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**DYNAMICS OF HEAD PROTECTION**  
**(Impact Protective Comparison of the SPH-4**  
**Flight Helmet to a Commercial Motorcycle Helmet)**

by  
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**BIODYNAMICS RESEARCH DIVISION**

July 1985

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## 20. ABSTRACT

The impact protection provided by a commercial motorcycle helmet is evaluated in this report. The motorcycle helmet utilizes an expanded plastic foam liner of 12 mm thickness, which is less than that used in most motorcycle helmets made in this country today. The thickness of the foam is identical to that used in the US Army Aviator's standard Sound Protective Helmet No. 4 (SPH-4). The impact protection provided by the commercial helmet is compared to the protection provided by the SPH-4 aviator helmet. A total of 16 metal headform impacts (8 for each of two helmets) were conducted using impact velocities ranging from 4.2 to 6.9 meters per second. By measuring the reaction force of the helmeted-headform impacts as well as the deceleration of the headform, we concluded that the helmets permitted transmission of injurious forces at all levels of energy beyond 4.5 mps contact velocity. The importance of increasing the thickness of the plastic foam liner in experimental SPH-4 helmets in order to reduce the deceleration force measured in the headform is demonstrated. Evaluations of this nature provide the necessary data base for developing helmet impact test standards as well as an awareness of the good and bad features of crash helmet design, regardless of the helmet type or the origin of manufacture.

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## INTRODUCTION

Impact protective headgear should be designed to distribute impact, absorb impact energy force, and resist penetration or fracture by impact with sharp-edged structures. Helmets have been accepted items for head protection in war, athletics, recreation, and all hazardous industries. In early days, aviation helmets were of the same type as motorcyclists' helmets, designed primarily to give protection against wind blast. Later, as expanded plastic foam energy-absorbing liners became available, they were made similar to football helmets with the idea of protecting against impact, and more recently to protect against wind blast, noise, and impact. Most motorcycle helmets are designed for wind blast and impact protection with little, if any, attention to noise protection for the ears.

A commercial motorcycle helmet is evaluated in this report and compared to the US Army Sound Protective Helmet No. 4 (SPH-4) aviator helmet, and to experimental helmets of the same configuration as the SPH-4. Such evaluations provide the necessary data base for comparison of helmet standards as well as awareness of both the good and bad features of crash helmet design, regardless of origin of manufacture. The importance of increasing the thickness of the plastic foam liner is demonstrated.

## METHOD

### MATERIAL

The commercial motorcycle helmet shown in Figure 1 was evaluated for impact performance; i.e., the transmission of force to an instrumented headform. The visor was cut short in order to permit the helmet to fit on the drop tower test fixture. The shell was white plastic of 4.2 mm thickness at the crown, with a thickness of 3.5 mm in the hatband region. The polystyrene energy-absorbing liner had 12 mm thickness, and covered the head as illustrated in Figures 3 through 6. Although not readily seen in the figures, the liner was located about 3 cm above the ear canal at the sides and about 2 cm below the occipital bone at the rear.\* The foam liner employed in the helmet required a pressure of 60 N per cm<sup>2</sup> to achieve 25 percent compression. The density was .07 gm/cm<sup>3</sup>. Retention of the helmet was accomplished by the chinstrap which was yoke-mounted to the shell. The yoke mount is preferable to a single swivel mount because rotation either forward or rearward is resisted more directly by the yoke.

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\* Additional coverage of the cranium would be desirable since it would allow rotational displacement of the helmet during impact without loss of protection.

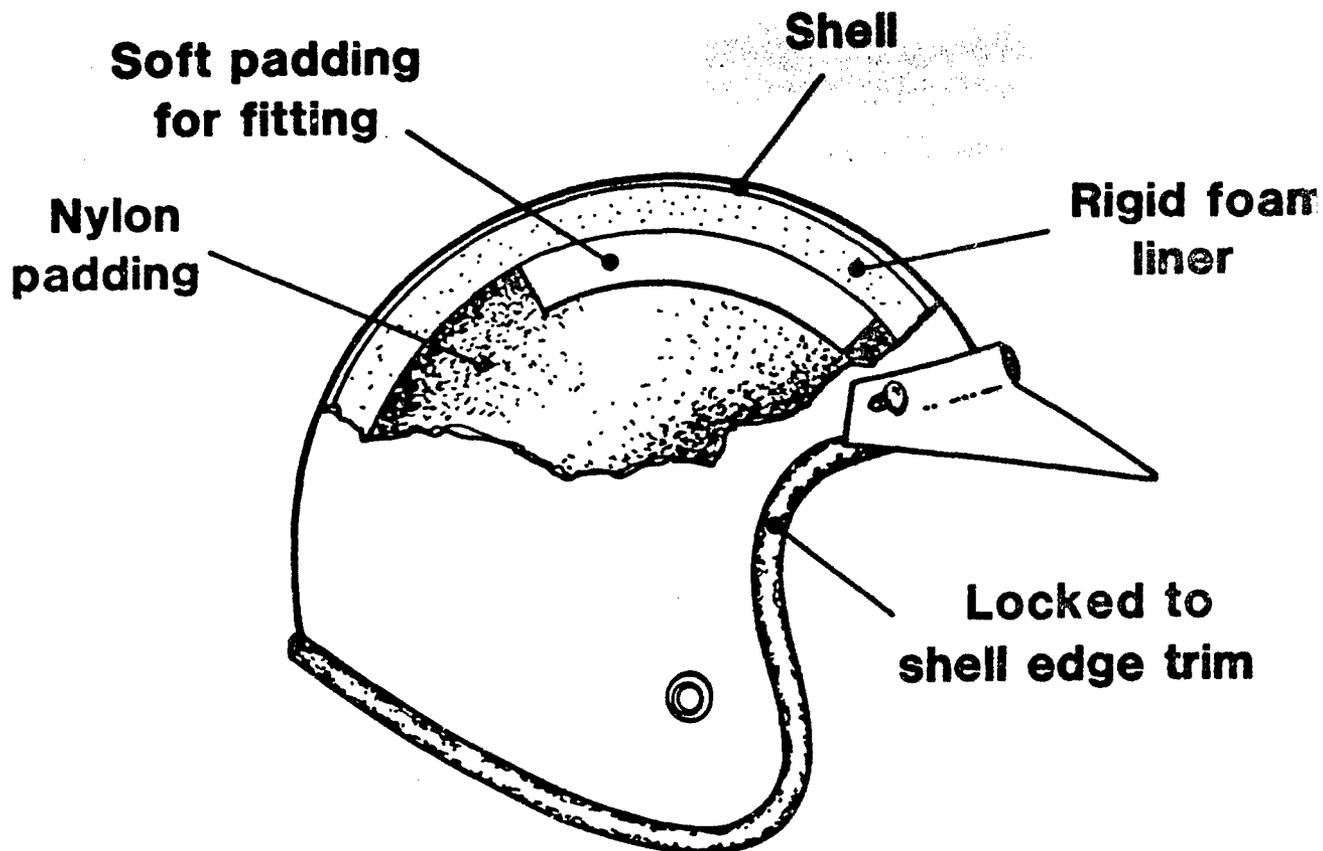


FIGURE 1. Cutaway View of the Motorcycle Test Helmet.

#### PROCEDURE

The impact test device is shown in Figure 2; the tower hardware and instrumentation equals or exceeds American Standard Association Z90.1-1971 Standards. The rigid base plate exceeds Z90.1 requirements by an order of magnitude since it weighs over 1,800 kilograms (kg). This mass insures that the headform acceleration is as accurate as it is feasible at high acceleration levels.

The helmets were placed on a medium-size (3.76 kg) cast magnesium headform with one accelerometer mounted near the center of gravity. The standard Z90.1 magnesium headform was attached to a lightweight cage and the cage was guided vertically on two steel cables. The headform, helmet, and cage were elevated on the vertical cables to a selected drop height for each impact test. The weight of the headform and cage was 11.0 pounds (5.0 kg) while the weight of the helmet was 2.9 lbs (1.3 kg) for a total drop weight of 13.9 lbs (6.3 kg).

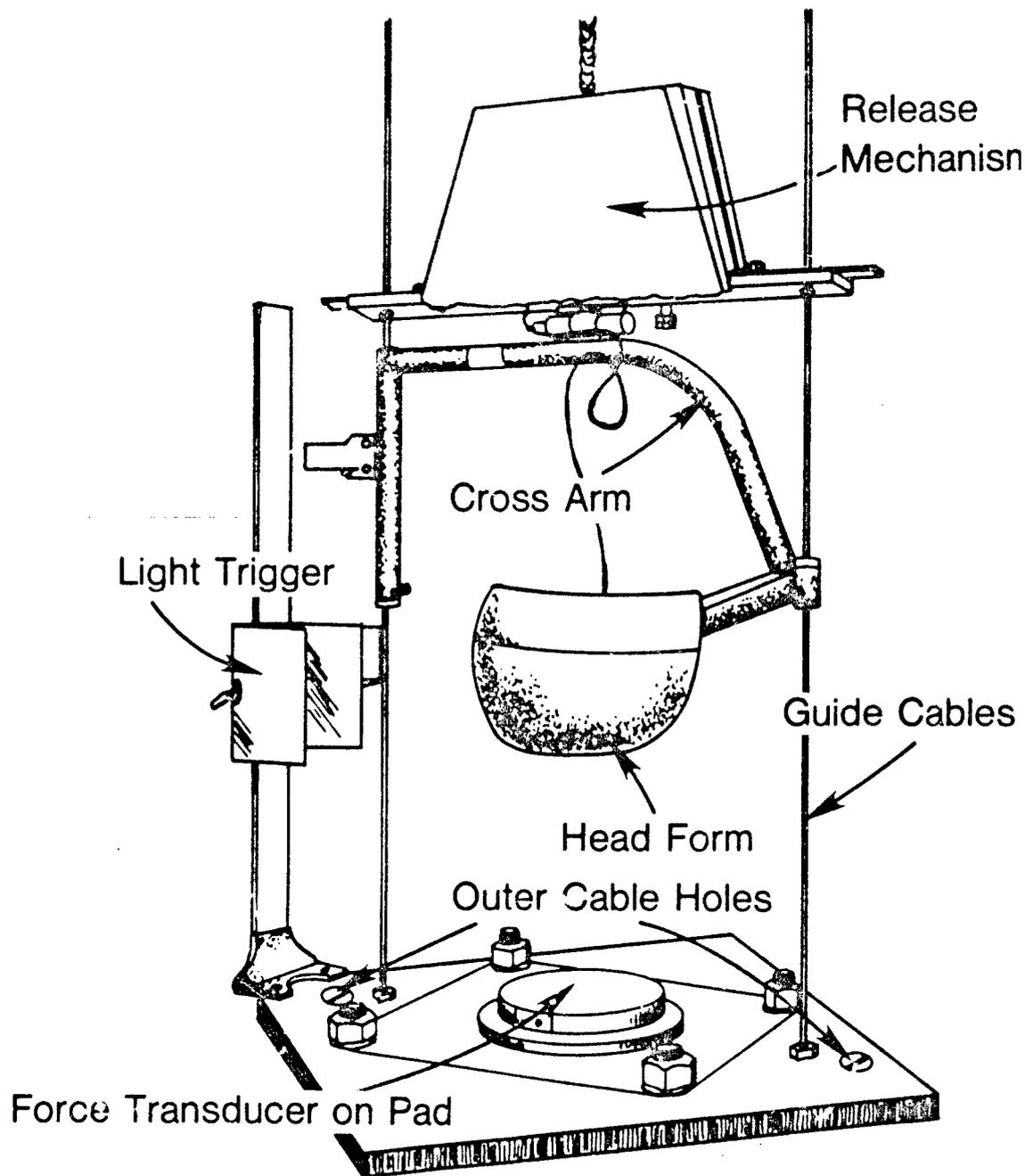


FIGURE 2. Helmet/Headform Free-fall Test Device.

The uniaxial accelerometer signal was amplified by a signal conditioner. Three piezoelectric load washers (Kistler type 9021)\* were positioned beneath a force plate in lieu of the calibration pad shown in Figure 2. The outputs of the accelerometer and force plate transducer were displayed on a two-channel digital oscilloscope and read also from peak voltage meters.\*

The helmeted headform was dropped 13 times from 0.91 to 2.44 meter (m) heights onto a flat surface. Three additional drops were made onto the Z.90.1 standard 4.8 cm radius hemispherical surface, to provide comparative data. The test sequence, impact locations, and energy of impact (drop height and total drop mass) for the two motorcycle helmets are shown in Table 1. The drop sequence is shown by test number in the table.

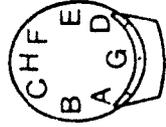
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\* See Appendix A.

TABLE 1  
PEAK G, TRANSMITTED FORCE, AND REBOUND VELOCITY  
MEASURED IN SIXTEEN (16) HELMETED-HEADFORM IMPACTS

HELMET NO.	DROPP NO.	DROPP LOCATION	IMPACT SURFACE	OFFSET (a) DIST. (cm)	DROPP HEIGHT (meters)	MEASURED (c) FORCE (NEWTONS)	DECELERATION			PULSE DURATION (millisec)	REBOUND VELOCITY (m/sec)
							Calc. (d) PEAK (G)	MEASURED PEAK (G)	Calc. (e) AVG. (G)		
1	10A	R FRT	FLAT	2.5	1.47	12,090	244	249	92.5	8.0	.58
1	13P	R SIDE	FLAT	2.5	1.47	13,890	279	258	105.9	7.7	.82
1	14C	R REAR	FLAT	2.2	1.47	14,810	298	287	113.7	6.8	.64
1	22D	L FRT	FLAT	2.1	2.44	19,620	394	402	117.4	8.0	.73
1	23E	L SIDE	FLAT	2.5	2.44	18,740	377	350	135.8	7.6	.98
1	24F	L REAR	FLAT	2.1	2.44	30,030	604	576	154.4	6.0	.67
1	25G	CTR FRT	FLAT	1.9	2.13	22,300	448	430	135.0	6.6	.82
1	26H	CTR REAR	FLAT	2.5	2.13	19,620	394	382	147.6	6.7	1.1
2	11A	R FRT	4.8cm rad. Hemisphere	1.4	1.47	16,850	339	353	132.4	5.4	.52
2	12B	R SIDE	"	2.7	1.47	10,170	204	196	82.2	10.0	.70
2	16C	R REAR	"	3.3	1.47	17,090	344	330	90.8	7.7	.58
2	17D	L FRT	FLAT	2.4	0.91	9,410	189	195	79.0	7.8	.61
2	18E	L SIDE	FLAT	2.5	0.91	10,070	202	174	83.5	7.6	.61
2	19F	L REAR	FLAT	2.1	0.91	10,470	211	176	83.9	7.2	.55
2	20H	REAR CTR	FLAT	2.1	1.22	13,930	280	252	108.8	6.3	.64
2	21G	FRT CTR	FLAT	2.5	1.22	13,270	267	237	98.2	7.5	.79

(a) Distance from shell outer surface to the metal headform  
 (b) Vertical distance from the impact surface to helmet's point of contact  
 (c) Reaction force in load cell at the impact surface  
 (d) This value is calculated as follows:  $G = \frac{f \times 10^3}{9.81 \times m}$  where  $f$  = Transmitted force in Newtons and  $m$  = mass of headform and guide cage of 5070 grams  
 (e) This value is calculated as follows:  $G_{avg} = \frac{\text{area under (accel x time) trace}}{\text{total pulse duration}} = \frac{\Delta V}{t}$



Front of Helmet

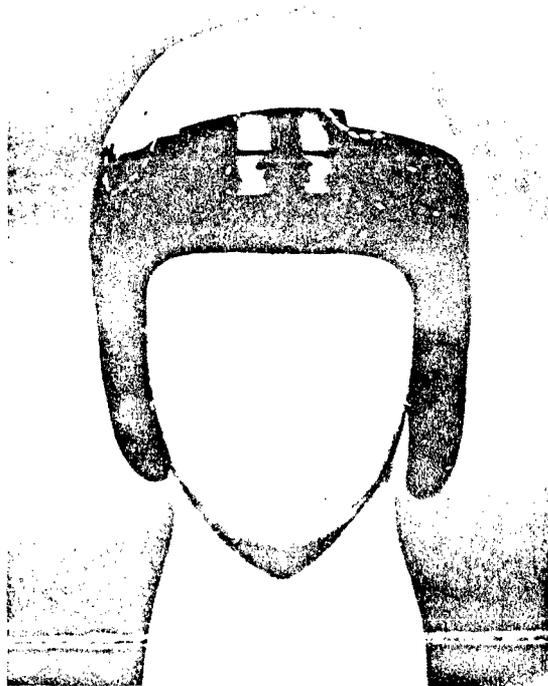
## RESULTS AND DISCUSSION

### MOTORCYCLE-TYPE HELMET TESTS

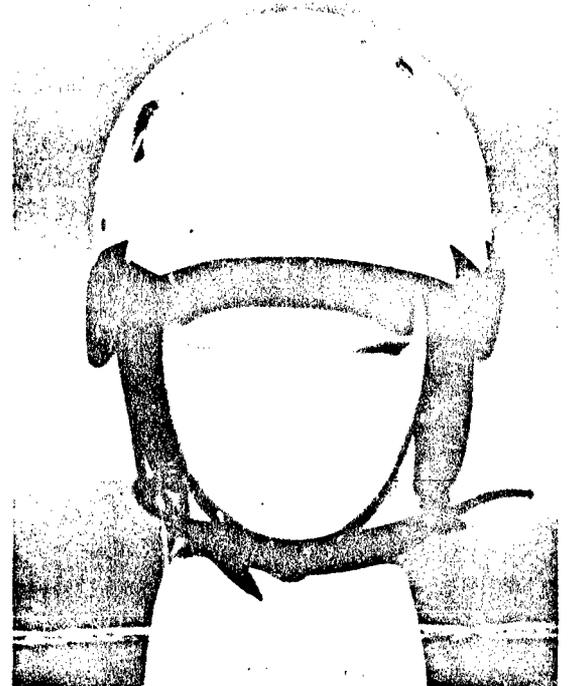
The two motorcycle-type helmets were subjected to the 16 impact tests as cited in Table 1. The appearance of helmet No. 2 after the impact tests is shown in Figures 3 through 6. The centroid of all impact points was at least 6 centimeters above the lower edge of the foam liner.



FIGURE 3. Side View of Impacted Helmet (Visor shortened to fit into impact test fixture).

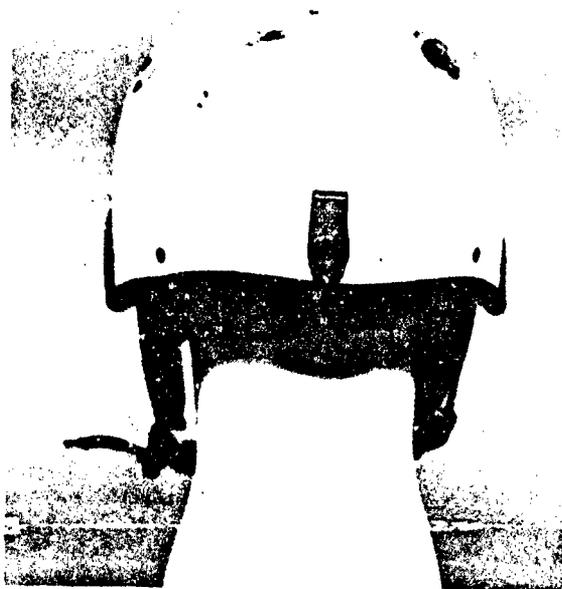


(Shell plus liner)



(Liner with outer shell removed)

FIGURE 4. Front View of Helmet Subsequent to Completion of Impact Tests (Integral Shell Visor Has Been Cut Off to Permit Drop Tests Without Interference).



(Shell plus liner)

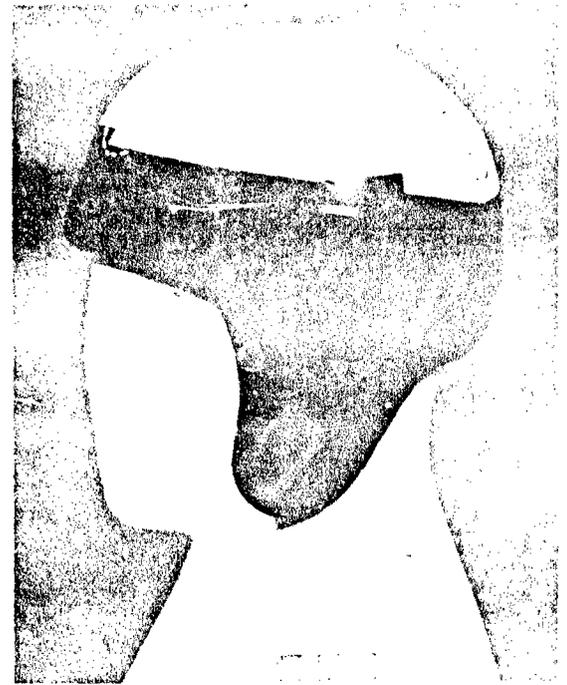


(Liner with outer shell removed)

FIGURE 5. Rear View of Helmet and Liner  
Subsequent to Impact Testing



(Shell plus liner)



(Liner with outer shell removed)

FIGURE 6. Left Side View of Helmet and Liner Subsequent to Impact Testing (Integral shell visor has been cut off to permit drop tests without interference)

The effect of increased drop height and concomitant impact energy is shown in the plot of acceleration versus time in Figure 7. The difference between a flat surface and a 4.8 cm radius surface for equal impact energy (1.47 m drop height) also is shown in Figure 7. Note that the acceleration values obtained for test Nos. 10, 13, 14, 17, 18, 19, 20, and 21, at three different drop heights (0.91, 1.22, and 1.47 m) are consistent. This indicates uniform quality of the helmets. The significant variation of the traces in the 4.8 cm radius drops shown is probably caused by friction between the guide cables and the headform guide cage. This type of problem is more likely to occur when impacting the spherical surface than

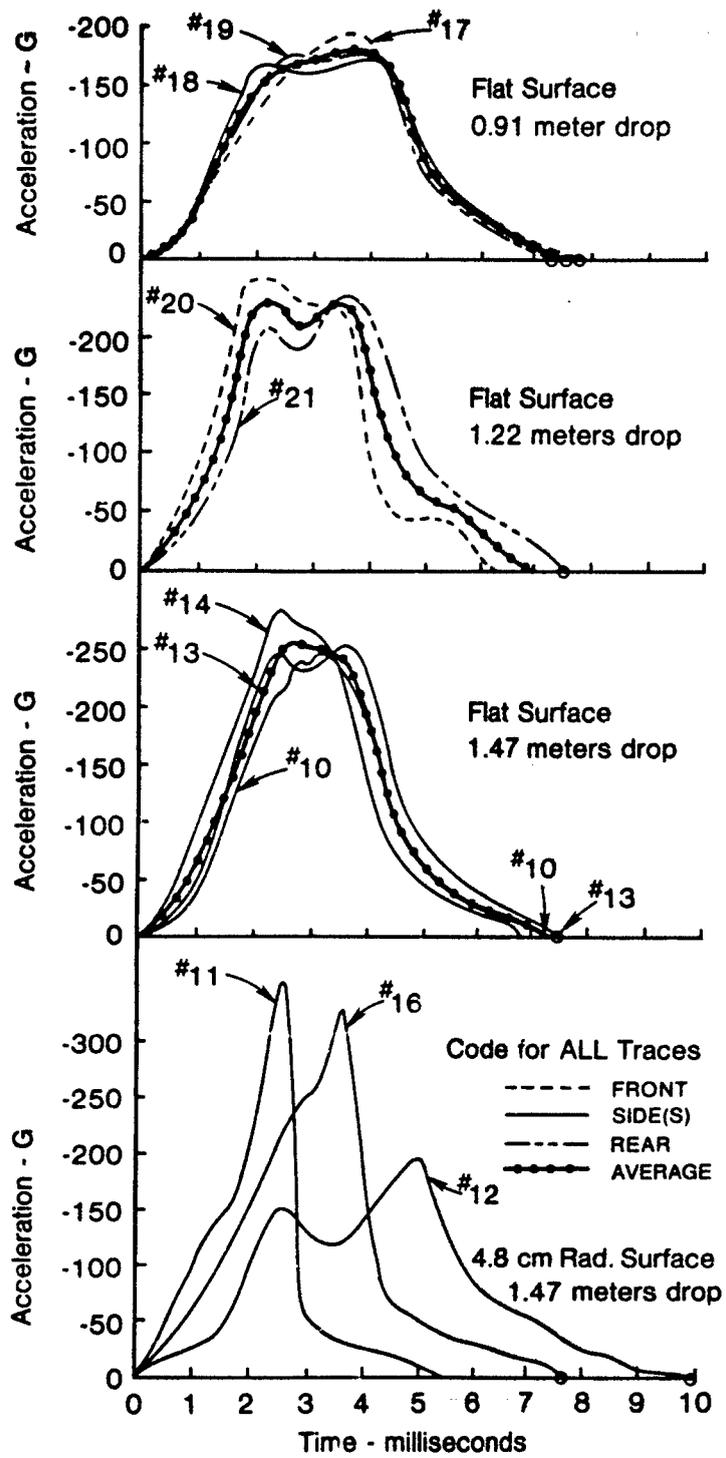


FIGURE 7. Variation of Transmitted Acceleration for Three Drop Heights

when impacting a flat surface due to the lateral movement of the headform and guide cage, as the helmet tends to "slip or slide" down the side of the spherical surface.

The effect of increasing the drop height to 2.13 and 2.44 m is shown in Figure 8. At the 2.13 m drop height, the two traces nearly are identical. At the 2.44 m drop height, the three traces differ as evidenced from comparison of the 580 peak G on run 24 F (left rear) and the 350 peak G run 23 E (left side). This large difference in peak G response most likely is caused by the "bottoming out" or total crushing of the foam liner in run 24 F. A difference of only 1 mm in crush distance can result in a significant change in peak acceleration level. It is possible that friction prevented the peak G in drops 22 D and 23 E from being greater than shown in Figure 8.

Peak headform deceleration versus drop height is shown in Figure 9. The peak decelerations (G) also are compared to the derived Wayne State University (WSU) tolerance curve (Haley et al., 1966). The derived curve reveals that all experimental impacts on these helmets resulted in injurious G values.

The 1975 Snell Foundation Helmet Specification (Snively, 1975) calls for the helmet to permit transmission of a peak acceleration of 300 G or less when dropped from a height of 3 meters. From Figure 9 it can be seen that drops 10, 12, 13, 14, 17, 18, 19, 20, and 21 would have passed the Snell specification, while the remainder would not have passed.

British Standard 2001 (1972) requires that a motorcycle helmet not cause a peak headform force greater than 4,400 pounds (19,580 Newtons) when a 5-kg headform mass is dropped from a height of 2.5 meters. From Table 1 it can be seen that experimental drops 22, 24, 25, and 26 resulted in a transmitted force greater than 19,580 Newtons, and would have failed the requirements of the British 2001 Standard. The U.S. Department of Transportation (DOT) 218 Standard (Office of the Federal Register, 1980) requires that helmets dropped from 1.8 meters not exceed 400 G peak; drops 22, 24, and 25 also failed this standard.

The fact that four of the impacts resulted in such a high level of transmitted force (19,580 N or more) and accelerations ranging from 382 to 576 G focuses attention on the inadequate liner provided in the helmet. The liner should be at least twice the thickness of 12mm used in these two helmets in order to lower the transmitted force to tolerable levels for impacts in the range of 2 meters drop height.

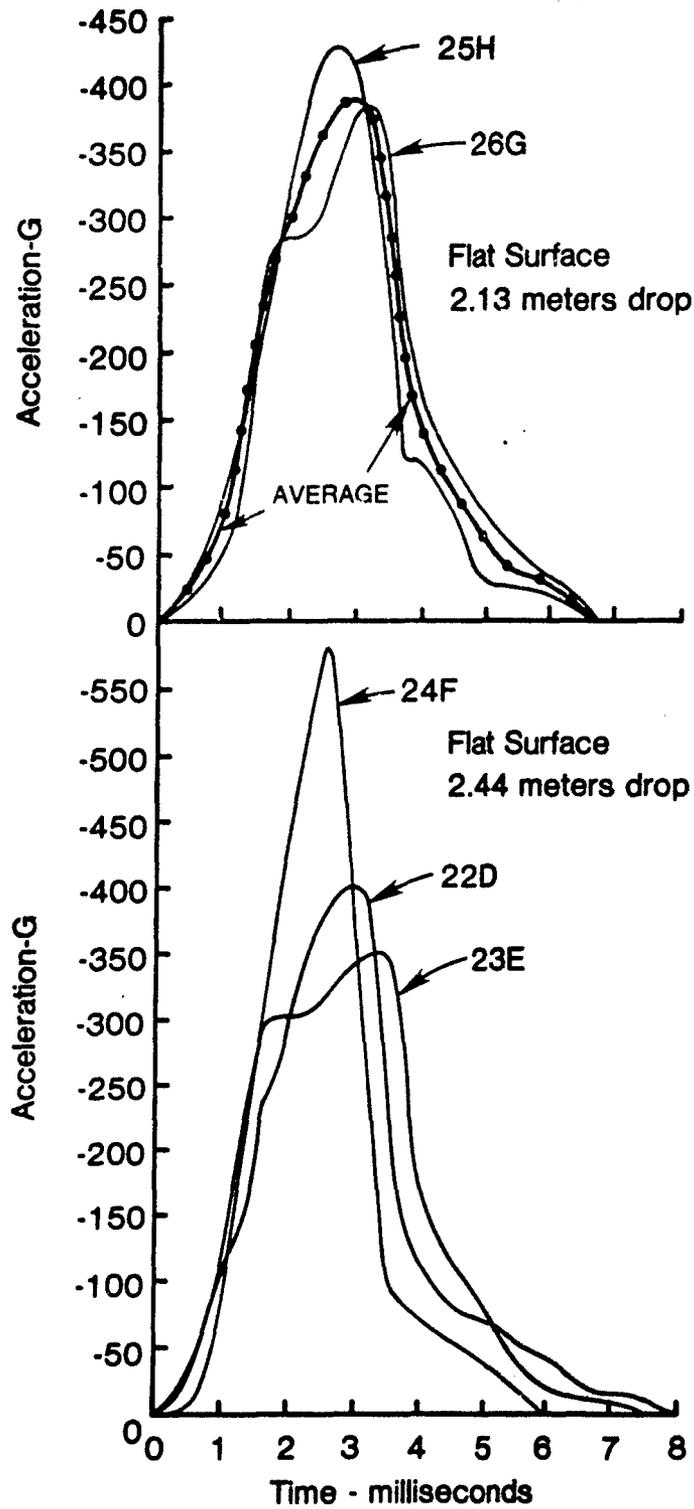


FIGURE 8. Variation of Transmitted Acceleration for Two Drop Heights

### MOTORCYCLE HELMET IMPACT IDENTITY SURFACE

- Helmet No. 1 - Flat Impactor
- Helmet No. 2 - Flat Impactor
- Helmet No. 2 - 4.8 cm Rad. Hemisphere Impactor

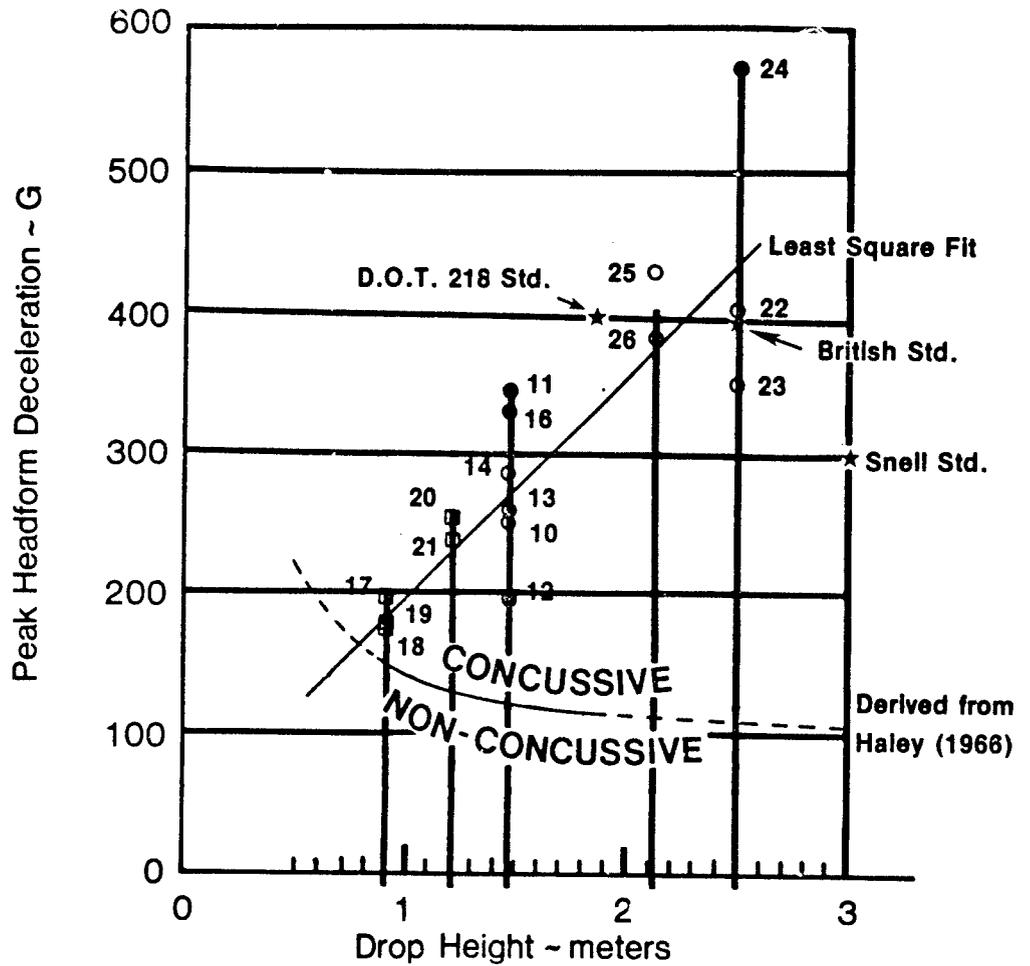


FIGURE 9. Peak Headform Deceleration vs. Drop Height Compared to Derived Wayne State University Tolerance Curve

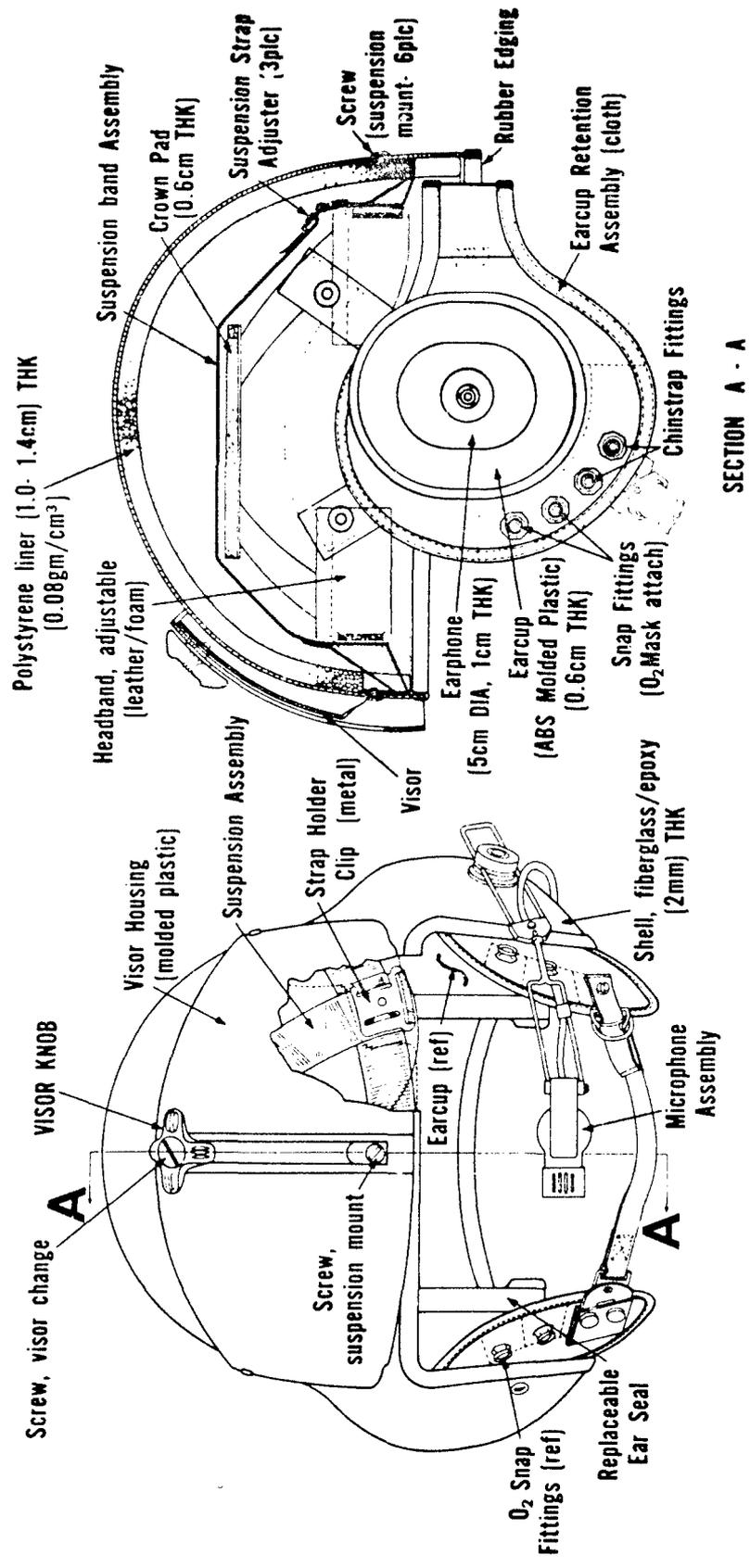
Since it may be expected that motorcyclists may fall or be thrown from heights of 1.6 m up to 3.0 m, it is clear that riders could receive various degrees of head injury while wearing the helmet. These energy values are within the limits of 3.0 meters (Snively, 1975) and 1.8 meters (DOT 218) for energy; however, both these standards permit transmitted acceleration to the head which is far in excess of the values recommended by others (Gurdjian, Lissner, and Patrick, 1962, Haley et al., 1983, Hundley, Haley, and Shanahan, 1981, Nahum, Raasch, and Ward, 1981, Slobodnik, 1980, and Ward and Nahum, 1979).

#### EXPERIMENTAL HELMET TESTS

The experimental helmet shell configurations were identical to the standard SPH-4 shell. The SPH-4 helmet is described in Figure 10. It was shown (Haley et al., 1966) that increased foam thickness would significantly reduce transmitted acceleration; therefore, the SPH-4 foam liner was increased up to 0.88 inch (2.24 cm) in these tests. Only two different shell and liner test constructions are summarized for this report in Figure 11. However, a total of 12 different shell and foam combinations were tested in this series. The two experimental shell and foam liner specimens summarized in Figure 11 were of identical contour as the standard SPH-4 flight helmet. The test sequence consisted of five drops from 3 feet (0.91 m) through 6.65 feet (2.03 m) onto a flat rigid surface. (The experimental configurations did not include a suspension system as shown in Figure 10.) The peak G for the experimental helmets was approximately half that of the standard SPH-4 helmet (1.3 cm foam) for these impacts.

#### COMPENDIUM OF US ARMY SPH-4 FLIGHT HELMET TESTING

For comparative purposes, the transmitted deceleration of the standard SPH-4 flight helmet for 1.40 to 1.52 meter drops is summarized in Figure 12. Peak deceleration values for the crown (apex), sides, front and rear for the SPH-4 are shown in Figure 12 along with the standard deviation for each location. It should be noted that the SPH-4 contains an energy-absorbing web suspension along with a polystyrene foam liner so that one would expect the SPH-4 helmet to yield lower peak G-values, especially in the crown region, than do the motorcycle helmets shown in Figures 7 through 9. Reference to Figure 7 shows an average value of 270 G for a 1.47-meter drop for the motorcycle helmet as compared to values of 165 G up to 300 G maximum in Figure 12 for a 1.47-meter drop for the SPH-4. Also, it should be noted that the wide variation shown in Figure 12 probably is caused by the foam thickness variation



SECTION A - A

FIGURE 10. U.S. Army Aviator Helmet--The SPH-4

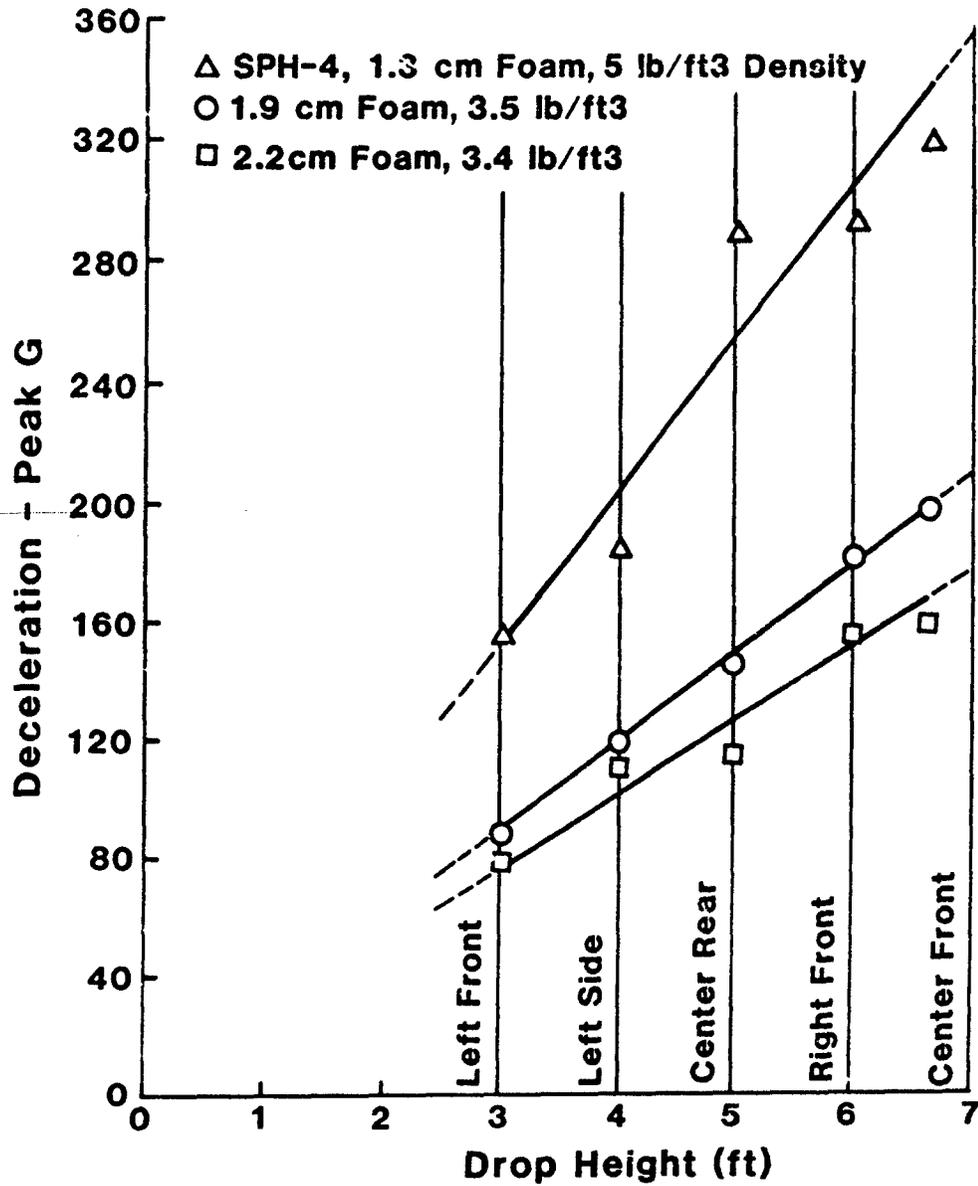


FIGURE 11. Comparison of Peak G to Drop Height With Three Different Foam Thicknesses and Densities For Flat Surface Impact

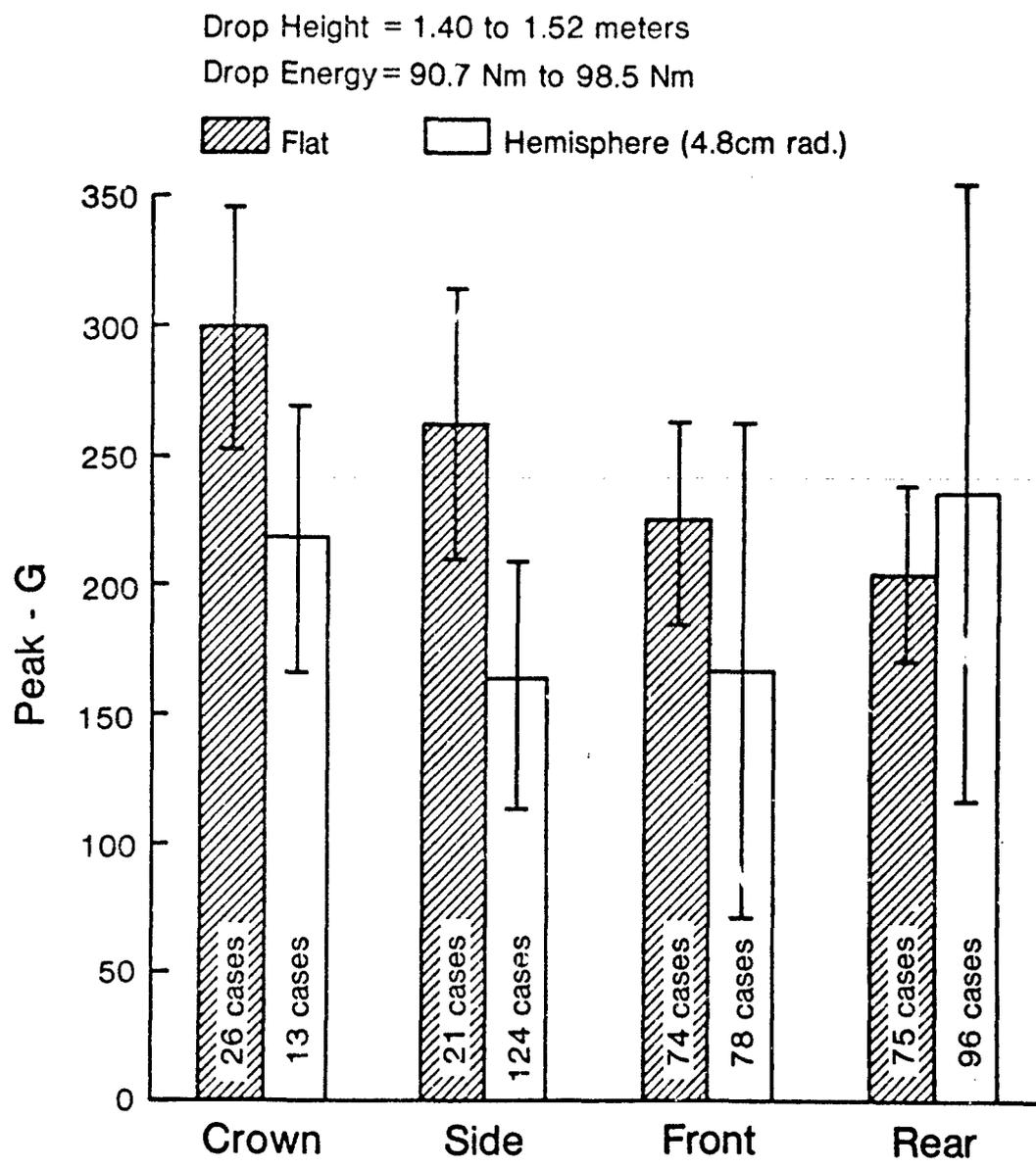


FIGURE 12. Transmitted Headform Deceleration With U.S. Army SPH-4 Flight Helmet for 507 Impacts

from 10 mm to 13 mm during the SPH-4's evolution and by the variable offset distance seen with the sling suspension.

With reference to Figure 11, doubling the thickness of the polystyrene foam liner of the SPH-4 can result in headform peak G values of only 120 G at a 1.5 meter drop height. This would increase the weight by only 0.1 kg because the thicker foam is of lower density and the exterior shell may be reduced in thickness and still provide adequate load distribution to the skull. Such dramatic improvement clearly points the way to improved impact protection for headgear.

#### DYNAMICS OF HEAD PROTECTION

As stated before, a motorcyclist should be protected from a wide range of impact velocities from 3 to 9 meters per second; e.g., falls from 2 meters height from moving bikes. To provide protection from various impact conditions, the protective helmet must be designed to do different things. In the case of the high velocity impact, the helmet must convert the high velocity energy, with its resultant high pressure distributed over a small area, to a pressure pattern which is well distributed to the scalp and skull and much lower in magnitude. This will require a helmet with a semirigid shell or a very thick layer of energy-absorbing material. To understand the principles of dynamic head protection, one should consider the unprotected head which impacts a flat, solid, unyielding surface. The head will be brought to rest (zero velocity) in less than 20 milliseconds while the scalp and skull deforms. The force of impact will be distributed over a rather small area of the skull and the pressure on the bone will be rather high. However, if an energy-absorbing material is placed between the head and the impacted surface, the material will absorb energy as it compresses and distribute the subinjurious force over a larger area in bringing the head to rest.

Assuming that brain damage is a function of the maximum acceleration applied to the head, the protection achieved by an ideal helmet is dependent both on the distance through which the material can be compressed before it bottoms out and on the peak compressive force. Thus, if head acceleration is the significant factor in brain damage, the ideal helmet energy-absorbing material would have to be four times thicker if the impact velocity were doubled.

Gurdjian, Lissner, and Patrick (1962), have shown that a drop of approximately 1.2 m and an impact velocity of 4.8 m/sec is the maximum condition which the unprotected head can tolerate before fracture. With an ideal energy-absorbing material of 3.8 cm thick, producing optimum deceleration ( $\leq 150$

G peak), it is possible for the helmeted head to drop a distance of 2.4 meters to a flat, hard surface, striking it with a velocity of 6.9 m/sec without suffering concussion. Thus, one concludes that a helmet so configured would improve nature's protection by a minimum of 2 to 1.

In summary, all conceivable impact conditions must be considered and provided for and the final helmet design must of necessity be a compromise in which the significance of each variable has been properly established and taken into account.

## CONCLUSIONS

1. The motorcycle helmets tested would not provide adequate force attenuation to prevent concussion and/or more serious injury at all energy levels associated with a drop height greater than 1-meter.
2. Existing helmet standards permit the production of helmets which provide less protection than is practical, and feasible.
3. Using the US Army's SPH-4 as a referent, the transmitted force from helmeted-head impact as measured by headform accelerometers can be reduced by 50 percent with only 0.1 kg increase in helmet weight. This dramatic force reduction is achieved by using a thicker, but lower-density foam liner and a larger, but thinner exterior shell.

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APPENDIX A

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