus response was compared by means of a controlled impact. An instrumented drop mass having a 3.8″ diameter, hemispherical anvil attached was dropped such that the potential energy of impact was equal to 40 ft.-lb., onto the Brinell apparatus. An MEP (1″ open blue Modular Elastomer Programmer, MTS Systems, Inc.) was mounted to the Brinell assembly. The weight of the MEP and its mounting was adjusted to equal the weight of the standard ISEA headform (Photograph 7).

Twenty drops were made with a calibrated load washer mounted in place of the impression ball and aluminum bar. These results, shown in Table 17, yielded a mean peak transmitted force of 3,423 pounds.

Next, the same apparatus with the standard indenter and aluminum impression bars (2S - O aluminum, 23.6 Brinell Hardness) was then subjected to 22 drops of the same magnitude. Computed

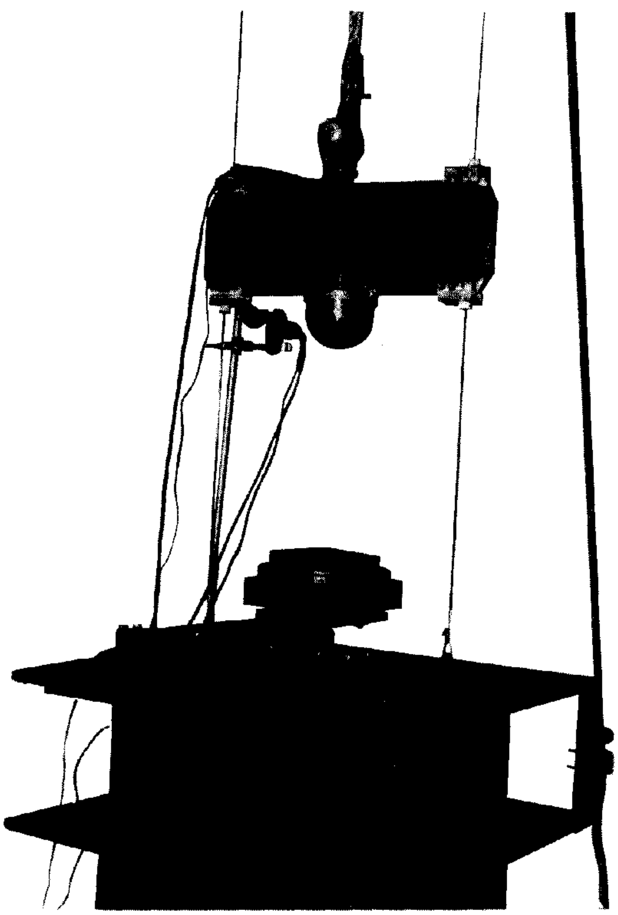


Photo. 1. Instrumented drop mass with load washer mounted in Brinell penetrator assembly.

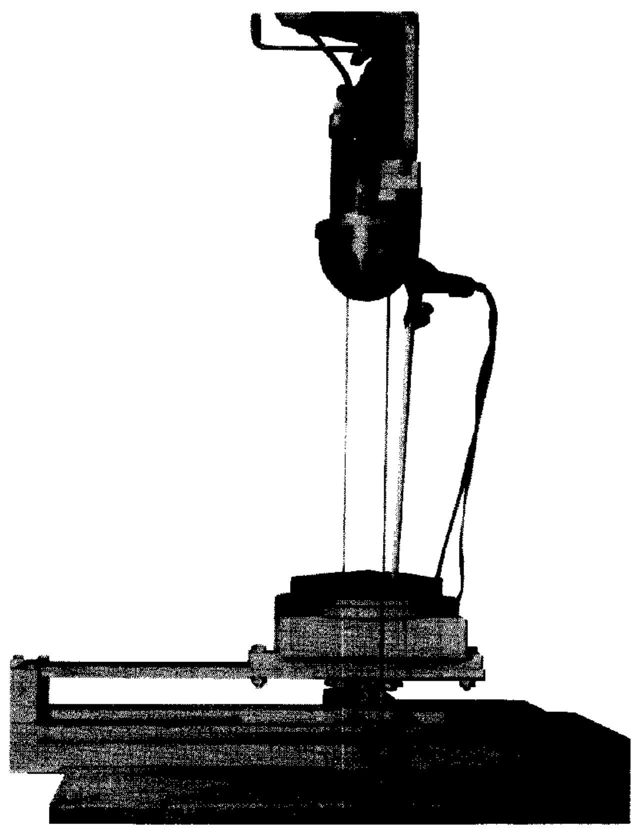


Photo. 2. Instrumented drop mass and Brinell penetrator assembly with aluminum bar.

Table 17. Statistical variation in 20 drops using instrumented drop mass and load washer mounted in place of aluminum impression bar

Drop No.	Load washer readings Force, F	(M-F)	$(M-F)^2$
43	3,401 lbs.	+22.4 lbs.	501.76 lbs.
44	3,368	+55.4	3,069.16
45	3,501	−77.6	6,021.76
46	3,463	−39.6	1,568.16
47	3,449	−25.6	655.36
48	3,417	+6.4	40.96
49	3,448	−24.6	605.16
50	3,524	−100.6	10,120.36
51	3,463	−39.6	1,568.16
52	3,467	−43.6	1,900.96
53	3,459	−35.6	1,267.36
54	3,366	+57.4	3,294.76
55	3,436	−12.6	158.76
56	3,418	+5.4	29.16
57	2,419	+4.4	19.36
58	3,310	+113.4	12,859.56
59	3,359	+64.4	4,147.36
60	3,379	+44.4	1,971.36
61	3,429	−5.6	31.36
62	3,391	+32.4	1,049.76
Σ	68,467 lbs.		50,880.60 lbs.

$$\text{MEAN (M)} = \frac{68{,}467}{20} = 3{,}423.4 \text{ lbs.}$$

$$\text{STANDARD DEVIATION } (\bar{s}) = \pm \frac{\Sigma(\text{M-F})^2}{\text{n-1}} = \pm \frac{50{,}880.60}{19}$$

$$(\bar{s}) = \pm\ 51.75 \text{ lbs. } (1.5\%)$$

values of peak force were made by measuring the diameters of the impressions in the aluminum bars (Photograph 3), using a toolmakers' microscope, and are shown in Table 18. The mean peak transmitted force is seen to be 3,122 pounds.

The differences may best be attributed to energy absorbed in deforming the aluminum bar [74].

The next series of tests were conducted by dropping the mass onto the MEP, where the MEP was rigidly mounted with a load washer beneath it to the back-up anvil. This instrumented mass/rigid anvil is basically the same configuration as the ANSI Z90.1 instrumented headform/rigid anvil as shown in Photograph 4. Converted to force, the acceleration readings, Table 19, show a mean peak transmitted force of 2,906 pounds.

The ratio, then, between rigid anvil drop mass acceleration (converted to pounds force) and Brinell pounds is:

$$\frac{\text{Drop mass}}{\text{Brinell}} = \frac{2{,}906}{3{,}122} = 0.931$$

We may now apply this ratio to the 1,000 pound Brinell failure level for individual blows.

1,000 Pounds x 0.931 = 931 Pounds

or,

$$\frac{931 \text{ lb}_f}{11.2 \text{ lb}_m} = 83.1\text{g}$$

It is thus concluded that when tested on the Z90 fixture, the head acceleration equivalent to the Z89 Brinell pounds is 83g.

Table 18. Statistical variation in 22 drops using instrumented drop mass and Brinell penetrator assembly

Drop No.	Force, F	(M-F)	$(M\text{-}F)^2$
	Aluminum impression bar readings		
21	3,110 lbs.	+ 12 lbs.	144 lbs.
22	3,550	−428	183,184
23	3,260	−138	19,044
24	3,171	− 49	2,401
25	3,150	− 28	784
26	2,606	+516	266,256
27	3,221	− 99	9,801
28	3,197	− 75	5,625
29	3,234	−112	12,544
30	3,164	− 42	1,764
31	2,636	+486	236,196
32	3,216	− 94	8,836
33	3,188	− 66	4,356
34	3,200	− 78	6,084
35	3,126	− 4	16
36	3,171	− 49	2,401
37	3,110	+ 12	144
38	3,159	− 37	1,369
39	3,357	−235	55,225
40	2,720	+402	161,604
41	3,011	+111	12,321
42	3,128	− 6	36
Σ	68,685 lbs.		990,135 lbs.

$$\text{MEAN (M)} = \frac{68{,}685}{22} = 3{,}122 \text{ lbs.}$$

$$\text{STANDARD DEVIATION } (\bar{s}) = \pm \frac{\Sigma(M\text{-}F)^2}{n\text{-}1} = \pm \frac{990{,}135}{21}$$

$$(\bar{s}) = \pm 217.14 \text{ lbs. } (7.0\%)$$

Table 19. Statistical variation in 20 drops using instrumented drop mass and MEP on rigid anvil

Drop No.	Acceleration, G	Force, F	(M-F)	$(M\text{-}F)^2$
	Accelerometer readings			
1	261 g's	2,913 lbs.	− 7.4 lbs.	54.76 lbs.
2	258	2,879	+26.6	707.56
3	259	2,890	+15.6	243.36
4	259	2,890	+15.6	243.36
5	261	2,913	− 7.4	54.76
6	260	2,902	+ 3.6	12.96
7	261	2,913	− 7.4	54.76
8	262	2,924	−18.4	338.56
9	260	2,902	+ 3.6	12.96
10	261	2,913	− 7.4	54.76

Table 19. Statistical variation in 20 drops using instrumented drop mass and MEP on rigid anvil — Cont'd.

Drop No.	Acceleration, G	Accelerometer readings Force, F	(M-F)	$(M\text{-}F)^2$
11	262	2,924	−18.4	338.56
12	261	2,913	− 7.4	54.76
13	257	2,868	+37.6	1,413.76
14	261	2,913	− 7.4	54.76
15	261	2,913	− 7.4	54.76
16	261	2,913	− 7.4	54.76
17	259	2,890	+15.6	243.36
18	261	2,913	− 7.4	54.76
19	261	2,913	− 7.4	54.76
20	261	2,913	− 7.4	54.76
Σ	5,207 g's	58,112 lbs.		4,156.80 lbs.

$$\text{MEAN (M)} = \frac{58{,}112}{20} = 2{,}905.6 \text{ lbs.}$$

$$\text{STANDARD DEVIATION } (\bar{s}) = \pm \frac{\Sigma(M\text{-}F)^2}{n\text{-}1} = \pm \frac{4156.80}{19}$$

$$(\bar{s}) = \pm 14.79 \text{ lbs. } (\pm 0.5\%)$$

For purposes of test, impact evaluations may be conducted with an 80g head acceleration failure criterion.

At this point, it is well to note the differences in measurement variation.

- Accelerometer readings — standard deviation = 0.5%
- Brinell penetration readings — standard deviation = 7.0%

The Brinell apparatus, even under closely controlled impact conditions is seen to be a comparatively imprecise measuring device.

For any given impact energy, helmet response will be different for the Z89 and Z90 fixtures due to differing impact velocities. To demonstrate this, impacts were conducted on twelve helmets of high density polyethylene shell/nylon suspension type; six on the Z89 fixture and six on the Z90 fixture. The results are shown below:

Fixture	Peak force
Z89	752
Z89	920
Z89	1188
Z89	732
Z89	705
Z89	720

Average = 836

Fixture	Equivalent Brinell force
Z90	636
Z90	777
Z90	843
Z90	701
Z90	742
Z90	757

Average = 743

The tendency of the samples tested to demonstrate suspension mounting failure was apparent under both test conditions as is shown in Photographs 5 and 6.

Regarding a tolerance limit of 80g, if the rigid body motion of the head is shown to be the controlling factor for apex blows, 80g may be expected to be well within tolerance limits [75, 76].

Input: Applied Impact Energy

A. *Falls to Different Levels.* From studies of accident data, it has not been possible to derive required impact energy from the fall to different level accident. Height of fall and conditions of impact are random occurrences.

It is therefore necessary that the applied impact is such that ". . . maximum possible protection is the desired goal" [77]. The state of the art must be assessed and the best available

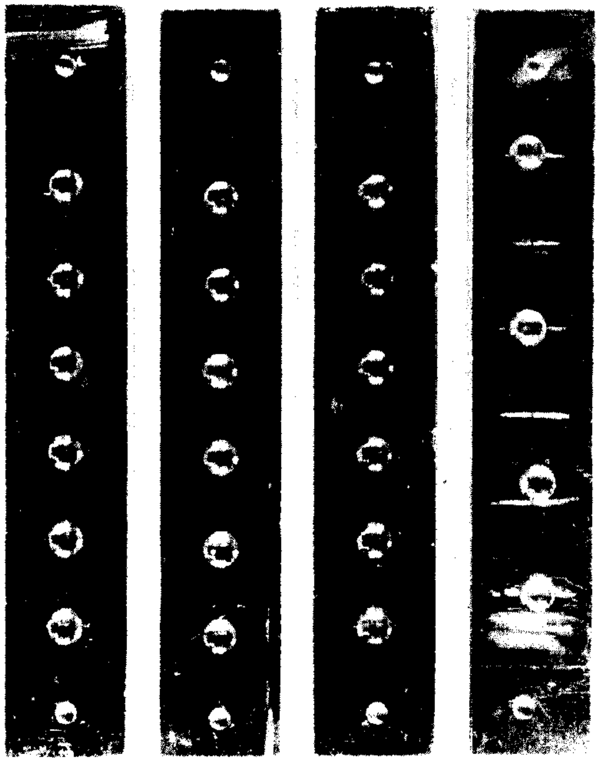


Photo. 3. Aluminum impression bars for impacts No. 21 through 42.

performance must be used as an indicator of current helmet technology.

Helmets designed for vehicular or military applications, while capable of high impact energy absorption are not suited to industrial uses. The quantities balancing protective features and human factors must be analyzed [78] and only a helmet designed for industrial applications is suited for state of the art assessment. The only industrial helmets produced which provide a high degree of lateral impact protection are those designed to NZS2264:1970. Standard maximum protection industrial helmets, supplied by Noel Daly, Ltd. of New Zealand were used for the analysis.

The impact test fixture used was the Z90 type with rigid flat steel anvil, chosen to simulate a rigid floor surface. Headform acceleration output was analyzed by computer and values of Head Injury Criterion calculated. The results, shown in Table 20, illustrate that the helmet is capable of passing the Head Injury Criterion tolerance limit of 1,000. Following the evaluation, the manufacturer stated that with modification to the helmet, consistent passing values could be expected.

Table 20. Impact results of maximum protection New Zealand industrial helmet, flat rigid anvil

Drop height, (inches)	Location	Head injury criterion
75	Forehead	1,295
75	Forehead	1,261
75	Forehead	1,168
72	Forehead	1,118
75	Left Side	974
75	Left Side	996
75	Left Side	841
72	Left Side	974
75	Right Side	1,095
75	Right Side	1,059
75	Right Side	846
72	Right Side	1,055
75	Rear	1,230
75	Rear	1,473
75	Rear	1,277
72	Rear	1,355

Average HIC = 1,126

It has therefore been concluded that an impact of 72 inches onto a flat anvil is within the capability of current helmet design.

B. *Struck By Falling Objects.* The philosophy which was necessary in arriving at the impact level for the fall to different level hazard applies in general to falling objects striking the head. We must look to the maximum attainable within the state of the art.

However, it is desirable that at least equal if not greater impacts be attenuated for top of head blows. For apex impacts, head acceleration must be limited to 80g.

An additional consideration is the impacting surface. The flat anvil is reasonable for approximation of the fall accident but is not a realistic random falling object.

A hemispherically shaped anvil such as the type used in ANSI Z90 (1.9″ radius) has been selected. It should be noted that the ANSI Z89 drop ball is also of 1.9-inch radius.

Using these constraints, impacts were conducted at varying drop heights on Z89 type helmets on the Z90 fixture impacting on the

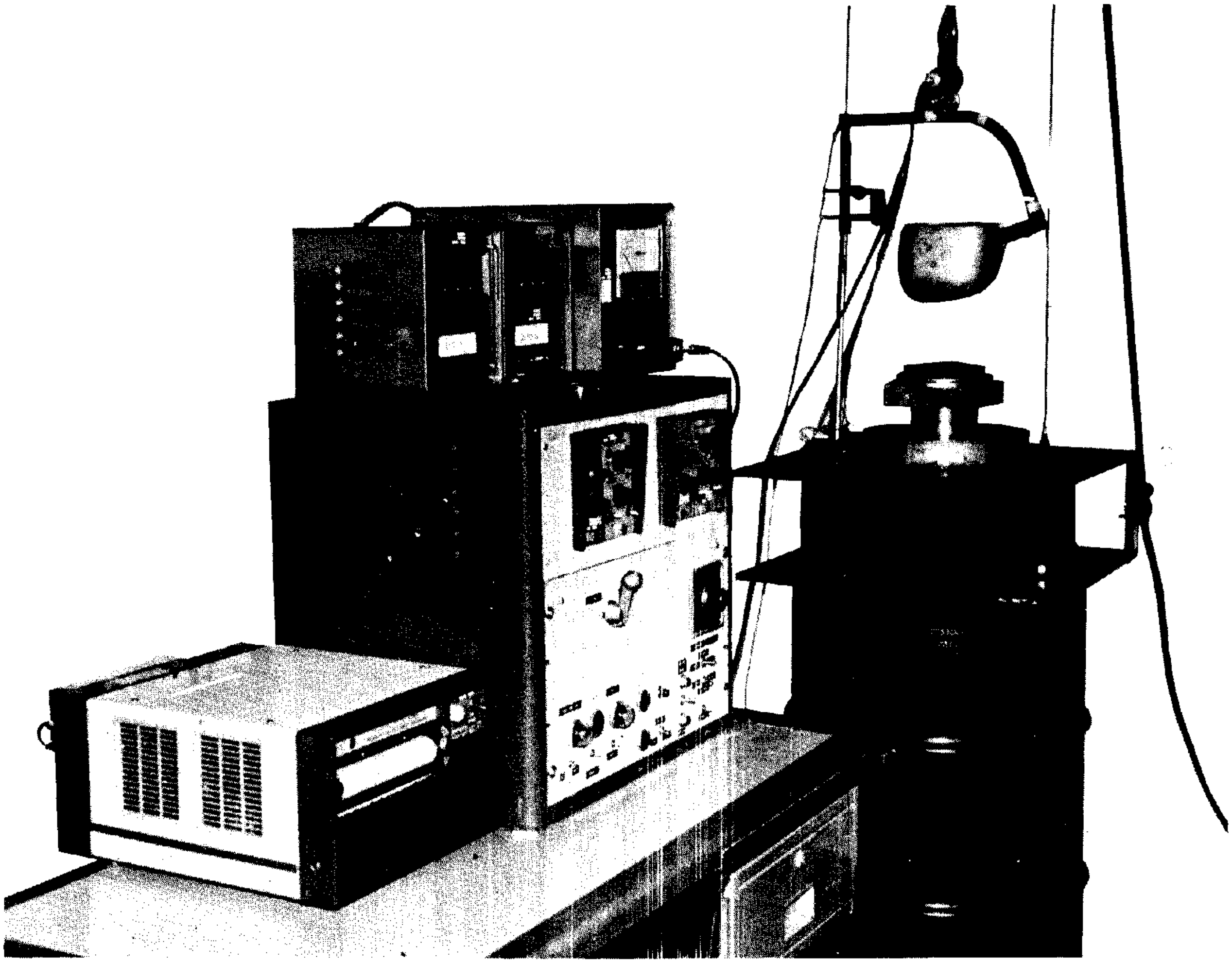


Photo. 4. Instrumented headform impact fixture.

hemispherical anvil, the results of which are shown in Figure 23.

For purposes of investigating the effect of a flat anvil drop, tests were also conducted on Z89 helmets on the Z90 fixture using a flat anvil, shown in Figure 24.

The post impact photographs of nine helmets, three each from three manufacturers, tested at a 75-inch drop height are shown in Photographs 10, 11, and 12.

It was noted that flat anvil impacts on occasion caused erratic suspension mounting failures. For helmet model A in Figure 23, no suspension mounting failures were seen until a height of 80 inches was reached, Photograph 13.

For helmet models B and C, suspension mounting failure as shown in Photographs 14 and 15 was seen at the 40-inch drop level and did not appear at the higher levels.

One particular helmet model, not depicted, showed repeated rivet pull-out when impacted on the flat anvil and no apparent damage when impacted on the hemispherical, all impacts being conducted at the 40-inch drop. These facts further indicate the undesirability of the flat anvil apex impact.

In summary, tests indicate that a 72-inch drop onto a hemispherical anvil with an 80g head acceleration has not been demonstrated with present helmets, however, at least one manufacturer feels that the level is attainable. Until such time as prototype research determines that such a level is not within the capabilities of current technology, the above requirement must be retained.

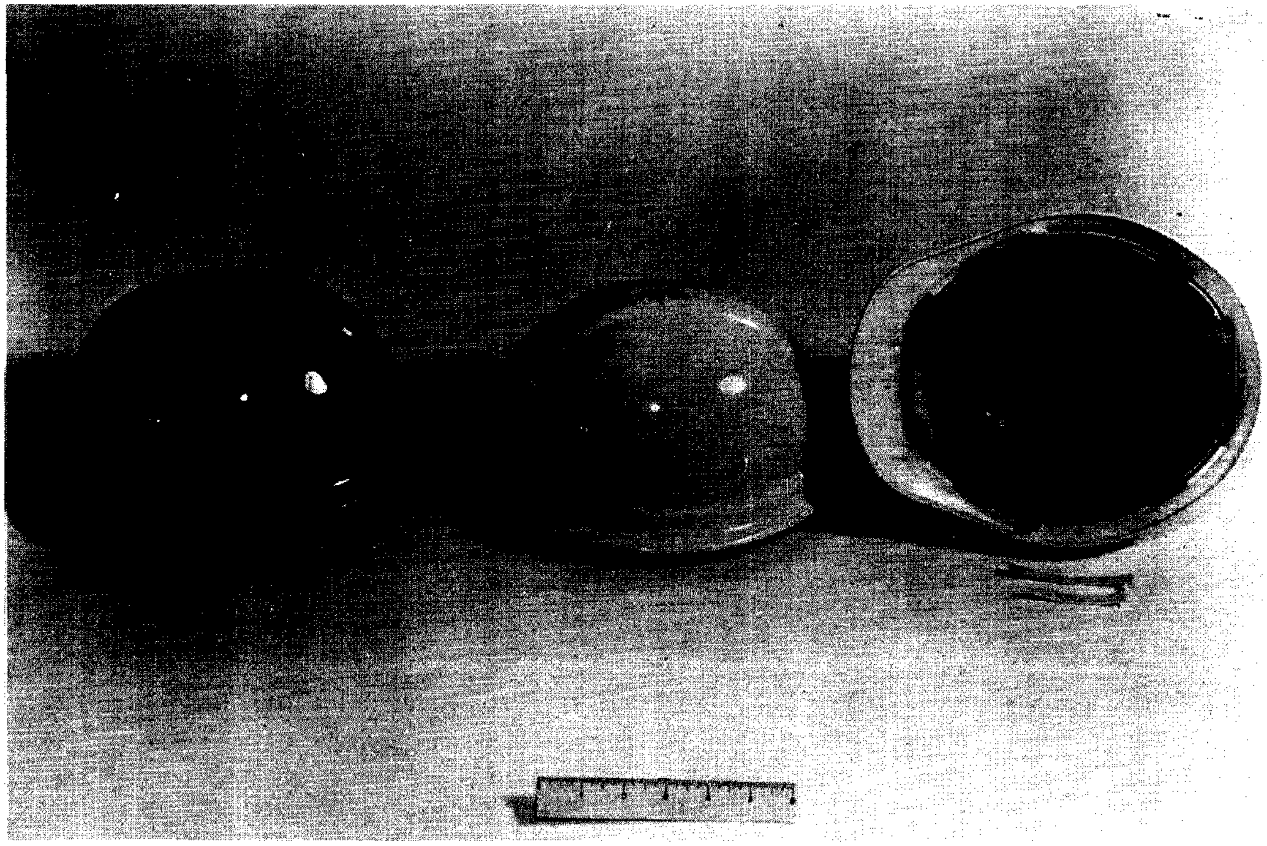


Photo. 5. Samples tested on Z89 apparatus, suspension mounting failure shown.

C. *Fall on same Level Impact.* Unlike the Fall to Different Level and Struck By Falling Object accident, the Fall on Same Level accident is somewhat more definable.

In the worst case, if one were to fall over, pivoting on the feet and the head struck the ground with no resistance to motion, impact energy would equal the height from the floor to the head times head weight. Such motion is not common place.

Falls to the left and right side will be "broken" by the shoulders. In frontal falls the hands may be used for protection. From a study of head bruises, contusions and lacerations for the state of Wisconsin, we find that in the fall on same level accident, impacts are four times more likely to occur at the rear of the head than at the front.

The severity of the fall accident will also be heavily dependent upon the rigidity of the impacting surface. For example, when an instrumented drop mass (with MEP attached) impacts a flat steel anvil, 8.8 ft.-lb. potential drop energy will yield 200g acceleration. When a ¼″ steel plate is impacted, 16.7 ft.-lbs. produces this same acceleration.

If we apply this 90% drop height differential to the 68-inch tragion (ear) to floor height for the 95th percentile male, we are left with a 35.5-inch head drop.

A 36-inch head drop for the light duty helmet, being one half the 72-inch drop distance for the maximum duty, is considered both necessary and sufficient to protect the head in this application.

Penetration Resistance

The penetration resistance requirement is the comparative ability of a helmet to resist the penetration of a pointed object. The present requirement

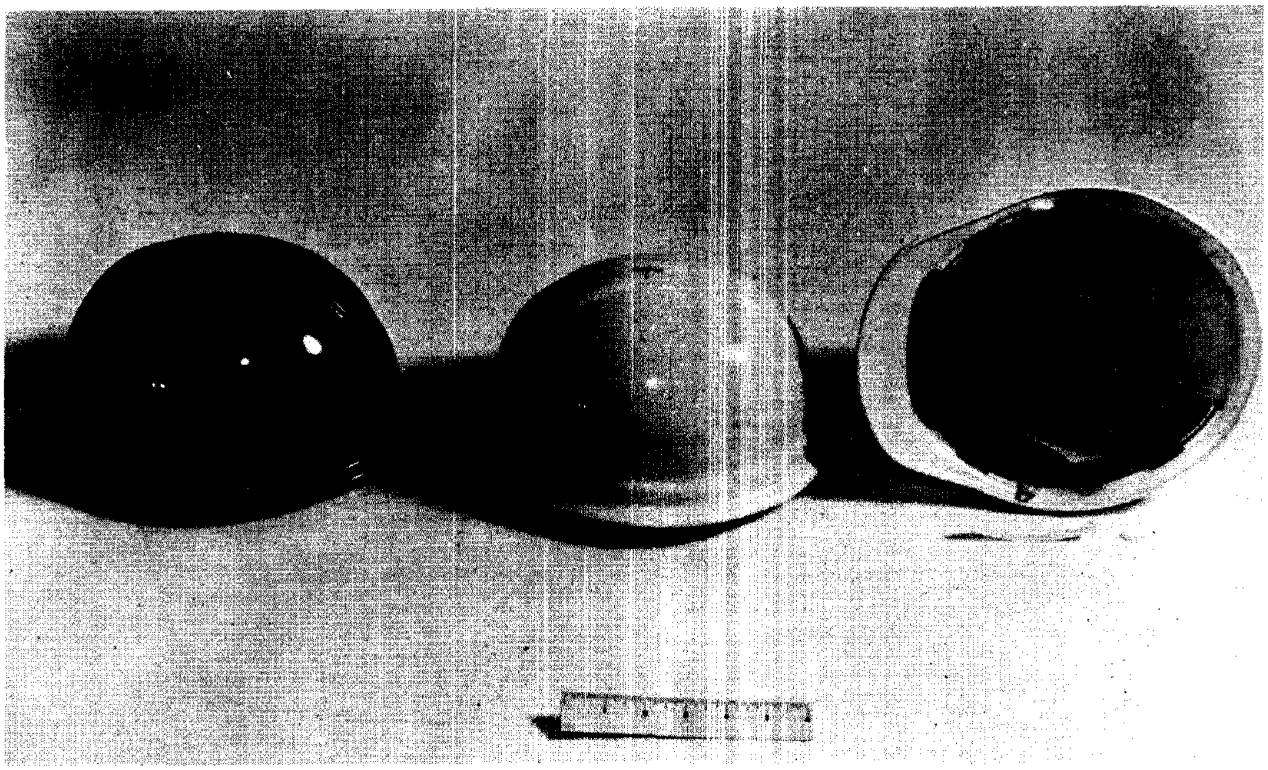


Photo. 6. Samples tested on Z90 apparatus, suspension mounting failure shown.

is that a 1-lb. plumb bob (35° included point angle) be dropped a distance of 120 inches onto the apex of the helmet. The striker must not penetrate the helmet more than 0.375 inch as measured along the side of the point.

The developers of the Brinell impression impact fixture evaluated this penetration requirement in 1949 [69] and concluded that it was "... adequate for determining the resistance of a protective hat to sharp pointed objects." The samples studied, however, were of the cotton canvas/phenolic resin and vulcanized fiber type.

Penetrations were conducted on three helmet models at low temperature (14°F), ambient, and high temperature (122°F) conditions on the apex, forehead, left side, right side and rear using the 35° point striker dropped 120 inches. A headform, conforming to the dimensions of that in the ANSI Z90.1 was rigidly mounted and able to pivot to allow penetrations, normal to the helmet surface, at all head locations. Measurements were made of:

- depth of penetration (along side of striker reinserted into indentation)
- headform contact (electrical continuity device)

The results, shown in Table 21 indicate that:

(a) the 0.375″ depth requirement at this level of penetration, is not a realistic value.

(b) penetrations at other head locations may yield contact of the striker with the head.

Identical helmets were then subjected to penetrations of the same magnitude, but with the included angle of the point reduced to 30°. The results, Table 22, show that both the penetration depths and number of occurrences of headform contact increase. Additional penetrations were then applied to the apex of these helmets with the 30° striker weight increased to 2.2 lbs., at ambient conditions, Table 23. The helmets are still seen to pass the 0.375″ depth requirement. Therefore, 2.2 times the applied penetration energies of the once considered sufficient requirement finds present Z89 helmets operable.

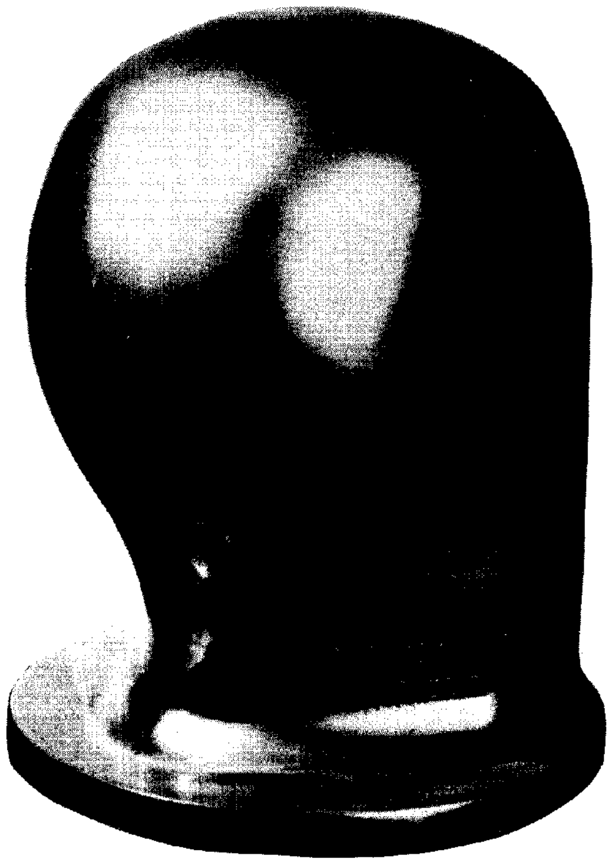


Photo. 7. Typical view of I.S.E.A. test headform.

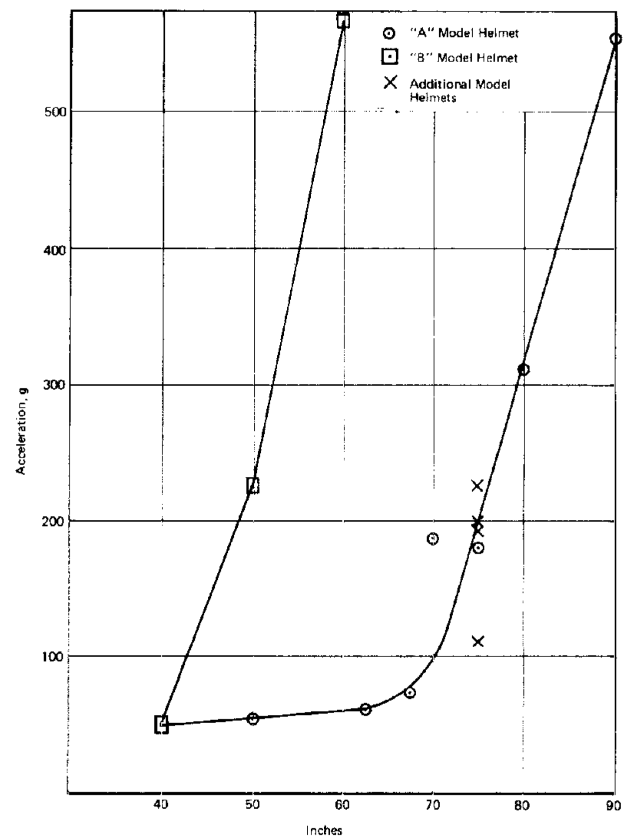


Fig. 23. Ultimate apex protection, Z89 helmets, hemi anvil

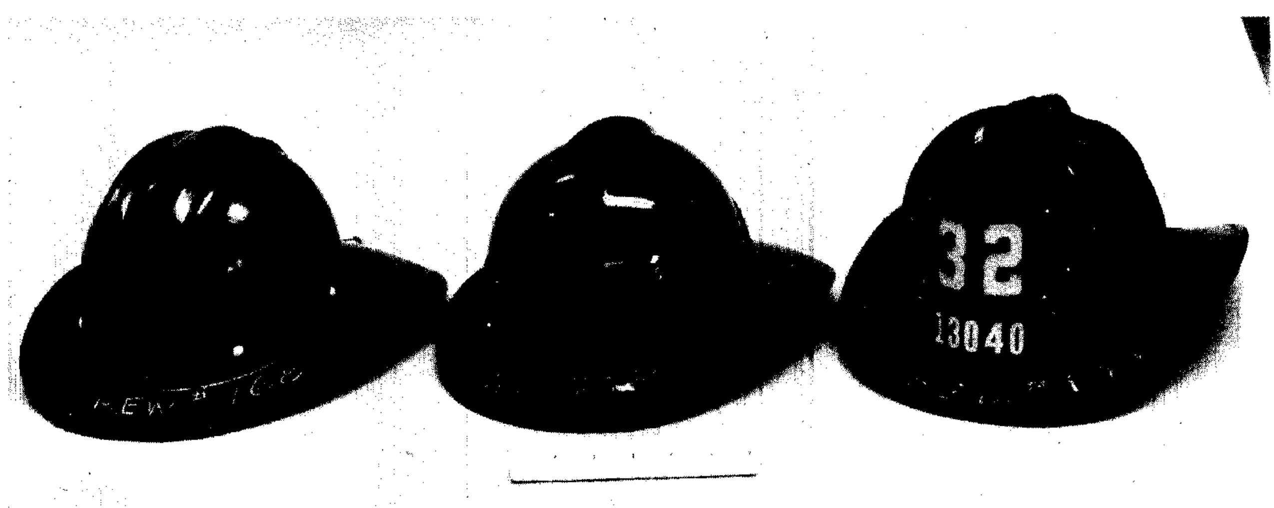


Photo. 8. Typical fire helmets. Left: fiberglass shell. Center: thermoplastic shell. Right: leather shell.

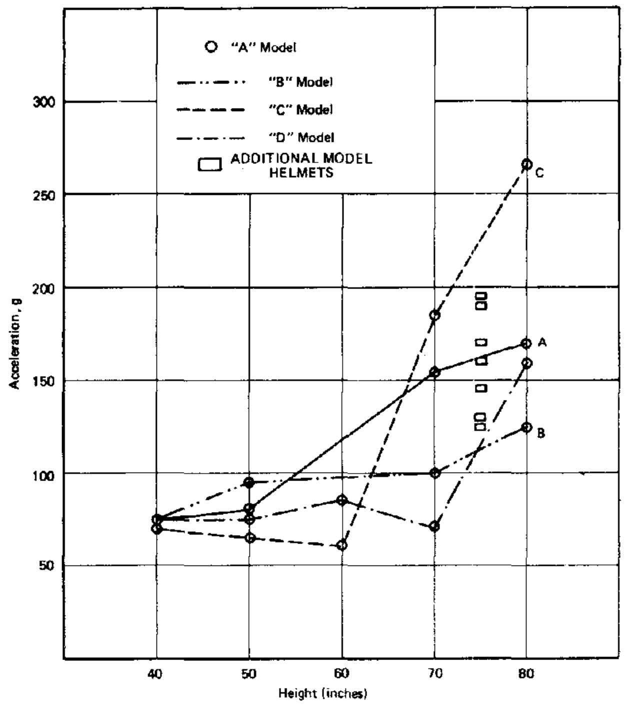


Fig. 24. Ultimate apex protection, Z89 helmets, flat anvil

Table 21. Penetration test results, 1-lb. striker, 35° point, all head locations

	Condition: Ambient		
Sample	Area	Penetration depth, inches, side	Headform contact
79	Apex	0.069	No
82	Apex	0.092	No
91	Apex	0.104	No
79	Front	0.092	No
82	Front	0.115	No
91	Front	0.127	No
79	Right side	0.115	No
82	Right side	0.081	No
91	Right side	0.092	No
79	Rear	0.081	No
82	Rear	0.127	Yes
91	Rear	0.104	No
79	Left side	0.081	No
82	Left side	0.092	No
91	Left side	0.092	No

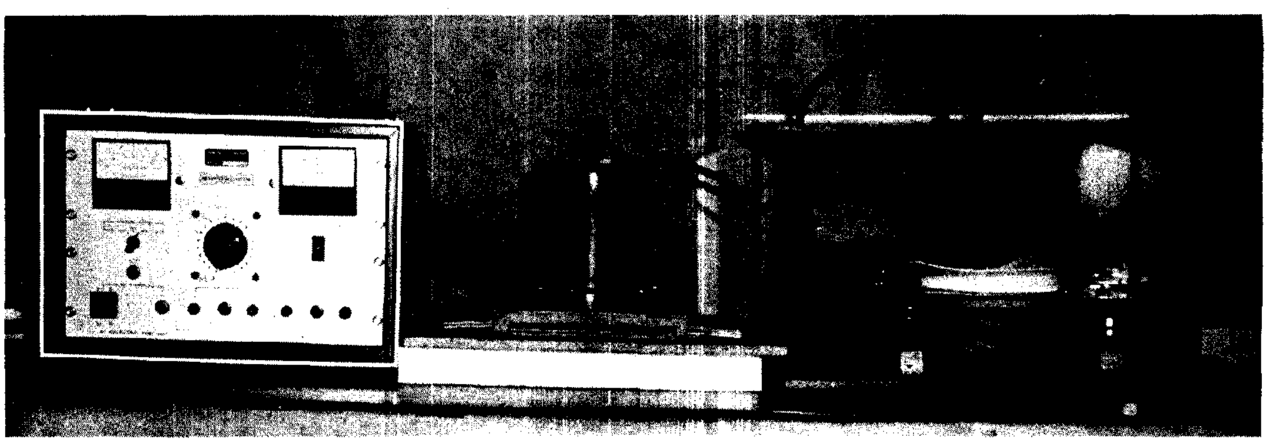


Photo. 9. Overall view of dielectric test set-up.

Photo. 10. Post shock absorption test on the apex area. Samples 126, 127, and 128.

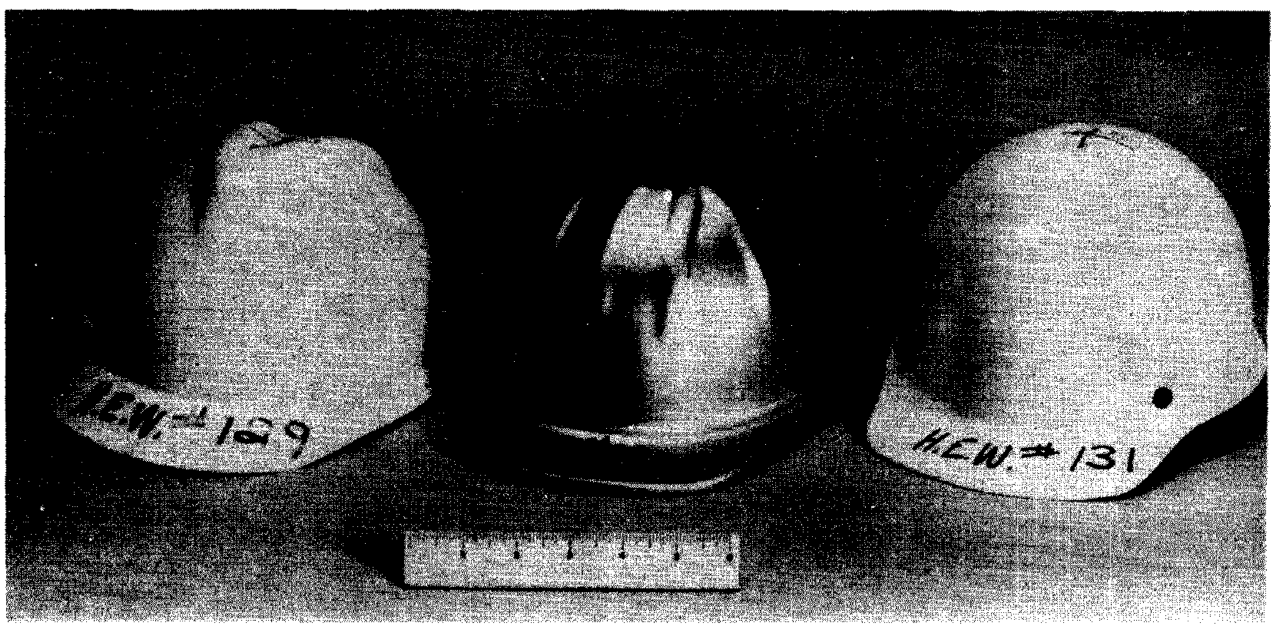


Photo. 11. Post shock absorption test on the apex area. Samples 129, 130, and 131.

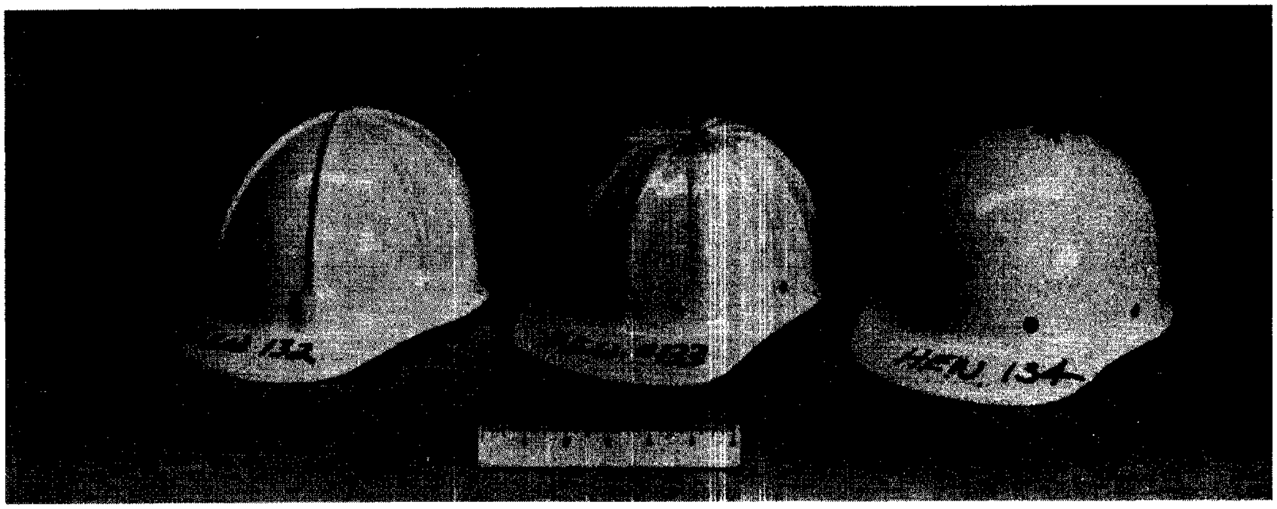


Photo. 12. Post shock absorption test on the apex area. Samples 132, 133, and 134.

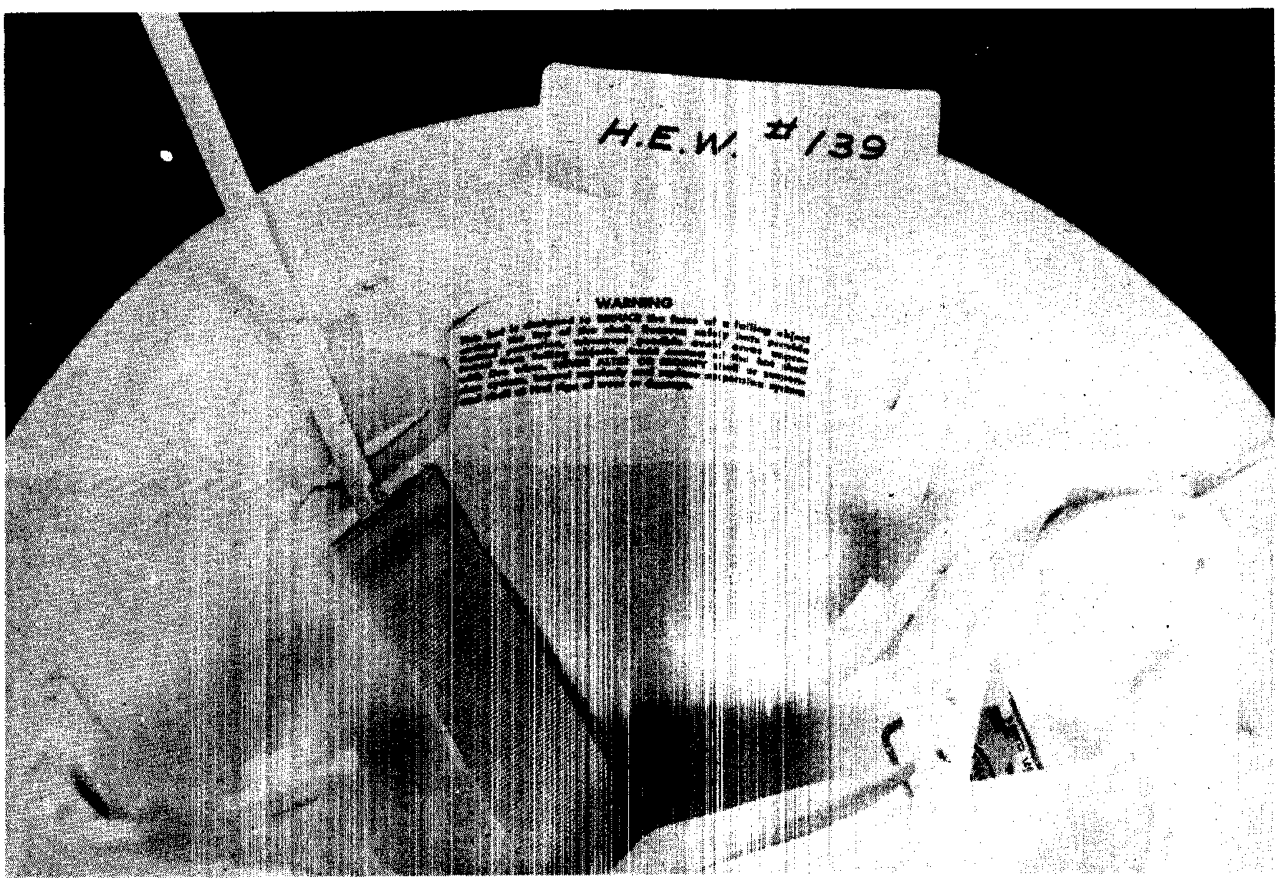


Photo. 13. Post shock absorption test, suspension mounting failure. Sample No. 139.

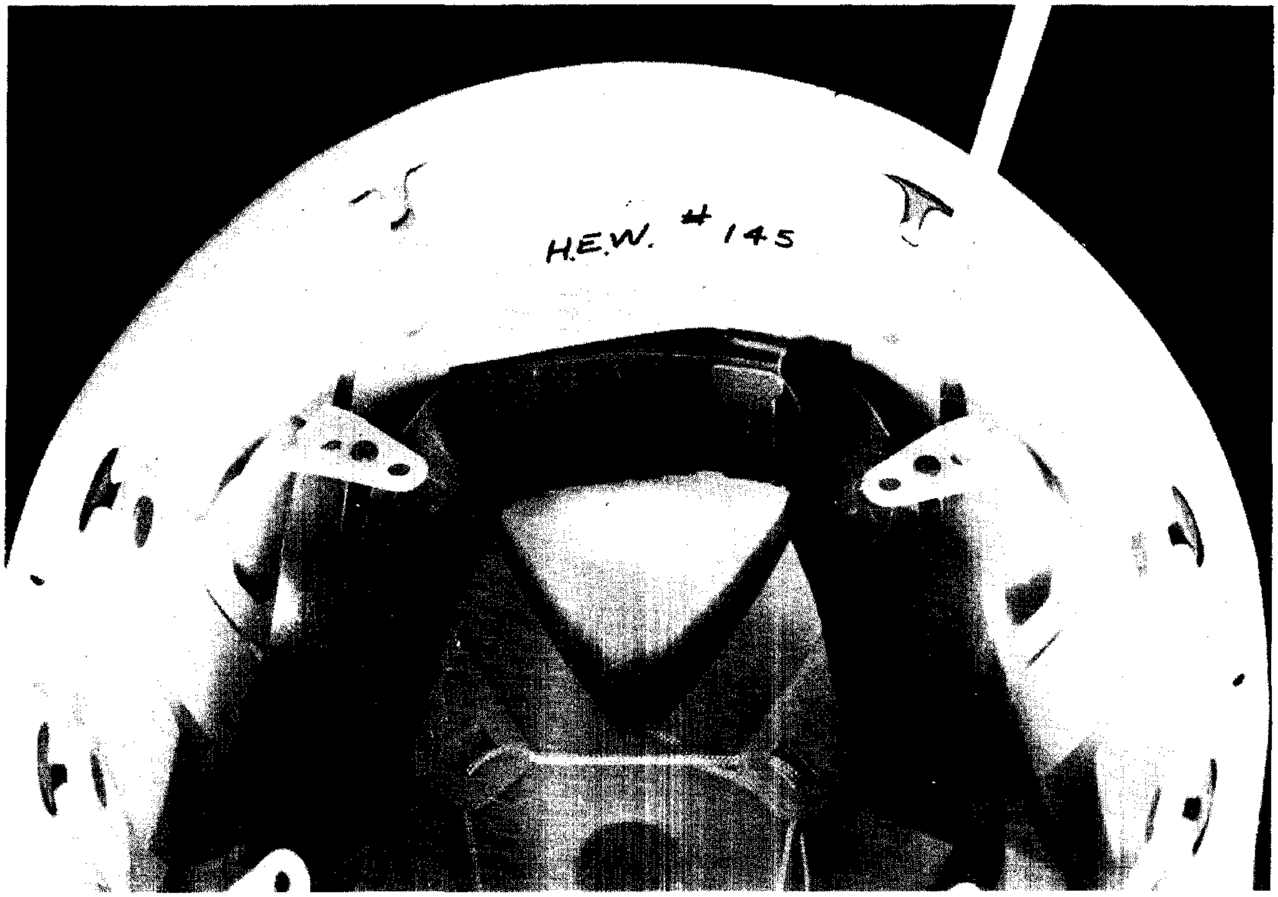


Photo. 14. Post shock absorption test, suspension mounting failure. Sample No. 145.

Table 21. Penetration test results, 1-lb. striker, 35° point, all head locations

Condition: High temperature				Condition: Low temperature			
Sample	Area	Penetration depth, inches, side	Headform contact	Sample	Area	Penetration depth, inches, side	Headform contact
80	Apex	0.081	No	81	Apex	0.081	No
83	Apex	0.081	No	84	Apex	0.069	No
92	Apex	0.104	No	93	Apex	0.104	No
80	Front	0.104	No	81	Front	0.138	Yes
83	Front	0.081	No	84	Front	0.092	No
92	Front	0.115	No	93	Front	0.127	No
80	Right side	0.104	No	81	Right side	0.104	No
83	Right side	0.069	No	84	Right side	0.081	No
92	Right side	0.104	No	93	Right side	0.092	No
80	Rear	0.081	No	81	Rear	0.092	No
83	Rear	0.115	Yes	84	Rear	0.092	No
92	Rear	0.115	No	93	Rear	0.115	No
80	Left side	0.115	No	81	Left side	0.127	No
83	Left side	0.092	No	84	Left side	0.092	No
92	Left side	0.092	No	93	Left side	0.081	No

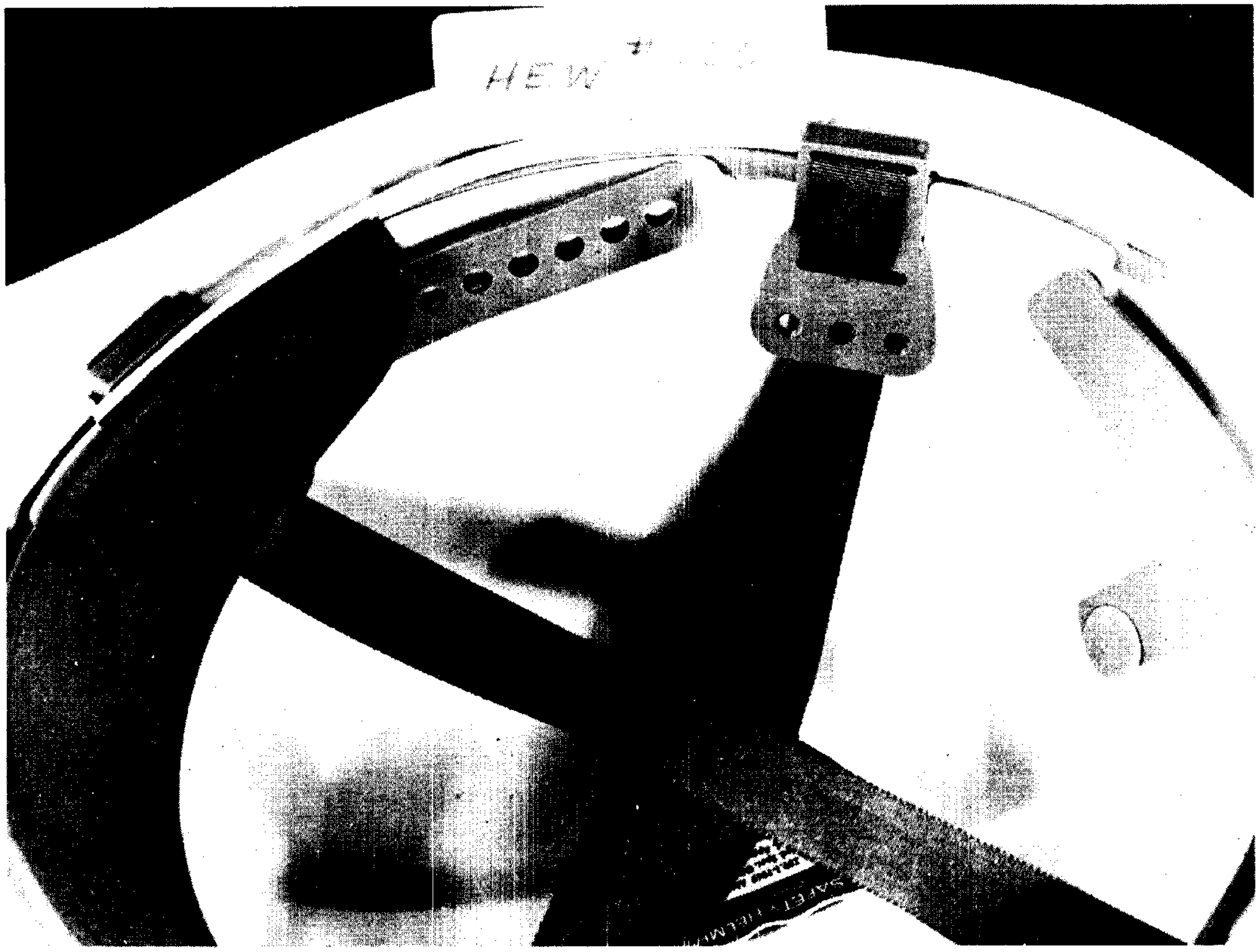


Photo. 15. Post shock absorption test, suspension mounting failure. Sample No. 150.

Table 22. Penetration test results, 1-lb. striker, 30° point, all head locations

Condition: Ambient				Condition: High temperature			
Sample	Area	Penetration depth, inches, side	Headform contact	Sample	Area	Penetration depth, inches, side	Headform contact
85	Apex	0.104	No	86	Apex	0.104	No
88	Apex	0.127	No	89	Apex	0.092	No
94	Apex	0.115	No	95	Apex	0.115	No
85	Front	0.138	No	86	Front	0.173	Yes
88	Front	0.150	Yes	89	Front	0.115	No
94	Front	0.127	No	95	Front	0.138	No
85	Right side	0.115	No	86	Right side	0.138	No
88	Right side	0.092	No	89	Right side	0.127	No
94	Right side	0.104	No	95	Right side	0.115	No
85	Rear	0.104	No	86	Rear	0.138	No
88	Rear	0.162	Yes	89	Rear	0.138	Yes
94	Rear	0.115	No	95	Rear	0.150	Yes
85	Left side	0.104	No	86	Left side	0.150	No
88	Left side	0.138	No	89	Left side	0.150	Yes
94	Left side	0.104	No	95	Left side	0.115	No

Table 22. — Cont'd.

Condition: Low temperature			
Sample	Area	Penetration depth, inches, side	Headform contact
87	Apex	0.092	No
90	Apex	0.127	No
96	Apex	0.104	No
87	Front	0.138	No
90	Front	0.138	No
96	Front	0.127	No
87	Right side	0.115	No
90	Right side	0.138	No
96	Right side	0.104	No
87	Rear	0.104	No
90	Rear	0.150	Yes
96	Rear	0.115	No
87	Left side	0.104	No
90	Left side	0.138	No
96	Left side	0.104	No

Table 23. Penetration test results, 2.2-lb. striker, 30° point, apex location

Sample	Penetration depth inches, side
80	0.156
81	0.133
82	0.133
83	0.121
84	0.104
85	0.156
86	0.139
87	0.133
88	0.133
89	0.115
90	0.133
91	0.127
92	0.133
93	0.127
94	0.121
95	0.121
96	0.115

It is thus concluded that in order to parallel the impact magnitudes, the following penetration requirements must be applied using a 2.2-lb., 30° angle striker.

(1) Falls to different levels — 3-meter drop (118.1 inches) and objects striking the head

(2) Falls on same levels — 1.25-meter drop (47 inches)

Insulation Resistance

Insulation resistance of industrial and firefighters' headgear, as previously shown, is necessary and the existing evaluation criterion (9 ma maximum leakage at 20,000 volts) and method, Photograph 9, is seen to have virtually eliminated electrocution deaths by contact of the head with electric current when used. The random occurrence of electrical contact accidents requires all industrial and firefighters' headgear to have these qualities.

Tests have shown that preconditioning of helmets (24-hour water bath) significantly decreases the insulation abilities of the helmets. It has also been found that for Z89 Class B helmets, impact testing prior to insulation resistance measurement does not place an undue burden on the helmet, as seen from the following data:

Sample	Model	Impacted	Leakage (at 20,000 V. 1 ma)
116	A	Yes	5.5
117	A	No	5.0
118	B	Yes	3.5
119	B	No	3.5
120	C	Yes	6.5
121	C	No	6.5
122	D	Yes	6.5
123	D	No	6.0
126	C	Yes	3.5
132	D	Yes	6.0
135	C	Yes	6.0
136	C	Yes	6.0
140	A	Yes	5.0
151	A	Yes	4.5
150	B	Yes	3.0

Flammability

The existing 3 inches/minute burn rate requirements for industrial headgear is considered sufficient for industrial headgear. Firefighters' headgear must exhibit self-extinguishing characteristics when tested for flammability. Most thermoplastic and fiberglass helmet materials self-extinguish when subjected to test.

Retention Ability

The chin strap of a helmet must be of sufficient strength to retain the helmet during impact. The chin strap must:

- exhibit load bearing ability
- have limited deformation under load
- be easily fastened and unfastened

The NZS2264:1970 requirement of 100-lb. load and maximum elongation of 1 inch is considered adequate for Maximum Duty and firefighters' applications.

Where a helmet is subjected to lesser hazards, a chin strap load of 25 lb. and 1" elongation is sufficient.

WEIGHT

Weight is an important human comfort factor which, although somewhat self-limiting by market wants, must be maintained within reasonable limits.

From consideration of expected design configurations and human weight tolerances, the following values of maximum weight are recommended for the various classes of headgear:

- Class 1 - 18 ounces
- Class 2 - 16 ounces
- Class 3 - 12 ounces
- Class 4 - 30 ounces

Some other helmet factors which will influence wearer comfort but for which no human comfort factors data are available are:

(a) Center of mass — Most present industrial helmets (Z89) offering only apex impact protection tend to be top heavy. Table 24 lists the center of mass locations for various types of helmets tested. The test method used was that used for aviator helmet evaluation [79]. The nomenclature is shown in Figure 25. It is apparent that as the protective area comes down from the apex so does helmet C.M. In the extreme case, for the total coverage (face, chin, and head) vehicular (Z90) helmet, C.M. is lowest but, as can be seen weight is greatest.

Table 24. Center of mass test results

Helmet type	Weight lb.	O.°	R
Z89 cap (aluminum)	0.79	76.5	3.48
Z89 cap (fiberglass)	0.78	84.0	3.52
Z89 cap (plastic)	0.84	79.0	3.72
Z89 hat (fiberglass)	0.90	75.0	3.75
Z89 hat (fiberglass)	0.94	78.0	3.72
NZS2264:1970 (max. duty)	0.96	80.0	2.99
Z90 (partial coverage)	2.21	71.0	3.34
Z90 (full head coverage)	2.27	66.0	2.31
Z90 (total face coverage)	3.63	81.0	1.86

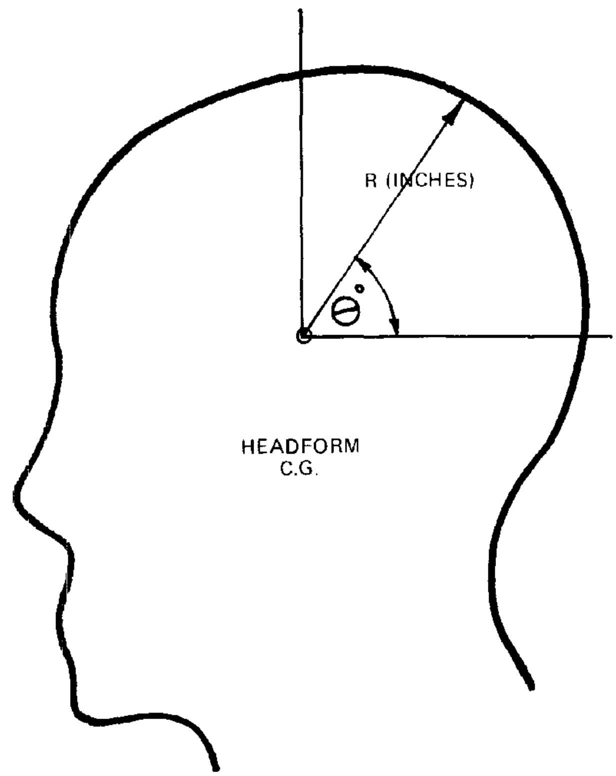


Fig. 25. Center of mass locations

(b) Moment of inertia — The ease with which the head may be rotated on the vertical axis will be dependent upon helmet mass moment of inertia. This quantity, though measurable, has also not been studied for industrial helmet comfort consideration. Illustrative examples for various types of helmets are shown in Table 25.

Table 25. Moment of inertia test results, head vertical axis

Helmet type	Weight lb.	Moment of inertia, slug-ft^2
Z89 cap (aluminum)	0.79	0.00331
Z89 cap (fiberglass)	0.78	0.00246
Z89 cap (plastic)	0.84	0.00246
Z89 hat (fiberglass)	0.90	0.00246
Z89 hat (fiberglass)	0.94	0.00331
NZS2264:1970 (max. duty)	0.96	0.00331
Z90 (partial coverage)	2.21	0.00779
Z90 (full head coverage)	2.27	0.00779
Z90 (total face coverage)	3.63	0.01508

The lack of human tolerance information in these areas precludes development of viable criteria.

ENVIRONMENTAL EXPOSURE

A. *Moisture* — To insure wearability in wet weather and to limit the use of materials which tend to absorb moisture and are thus not easily cleanable. Exposure to a water bath for a period of 24 hours must not increase helmet weight by more than 5%.

B. *Temperature* — The normally used helmet test temperature range of 14°F to 122°F, is considered sufficient to demonstrate helmet performance extremes as shown in Figure 26 for industrial headgear. In addition, the manufacturer must design the helmet to withstand 160°F storage temperatures. High temperature conditioning for fire helmets must be in the order of 300°F for shock duration exposure. Initial evaluation of available fire helmets, Photograph 8, were conducted by conditioning each at a temperature of 350°F for 5 minutes. The following was noted:

(a) Fiberglass helmet — shell showed no signs of damage from the exposure, medium density polyethylene parts of suspension melted.

(b) Thermoplastic shell — shell and medium density polyethylene parts of suspension melted.

(c) Leather shell — shell softened, no visible damage to cloth cap suspension.

Additional helmets were then subjected to 350°F for 2 minutes, then impacted. The results combined with test data for samples tested at 14°F and ambient temperatures are shown in Figure 27. These indicate that exposure was below critical.

For test evaluation an exposure of 300°F for three minutes to allow stabilization is considered adequate.

Test Requirements

A description of the development of test methods, procedures and equipment used for the evaluation of industrial and firefighters' headgear is as follows:

Samples for Testing

The helmets must:

- be in a condition as offered for sale.
- have all attachments necessary to meet the minimum performance requirements installed at the time of test.

In order to minimize testing time, as small a number of samples as possible should be used for evaluation. In addition, a measure of the durability of the helmet will be accomplished by subjecting one helmet to many tests.

The samples used for testing should comprise a set and a failure of any one helmet should require retest of an additional set. This minimizes the possibility of a helmet model prone to cumulative performance degradation being resubmitted for one test only.

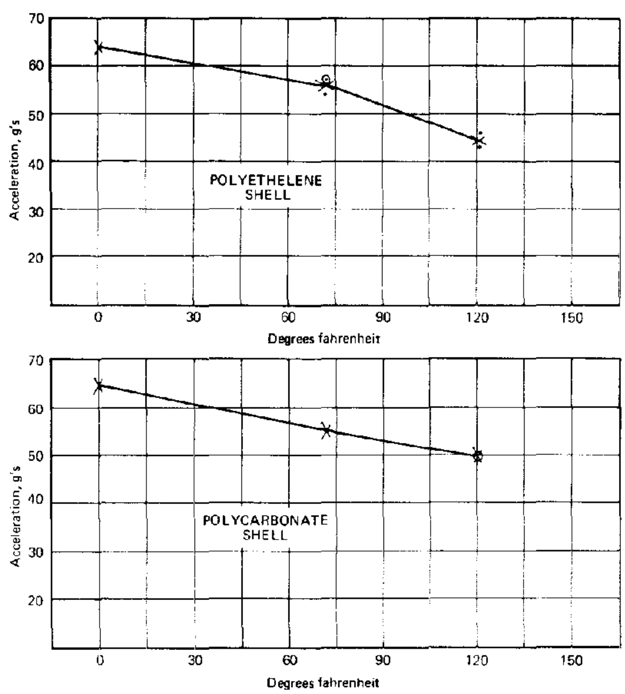


Figure 26. Temperature effects on impact performance, industrial helmets

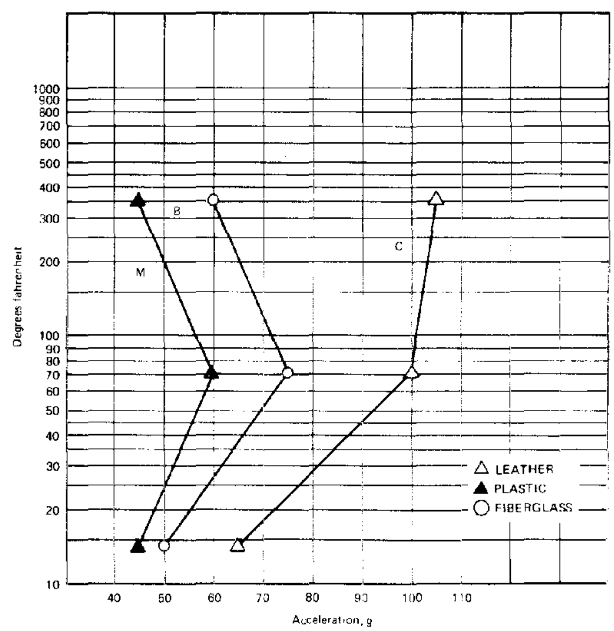


Fig. 27. Temperature effects on impact performance, firefighters' helmets

Conditioning

Limitations on cumulative conditioning time must be expressly stated.

Impact Testing

Some of the more common helmet impact test methods available to the testing agency are:

- instrumented headform/rigid anvil
- drop mass/swing away headform
- drop maśs/instrumented rigid headform
- drop mass/Brinell Penetrator Assembly

The performance criteria requires that the test method:

- accurately measure head acceleration — time impact history
- be capable of testing over the entire upper head area

The instrumented headform/rigid anvil apparatus, as specified in ANSI Z90.1 and FMVSS No. 218, shown in Photograph 4, has been selected. Headforms used should be of the standard sizes shown in Figure 6.

Headform response and material is presently under considerable study. Hodgson, et al [28] has reported considerable differences between cadaver head and metal headform response. As seen in Figure 28, the differences are accentuated with the use of resilient protective padding as opposed to the non-resilient material where response differences are essentially constant. As a result, Hodgson has developed a human head model expressly designed for use in impact testing of protective helmets [80].

The model consists of:

(a) a rigid urethane foam skull, Photograph 16

(b) a silicone rubber gel brain

(c) a silicone rubber outer skin

The entire model, as shown in Photograph 17, is mounted on a drop assembly for impact onto the rigid anvil. A triaxial accelerometer is mounted at the headform center of gravity.

A test program was initiated to investigate impact response differences between the metal headform system used at Dayton T. Brown, Inc. and the head model apparatus at Wayne State University.

The results of impacts on an MEP, are shown in

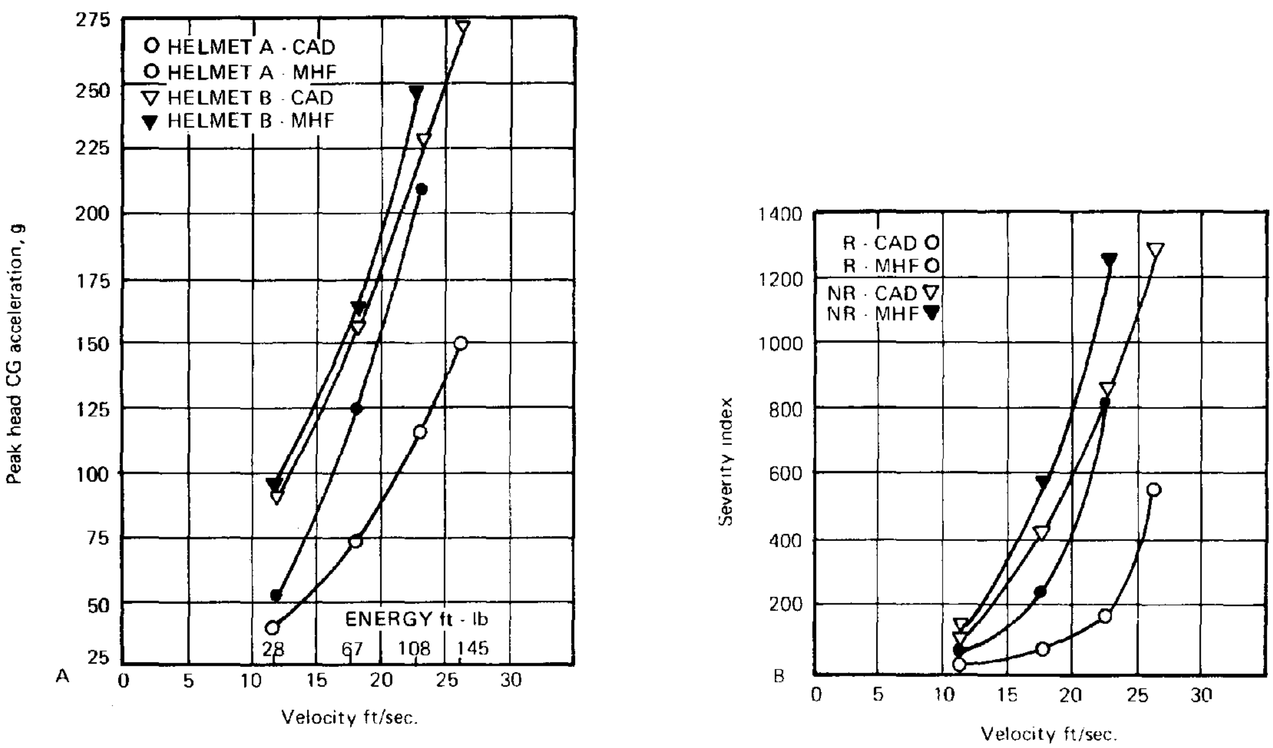


Fig. 28. Metal headform compared with cadaver head

COMPARISON OF THE DIFFERENCE IN RESPONSE BETWEEN METAL HEAD FORM AND CADAVER HEAD WEARING RESILIENT (A) AND NONRESILIENT (B) HELMETS ON THE BASIS OF: (a) PEAK HEAD ACCELERATION (b) SEVERITY INDEX

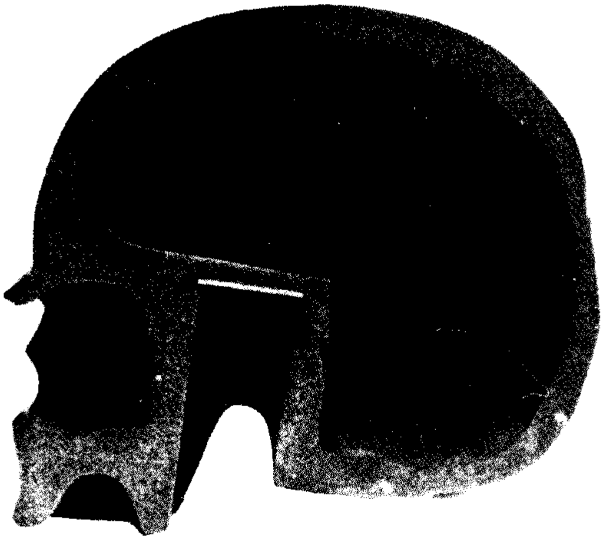


Photo. 16. Cross section view of head model skull structure.

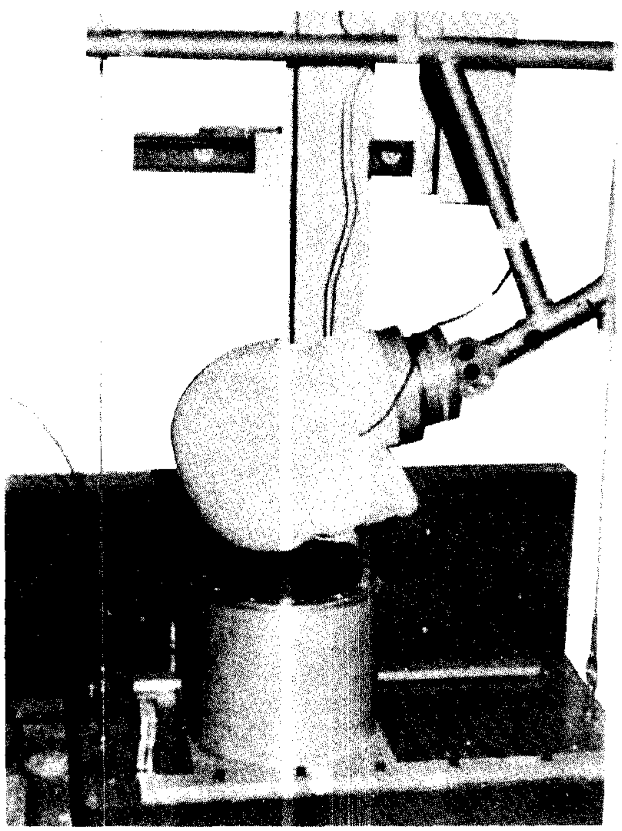


Photo. 17. Typical view of head model impact fixture.

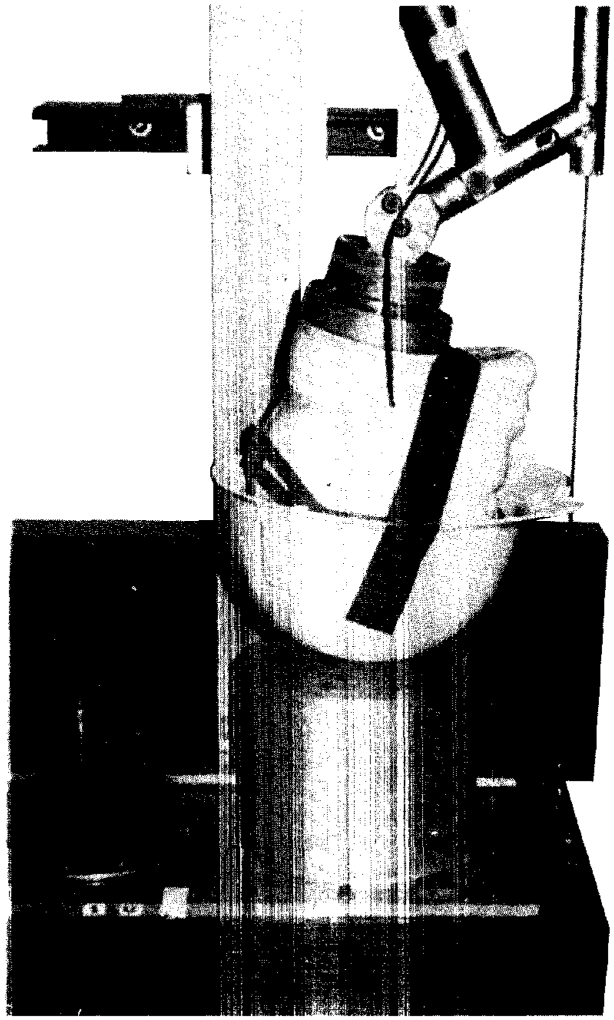


Photo. 18. View of thermoplastic shell industrial helmet on head model.

Figure 29. It is seen that the response differences on this elastomeric material follows the pattern of the cadaver/metal headform comparison.

Figure 30 shows the results of impacts on expanded polystyrene foam and ethafoam materials samples (Figure 11). Below are shown the results of impacts with industrial (Z89) helmets. The erratic nature of these results is attributed to individual

		Peak g		Head injury criterion	
Anvil	Helmet	Metal Headform	Head Model	Metal Headform	Head model
Flat	Thermoplastic	54	59	124	144
Flat	Fiberglass	73	65*	196	177*
Flat	Aluminum	65	55*	175	128*

*Average of two readings

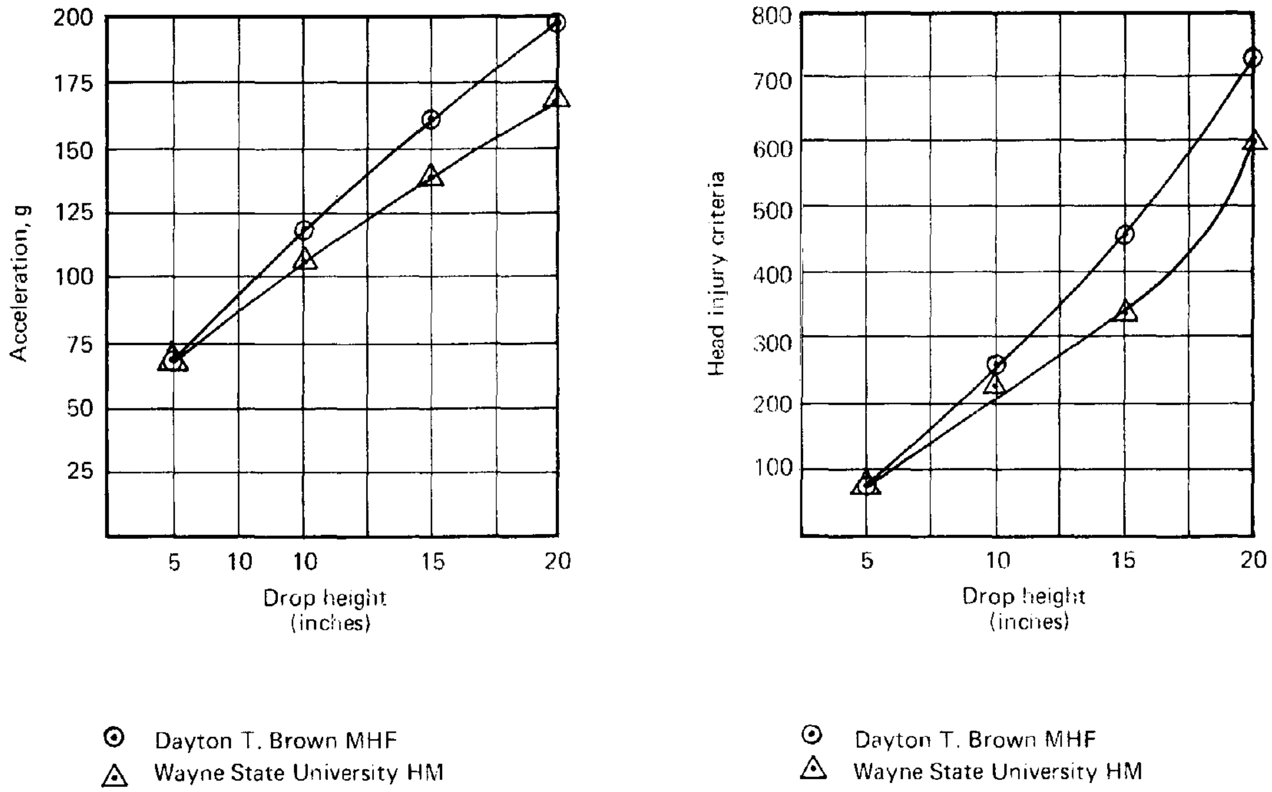


Fig. 29. Metal headform compared with head model impact response, MEP drops

sample performance and limited data. In Photograph 18, the helmet test configuration is shown.

This information is sufficient to conclude that though the metal headform and cadaver or head model responses are not proportional for different energy absorbing systems, a conservative injury estimate from the metal headform may be expected.

The viability of the head model for compliance testing is hindered by:

- limited availability
- non standard dimensions
- frangibility of headform (MEP drop were limited to 20" maximum to avoid head model damage)

The standard magnesium headforms as specified in FMVSS No. 218 are thus considered sufficient for testing of industrial helmets. Other important system considerations are:

- A uniaxial accelerometer, mounted at the headform center of gravity of the headform must have its sensitive axis aligned with the point of impact, Figure 31, for accurate acceleration measurement
- Anvils must be of standardized dimension, hardness and finish
- Anvil must be backed up by sufficient mass to insure rigidity
- Guide wires for drop assembly must be of a type which will minimize velocity losses

For purposes of peak g and Head Injury Criterion analysis, the instrumentation system as shown in Figure 32 was used. The Z90.1 instrumentation was retained to enable the technician to examine the oscillograph acceleration-time curve for possible equipment malfunction.

The equipment used was as follows:

- Piezoelectric accelerometer - Kistler 808A
- Charge amplifier - Kistler 503
- Power amplifier - Kistler 567A
- Oscillograph - C.E.C. 5–124A
- Galvanometer - C.E.C. 7–326
- Power amplifier - Kistler 567A
- Variable filter - Kron Hite 3202R

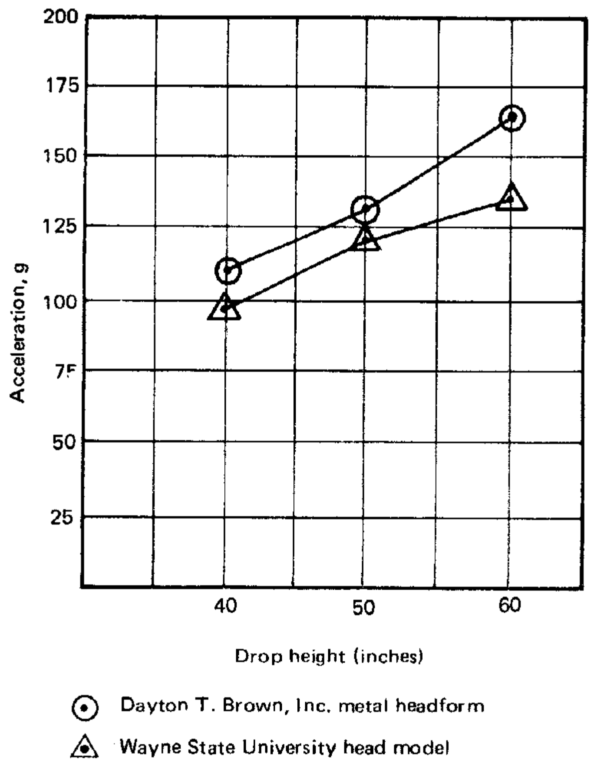


Fig. 30. Metal headform compared with head model impact response, polystyrene foam

- DC power supply - Hewlett Packard 6207B
- Digital computer - Digital Equipment Corp. PDP 8/L
- Instrument amplifier - Dynamics 7514B
- Photocell - Power Instruments Corp. C-836

This equipment, previously reported on for use in motorcycle helmet testing [81], was developed to meet the requirements of the proposed federal motorcycle helmet specification [82].

Some basic attributes of the system are:

(a) For computational accuracy, a 5 kHz sampling rate is used, the Digital Equipment Corporation PDP 8/L computer acquires data directly. Software was written to synchronize the sampling of the analog to digital converter with the real time clock of the computer. A/D converter readings were deposited sequentially into a buffer area of 1,000 core locations for later processing.

(b) Amplifiers were used to match the levels of the Figure 32 instrumentation. A variable filter was used to limit the frequency response of the system. A photocell was located several inches above the rigid anvil which provides a signal initiating sampling by the computer every 200 microseconds.

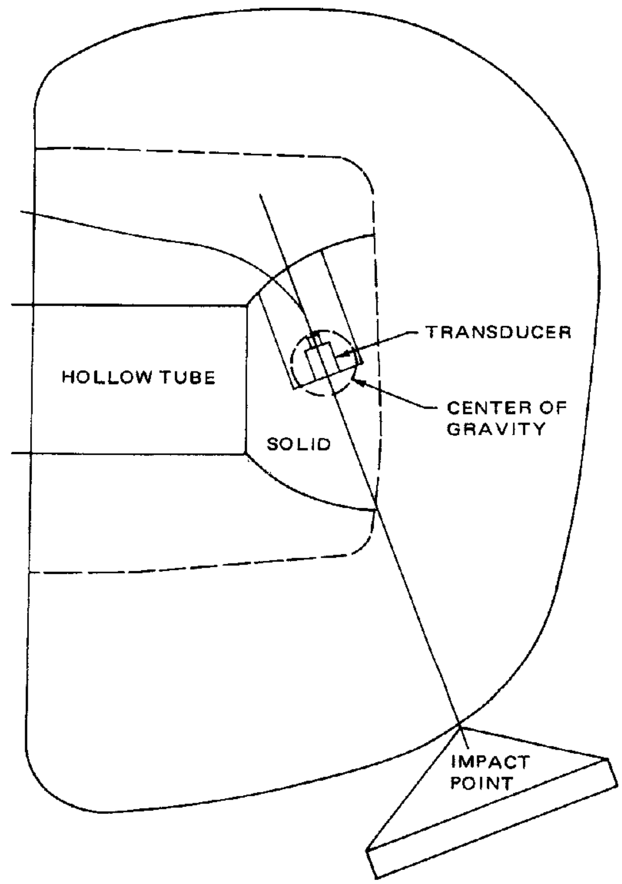


Fig. 31. Head form and transducer mounting

(c) To expedite testing, the sampled acceleration pulse was punched out on paper tape together with identifying information for later processing.

(d) Prior to impact, the computer system was calibrated by inserting a signal equivalent to 500g acceleration into the system. This signal was used in converting A/D converter readings into equivalent accelerations. This is a precaution against any long term drift of the system components.

(e) As a check, peak acceleration, time duration at 150 and 200g were relayed to the technician via teletype for visual comparison with the oscillograph record.

(f) The frequency response of the system was

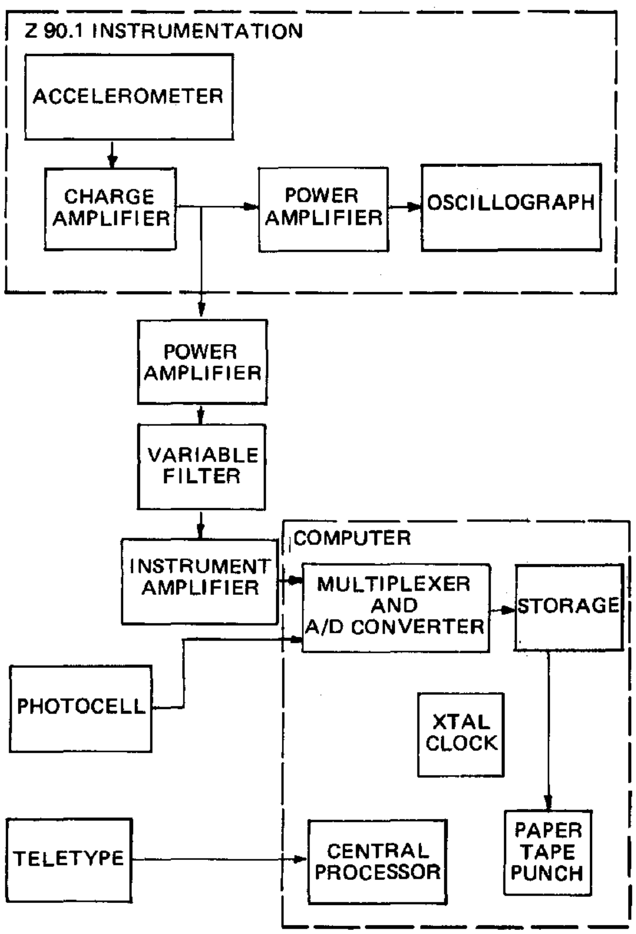


Fig. 32. Impact instrumentation flow chart

tailored by introduction of a low pass filter so that the data channel exhibited the characteristics of Class 1000 channel, Figure 33, as defined in SAE J211a for head impact acceleration evaluation [83]. A frequency response characteristic such as Class 600 would tend to produce lower acceleration values.

(g) As a precaution against A/D converter time to conversion error a sample and hold module within the A/D converter was used. This unit samples the input at the start of conversion and holds that voltage until completion.

The PDP 8/L Computer had the following peripheral equipment:

- An analog multiplexer consisting of an AM08 multiplexer control and an AMO2A high-level multiplexer
- An AD08A 10 bit analog to digital converter with AH03 input amplifier and AH02 sample and hold module
- A KW8L–F 10 kHz programmable interval real time clock
- A PC8L high-speed paper punch tape reader and punch

In addition, a great deal of the computer software required to perform the data acquisition was especially written.

Head Injury Criterion Computation:

Computation of the Head Injury Criterion was performed by the use of the trapezoidal rule approximation to obtain the required averages. A simplified flow chart of the reduction program is shown in Figure 34.

Starting at the first sample, the program computes the Head Injury Criterion expression for all possible end points and saves the maximum value. It then does the same for the second sample and all succeeding samples. The maximum value of all these computations is then reported as the largest Head Injury Criterion for that sample.

Output of the computer, Figure 35 consists of:

(1) Acceleration values (in g) for each 200 microsecond sample

(2) The maximum Head Injury Criterion value for each start and end point greater than 100

(3) A restatement of the largest Head Injury Criterion value

(4) A plot of acceleration vs time with the interval yielding the largest Head Injury Criterion value shaded.

The data for Figure 35 was obtained from the impact of a New Zealand Maximum Duty industrial helmet dropped 72 inches onto a flat anvil.

For purposes of production-lot testing, the Head Injury Criterion calculation may be expected to place an over burden on the manufacturer. Under these circumstances, a simplified evaluation is beneficial.

Figure 36 shows a plot of the ratio of Head Injury Criterion to Gadd Severity Index for 91 impacts conducted on material samples, Z89 industrial helmets, and New Zealand industrial helmets. A least squares fit of the data shows that for these pulses the two indices are related as follows:

Head Injury Criterion = 0.836 Gadd Severity Index

In addition, is shown the line:

Head Injury Criterion = 0.879 Gadd Severity Index

which was determined from a least squares fit of 514 motorcycle helmet impacts.

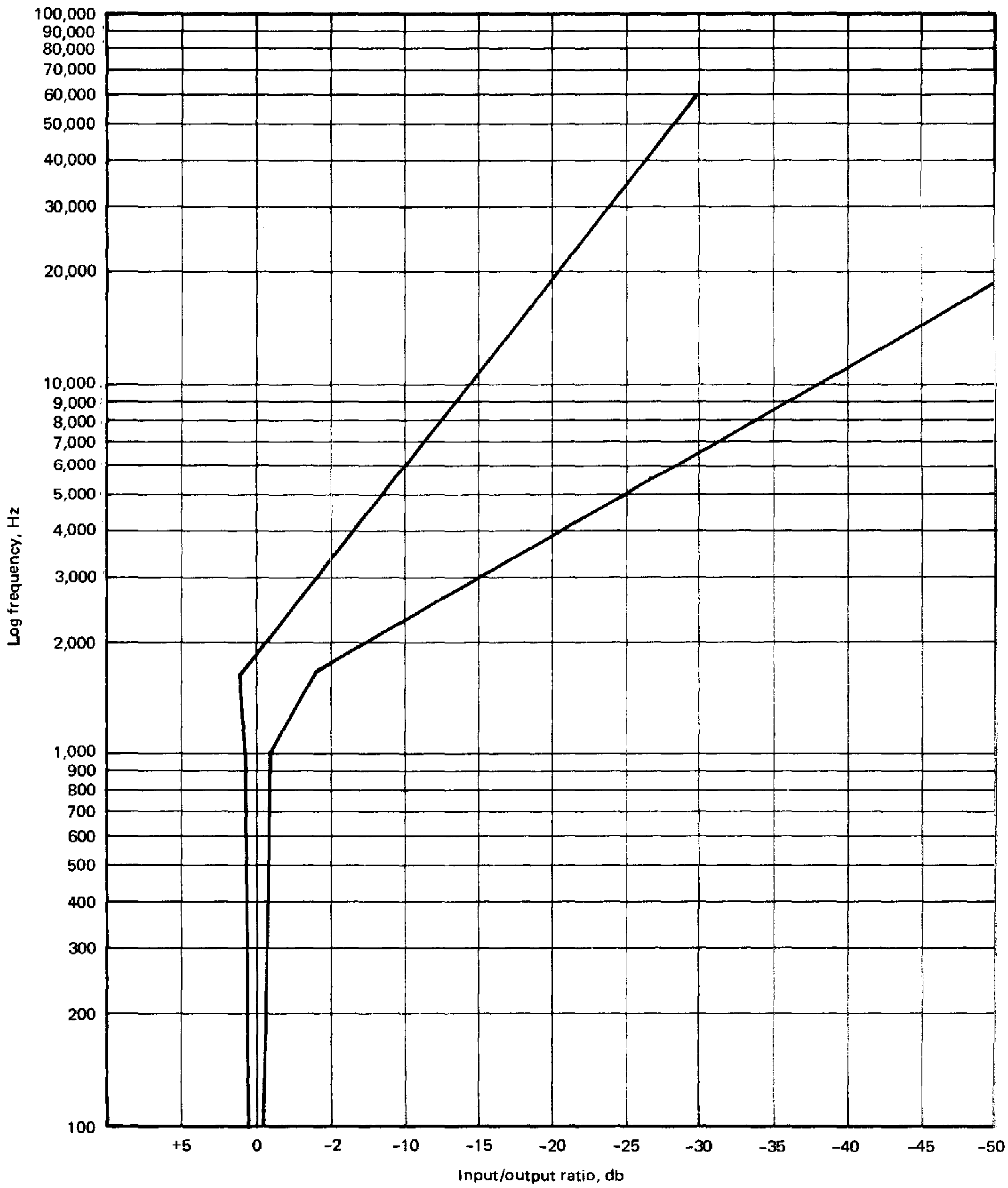


Fig. 33. Frequency response characteristics SAE class 1000

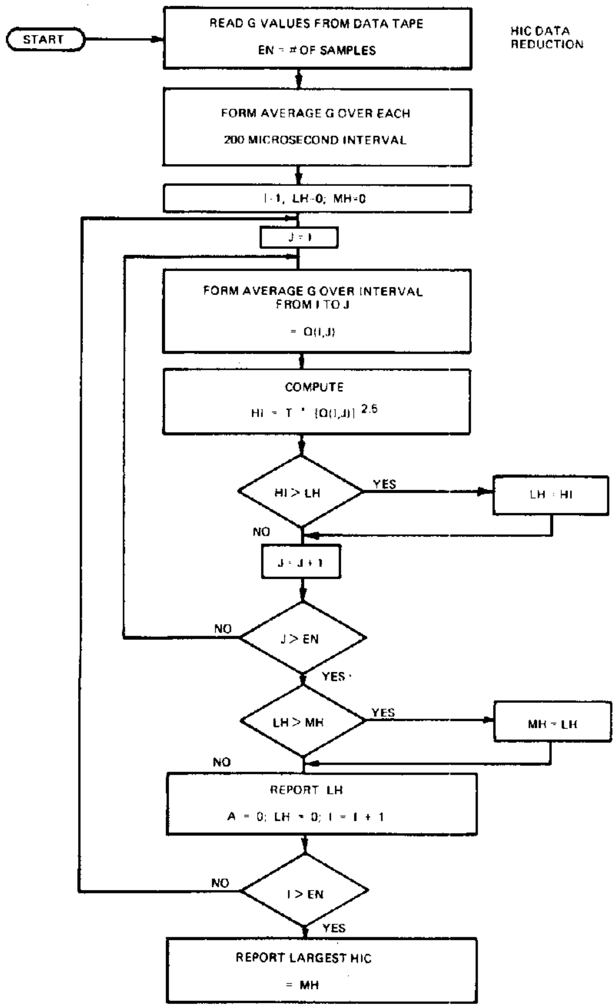


Fig. 34. Flow chart for head injury criterion

g Values each 200 microseconds

1.06	111.64	51.85
1.06	119.05	45.60
1.06	129.63	40.21
1.06	141.27	37.04
1.59	153.97	33.86
3.18	165.61	30.16
5.29	171.43	26.93
7.94	175.66	22.75
11.11	175.66	19.58
16.93	173.55	16.93
23.28	170.37	13.23
31.75	161.91	9.52
38.10	152.38	5.29
46.03	141.80	3.70
55.03	130.69	2.12
69.31	115.34	1.06
84.13	98.94	1.06
103.71	83.60	0.53
116.40	69.84	1.06
117.46	63.49	
112.70	57.67	

HIC	START	END			
766.757	8	41			
797.534	9	41			
828.759	10	40			
859.210	11	40			
887.403	12	40			
913.041	13	40			
936.007	14	40			
956.277	15	39			
969.948	16	39			
973.858	17	39			
965.018	18	39			
943.495	19	39			
916.555	20	39			
891.510	21	39			
869.432	22	39			
845.104	23	39			
813.160	24	39			
771.392	25	38			
718.678	26	38			
654.337	27	39			
582.476	28	39			
506.579	29	39			
429.639	30	39			
354.712	31	39			
283.336	32	39			
219.939	33	40	LARGEST HIC		
165.330	34	41			
121.601	35	42	973.858	17.000	39.000

Fig. 35. Computer analysis of head injury criterion G values each 200 microseconds

As none of these data show the Gadd Severity Index exceeding the line:

Head Injury Criterion = Gadd Severity Index

It is considered adequate that for production testing the Gadd Severity Index be substituted for the Head Injury Criterion. For qualification purposes, however, the Head Injury Criterion is necessary.

The Gadd Severity Index may be computed manually for acceleration time data, as shown in Table 26, which follows the general format of SAE J885a [84] for Severity Index calculation.

Procedure: The procedural requirements of the impact test must address the following:

- equipment warmup
- system accuracy
- system components specifications
- system verification procedures
- impact velocity verification
- mounting of samples
- standard drop heights
- acceleration reference calibration
- sample breakage

Penetration Testing

The basic system components for penetration testing include:

(a) Penetration striker — having an included angle of 30°, a minimum cone height of 1.5 inches, Figure 37. The striker tip must be of specified hardness and be electrically conductive

(b) Penetration headform must be metallic with an electrically conductive surface

(c) Contact sensor with sufficient detection ability. The system used at Dayton T. Brown, Inc. incorporates a Mallory and Co. Sonalert SC628 continuity checker, Figure 38.

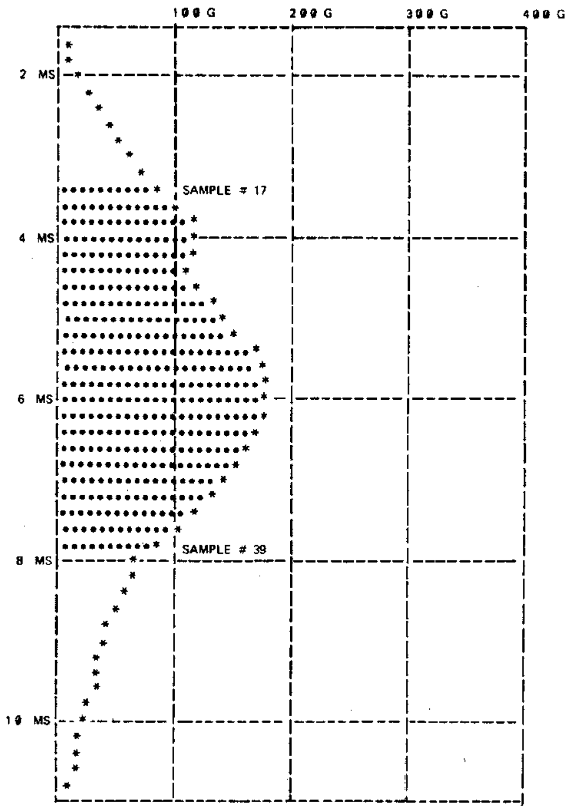


Fig. 35. Computer analysis of head injury criterion (continued)

Electrical Insulation Test

The test method and procedure used in ANSI Z89.2–1971 is considered sufficient for testing purposes, however, voltmeter and milliammeter accuracy should be specified.

Test equipment used at Dayton T. Brown, Inc. consisted of (Photograph 9):

- Hipotronics 730-2 high-voltage AC power supply
- Belden 60,000 volt wire
- Glass tank

Flammability Test

ASTMD635 - "Flammability of Self Supporting Plastics," is considered adequate for the flammability test, except that only three samples need be cut from outer shell of the helmet. The self-extinguishing characteristics of firefighters' helmets may be evaluated using the same method. However, a maximum burn rate of 0.5 inches/minute should be specified as opposed to the 3 inches/minute for industrial use helmets.

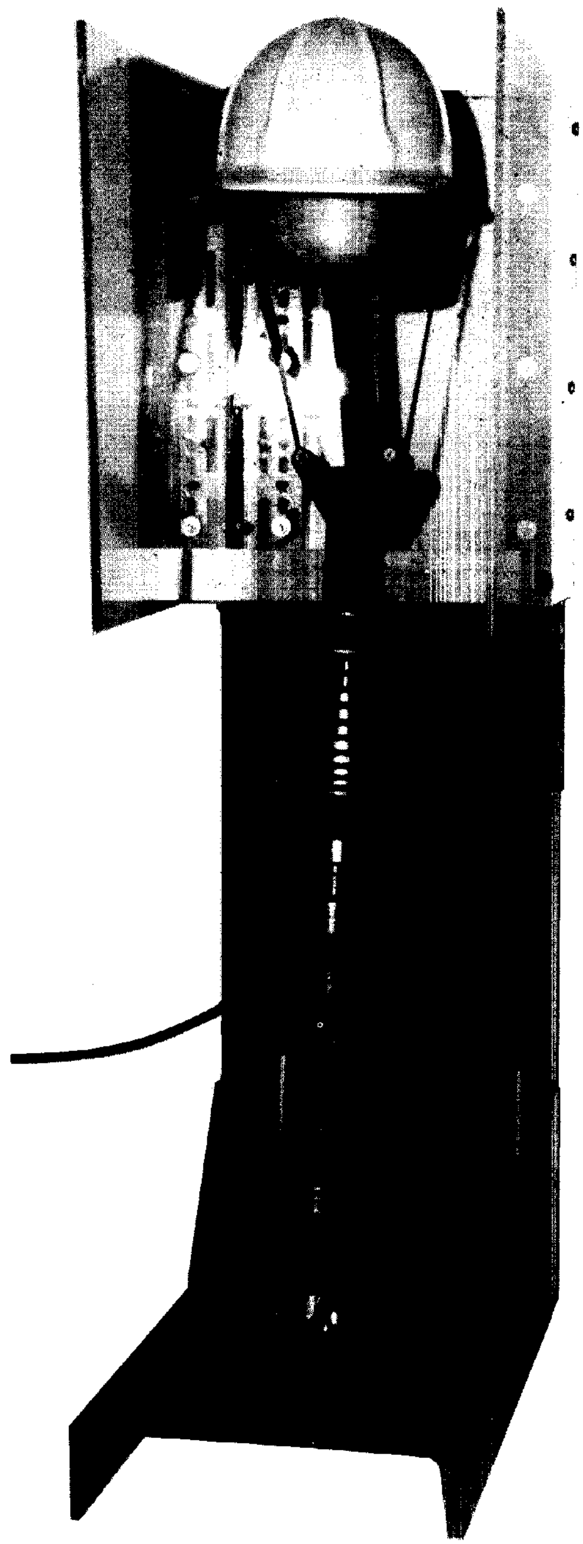


Photo. 19. Overall view of retention text fixture.

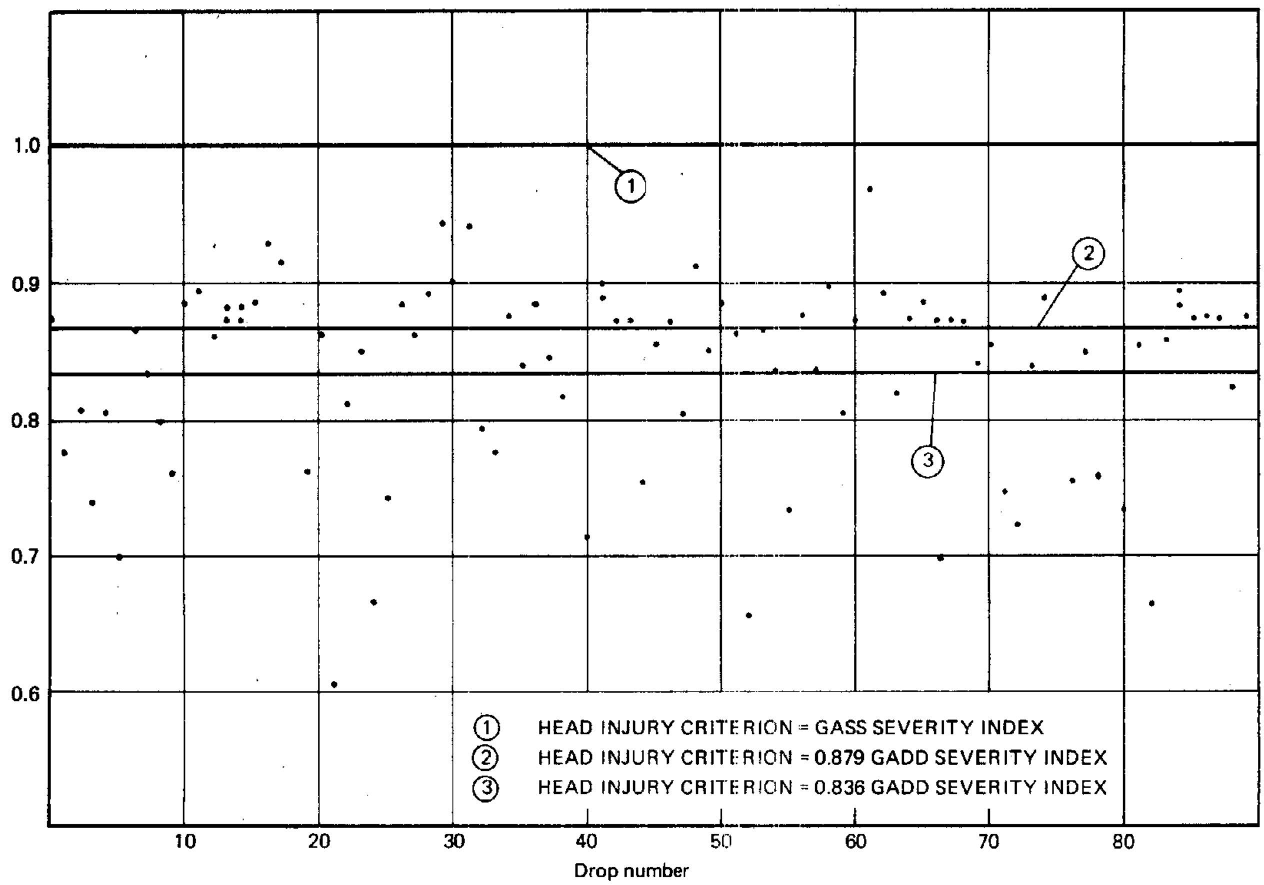


Fig. 36. Ratio of head injury criterion to gadd severity index

Retention Test

The test of the retaining strength of a helmet chin strap may be conducted as shown in Photograph *19*. Figure 39 shows the basic dimensions necessary for a standard mechanical chin structure.

A procedure for assuring the helmet has "seated" prior to elongation measurements must be stated.

Recommendations to the User

As with any personal protective device, a helmet can only be beneficial if it is worn and used correctly. It is with this in mind that recommendations to the user should comprise:

- a method of selection
- proper use
- recommended maintenance

Selection

Helmets must be able to be selected with a minimum of difficulty. This requires that:

(a) hazards applicable to a specific class of headgear be easily identifiable.

(b) the number of distinct classes should be kept as low as possible to avoid confusion.

(c) identification of various classes of helmets must be as simple and as readily apparent as possible. A large arabic numeral appearing on the forehead of the helmet would best suit this need. In addition, the class of the helmet, appearing on the underside of the peak or brim allows the worker, unaccustomed to the class designations, to identify the helmet.

The user should be cautioned that:

- his specific application may require a specialized helmet
- his helmet will not protect from all accidents

Use of the Helmet

Following selection, the user must correctly adjust the headgear to his head. Thus, when sold, the helmet must be accompanied by an instruction sheet

Table 26. Gadd Severity Index manual calculation of sample pulse in figure 35

Increment no.	Time of increment (seconds)	Midpoint (g)	$g^{2.5}$	Incremental SI Index (time X $g^{2.5}$)
1	0.0006	0.5	—	—
2	0.0006	2.1	6	—
3	0.0006	7.2	139	—
4	0.0006	21.4	2119	1.3
5	0.0006	43.4	12409	7.5
6	0.0006	79.37	56123	33.7
7	0.0006	108.2	121777	73.1
8	0.0006	121.2	161717	97.0
9	0.0006	147.6	264676	158.8
10	0.0006	170.6	380143	228.1
11	0.0006	168.8	370195	222.1
12	0.0006	146.3	258887	155.3
13	0.0006	107.1	118706	71.2
14	0.0006	70.7	42029	25.2
15	0.0006	48.9	16721	10.0
16	0.0006	35.2	3751	2.3
17	0.0006	25.1	3156	1.9
18	0.0006	14.6	814	0.5
19	0.0006	5.8	81	—
20	0.0006	1.3	1.9	—
			Gadd Severity Index: Σ	1,088

from the manufacturer which will provide a procedure for these adjustments. The instruction sheet must also tell the user where and how he may apply his personal identification to the helmet. The user should be cautioned, by means of a durable label affixed to the inside of the helmet, that a severe blow to the helmet may result in permanent damage to it.

In the user's standard, the user must be cautioned that:

(a) The helmet must be secured to the head to offer best protection.

(b) The helmet's materials may be adversely affected by uncommon chemical exposure or environmental conditions.

(c) The helmet's ability to protect will be degraded by alteration.

(d) The helmet's performance may be degraded by application of decals or paint, unless otherwise stated by the manufacturer.

(e) The helmet's electrical insulation characteristics are not intended to make it suitable for use as an electrical insulator.

Maintenance of the Helmet

The ability of the helmet to withstand the constant use of the wearer will be heavily dependent on design, construction, and materials. For this reason, in the instruction sheet, the manufacturer must provide the user with a method of visually examining the helmet for damage and wear.

Damages to the helmet which require immediate action of the user are:

- shell breakage or fracture
- shell disfiguration, warpage or softening
- suspension or chin strap breakage or fraying

If it is deemed necessary to replace defective parts of the helmet, to aid the user in identifying the manufacturer and model designation, this information must appear on the underside of the peak or brim of the helmet.

The manufacturer must supply the user with a recommended method of cleaning and disinfecting the helmet. The recommended cleaning agent must be readily accessible by appearing on the underside of the peak or brim.

As helmet deterioration will be a function of age

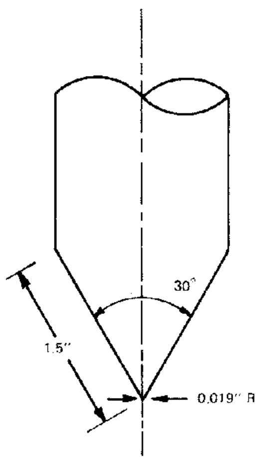


Fig. 37. Penetration striker point

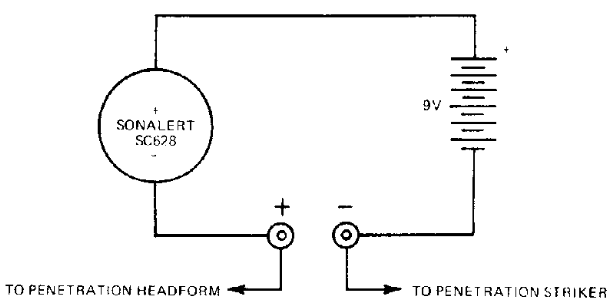


Fig. 38. Penetration continuity checker

and use abuse, unless specified by the manufacturer, the user must decide when to replace a helmet which shows no apparent signs of damage. To assist him in this decision, the month and year of manufacture should appear on the underside of the peak or brim.

The user should be cautioned not to abuse the helmet. When continual electrical hazards exist in the working environment, the user should be informed that periodic testing may be necessary. As a final precaution, the user should be made aware

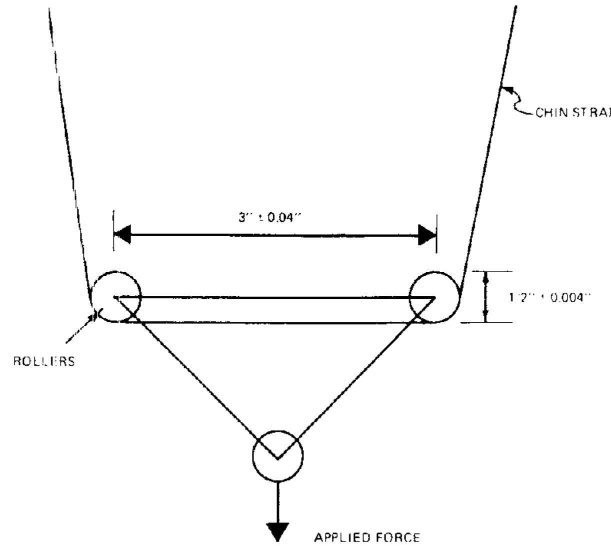


Fig. 39. Standard mechanical chin structure

that a helmet found to be unsuitable for further use should be rendered incapable of being worn.

Summary

This report represents the results of a research project to develop criteria for a performance standard, a testing standard, and a user's standard for industrial and firefighter's head protective devices. On the basis of these criteria, standards, in a developmental stage at the present time, are being prepared for publication and will be available for the purpose of review and comments.

In this study it has been found that adequate industrial and firefighter head protection necessitates the use of four distinct levels of protection, and the use of these protective devices must be determined by the occupational hazard.

Currently available head protective devices have been found to offer impact protection to a limited area of the head and are not well suited to the broad range of accident types found in the industrial environment.

A human head injury index, the Head Injury Criterion, has been applied as an impact performance evaluation technique, and the test methods, equipment, and procedures necessary for accurate measurement have been developed. Whenever possible the analysis of the needs of the industrial and firefighter's protective headgear have considered comfort factors and wearability as paramount considerations. These efforts are considered to have greatly improved the head protection afforded the industrial worker and the firefighter.

Recommendations

The standards developed on the basis of the criteria contained herein may be sufficient for the implementation of a testing and certification system for an improved level of industrial and firefighter's head protection. The following are recommended for the continuing improvement of our knowledge of the needs of the worker, head protective devices made available to him, and the methods by which the performance of these devices are measured.

1. The accident reporting system used in the United States should be modified to enable more in-depth study of the industrial and firefighting accident. Such a system must strive for uniformity in reporting and should provide sufficient resolution to be effective in analyzing the effectiveness of head protective devices.

2. Additional study of the industrial head injury accident should be conducted by means of field investigation. This is considered particularly important for the firefighting environment where accident reporting systems vary with the individual fire department.

3. Efforts must be continued in the search for accurate head impact tolerance values. The factors of degree of head injury, head rotational injuries and human tolerance to top of head impact deserve considerable attention.

4. Investigations to define industrial helmet comfort factors especially in the areas of weight, center of mass, and moment of inertia should be conducted.

5. Additional study should be made of the interaction of industrial head protection with eye, face, ear and respiratory equipment. Such would facilitate the development of a one-piece firefighter's protective suit.

6. Additional study is necessary for the development of a test headform with human-like response, which is suitable for use in certification testing.

7. The performance of head protective devices must be continually monitored to determine advances in state of the art technology.

8. Additional study of industrial head protection of specialized industries should be conducted.

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