UM-HSRI-77-48

SAFETY HELMET-HEAD INTERACTION STUDY

USING HIGH-SPEED CINERADIOGRAPHY

Prepared for:

National Institutes of Occupational Safety and Health
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Morgantown, West Virginia 26505

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Final Report for Period

August 29, 1977 through October 30, 1977

October 31, 1977

Technical Report Documentation Page

1. Report No. UM-HSRI-77-48

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Safety Helmet-Head Interaction Study Using High-Speed Cineradiography

5. Report Date 10-31-77

6. Performing Organization Code

7. Author(s)
Stalnaker, R. L., Bender, M., and Melvin, J. W.

8. Performing Organization Report No. UM-HSRI-77-48

9. Performing Organization Name and Address
Highway Safety Research Institute
The University of Michigan
Ann Arbor, Michigan 48109

10. Work Unit No. (TRAIS) 015624

11. Contract or Grant No. 77-12122

12. Sponsoring Agency Name and Address
National Institutes of Occupational Safety & Health
944 Chestnut Ridge Road
Morgantown, West Virginia 26505

13. Type of Report and Period Covered
Final
Aug. 29, 1977 - Oct. 31, 1977

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Six specimen industrial safety helmets supplied by NIOSH were subjected to impact force by an 8 lb. spherical mass, dropped from a vertical height of 5 ft., while worn on the head of a seated HSRI dummy. The purpose of these tests was to evaluate helmet-head dynamic performance by means of information obtained from 1000-frame-per-second x-ray cinematography, and impactor and dummy head acceleration instrumentation. Peak and average forces, force durations, component and average resultant head accelerations are reported for each helmet type. Analysis and discussion include a defined helmet-head stiffness parameter, and consideration of the data on the basis of the Mean Strain Criterion Head Injury Model. All six specimen helmets were found to function properly under the test conditions.

17. Key Words
Safety Helmet, Crash Test Device Impact, High-Speed Cineradiography

18. Distribution Statement
Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	42	

Reproduction of completed page authorized

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ACKNOWLEDGMENTS

This research program was carried out by the staff of the Biosciences Division of The Highway Safety Research Institute, the University of Michigan. The authors would like to thank Mr. W. I. Cook of NIOSH for his cooperation and support.

1.0 INTRODUCTION

1.1 Background

Industrial protective helmets are designed for the protection of heads of occupational workers from impact and penetration from falling and flying objects under average conditions. There are a number of different approaches to head protection in various protective helmet designs, but, in general, all of them consist of two principal components: 1) a shell, which is a hard, resilient, dome-shaped seamless covering, which contains 2) a suspension system, or internal cradle of the helmet, which holds it in place on the head and is made up of a headband and crown straps capable of being fitted to the head. The combination of shell and suspension dissipates, distributes, and attenuates impact loads.

1.2 Purpose

The purpose of this investigation was to observe and compare differences in performance of six helmet types, supplied by National Institutes of Occupational Safety and Health, by means of 1) direct observation of impact events with a high-speed x-ray cinematographic system developed by HSRI; 2) analysis of high-speed cineradiographic films obtained, and 3) analysis of force and acceleration data resulting from impact of an 8-lb. spherical mass dropped from a vertical height of 5-ft., as specified by American National Standard ANSI Z89.1-1969, (1)* onto the helmets as worn by an anthropomorphic dummy, also developed by HSRI. One 9-ft. drop on one helmet type and one 5-ft drop with no helmet were also conducted.

This report consists of a description of the test methodology, results obtained, and an accompanying 16-mm motion-picture film depicting x-ray radiography of each helmet impact event and associated helmet-head behavior.

* Numbers in parentheses refer to references in Section 6.0

2. TEST METHODOLOGY

Test apparatus consisted of the following elements: 1) a dummy head, which was an integral part of the HSRI dummy, described in reference 2; the dummy was adjusted in a seated position; 2) a hemispherical steel mass weighing 8-lb, mounted on a vertical column and coupled to the column by Thompson linear bearings; 3) a Setra 111 uniaxial accelerometer mounted in the impacting mass, from which force was derived, and a Setra 113 triax pack mounted at the c.g. of the dummy head, from which resultant acceleration was derived; and 4) the HSRI high-speed cineradiographic system, described in reference 3.

The test configuration showing the seated dummy positioned under the impactor, and adjacent to the input screen of the high-speed cineradiographic detector, is shown in Figure 1.

2.1 Mounting of Specimen Helmets

Suspensions of each of the six specimen helmets were removed; headbands were adjusted to fit the dummy head. Helmet shells were then replaced. The center of the crown of each specimen was centered as nearly as possible with the vertical axis of motion, with the impactor at rest on the crown. Each specimen was mounted with the back toward the vertical drop column. Specimen shells and their suspensions are shown in figures 2, 3, 4, 5, 6 and 7.

2.2 Test Procedure

The impactor mass was dropped vertically on the helmet crown from a height of 60 inches, measured from the bottom of the ball to the top of the shell.

Accelerometer outputs were received by Setra signal conditioners and then stored on magnetic tape by a Honeywell 7600 tape recorder. Input recording rate was 30 inches per second. Recorded accelerometer data were then filtered by Class 1000 filters to 1650 Hz, at 16:1 reduction at a playback rate of 1-7/8 inches per second.

Resultant decelerations were obtained from analog computation by a Model 1710 Thomas Instrumentation Impact Computer, which received component decelerations in x, y, and z, after signal conditioning and filtration. Impact force data were obtained from the product of a scale factor corresponding to the mass of the impactor and deceleration data

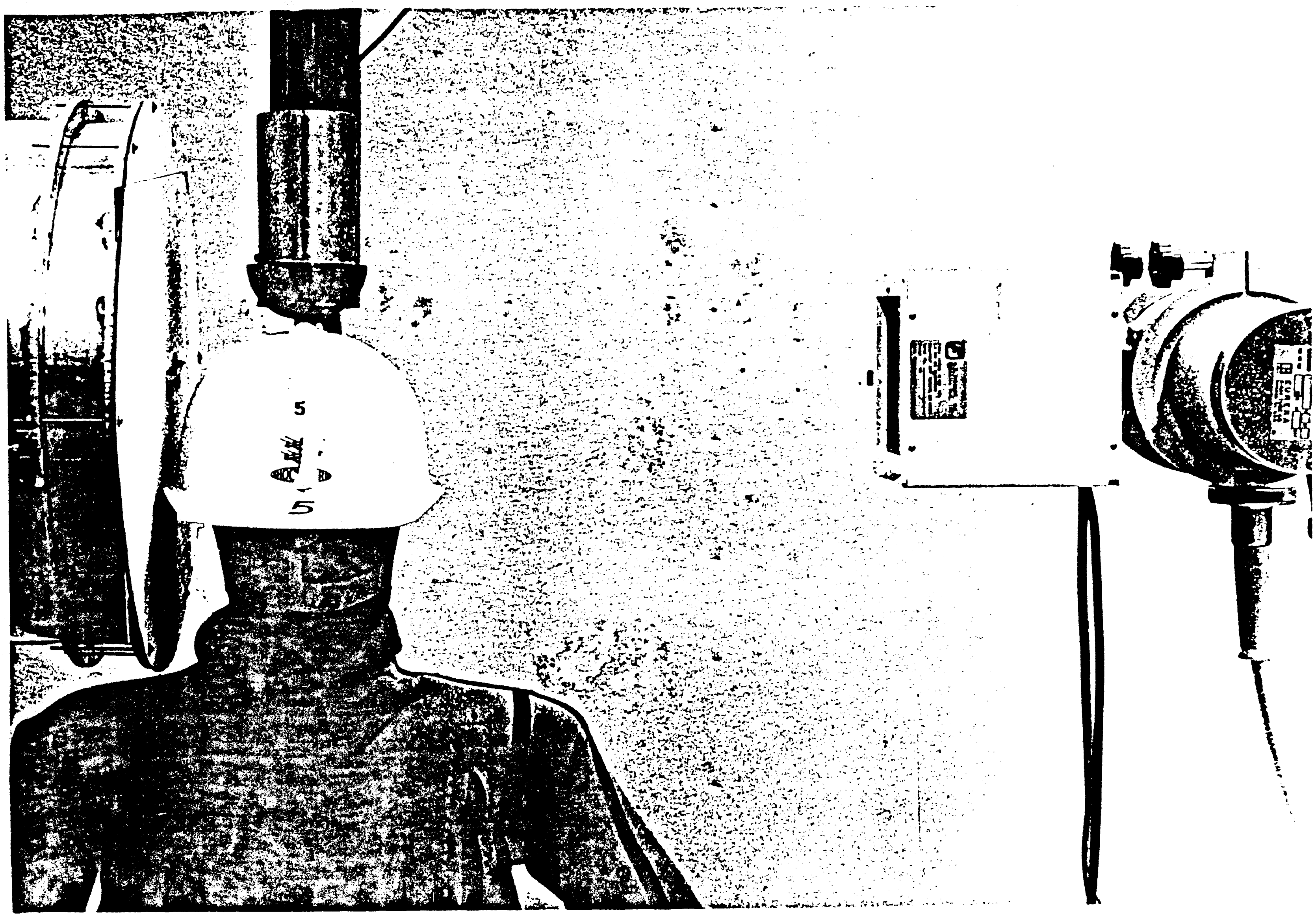

Figure 1. Helmet test apparatus configuration.

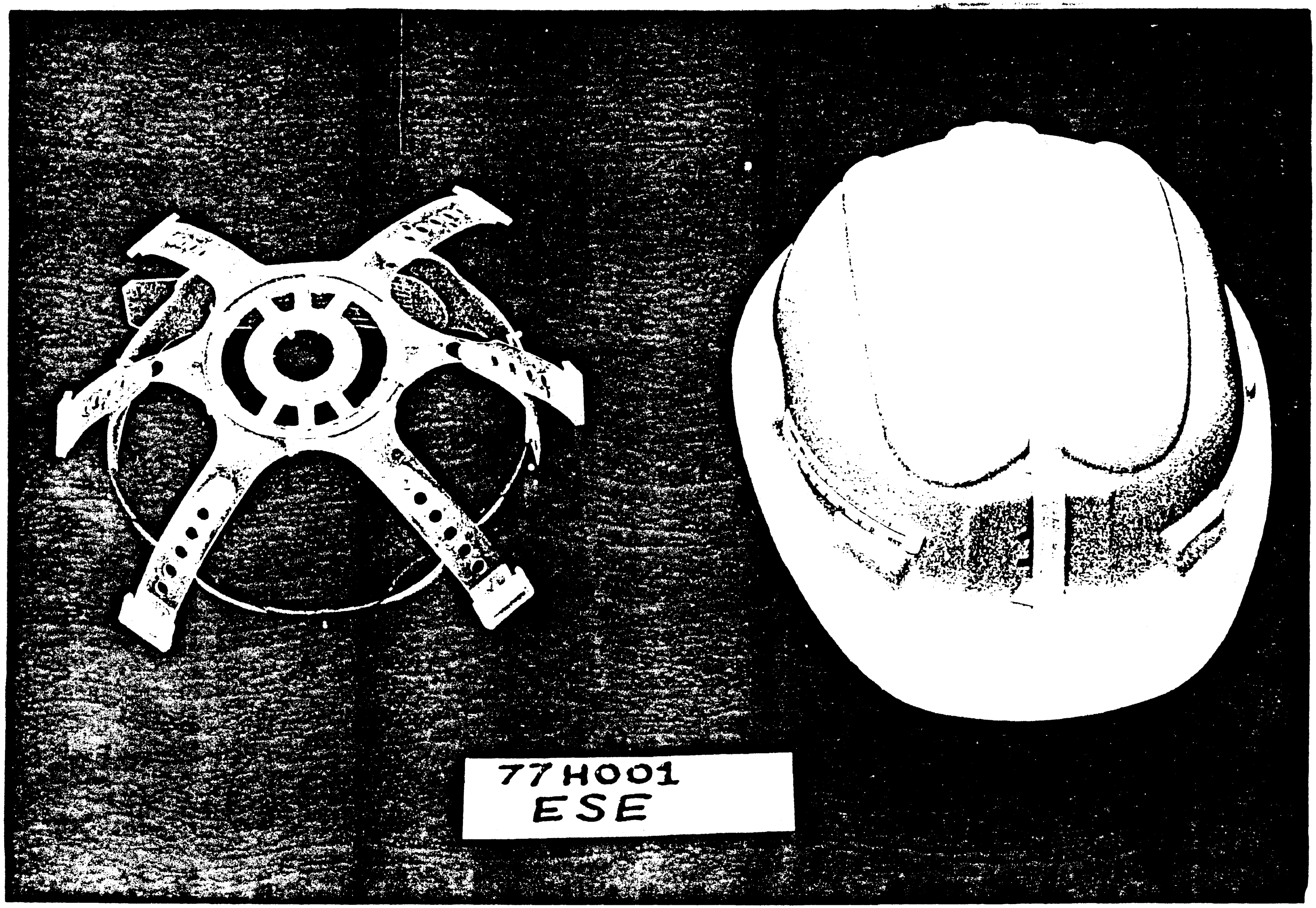

Figure 2. Helmet type ESE, shell and suspension.

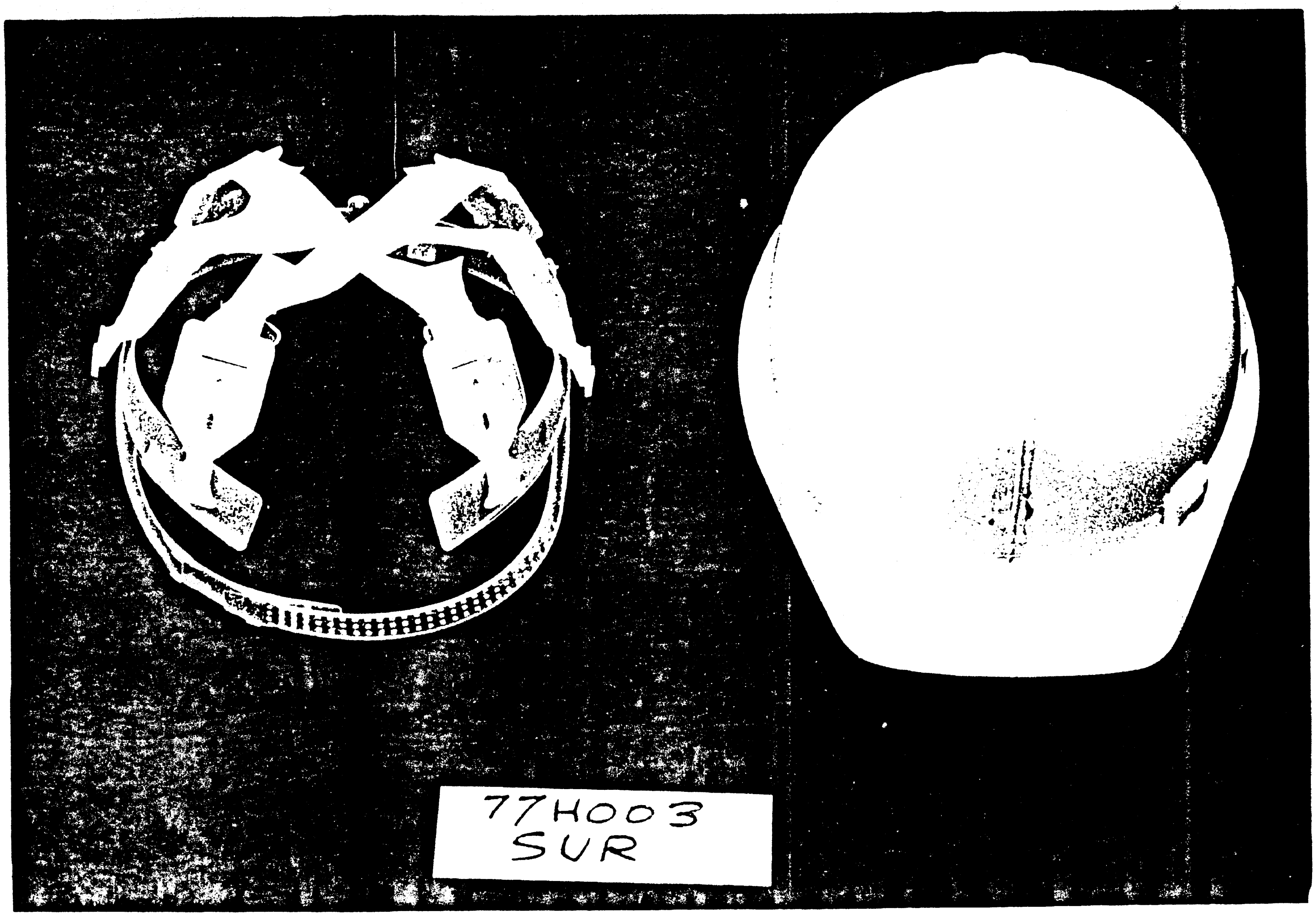

Figure 3. Helmet type SUR, shell and suspension.

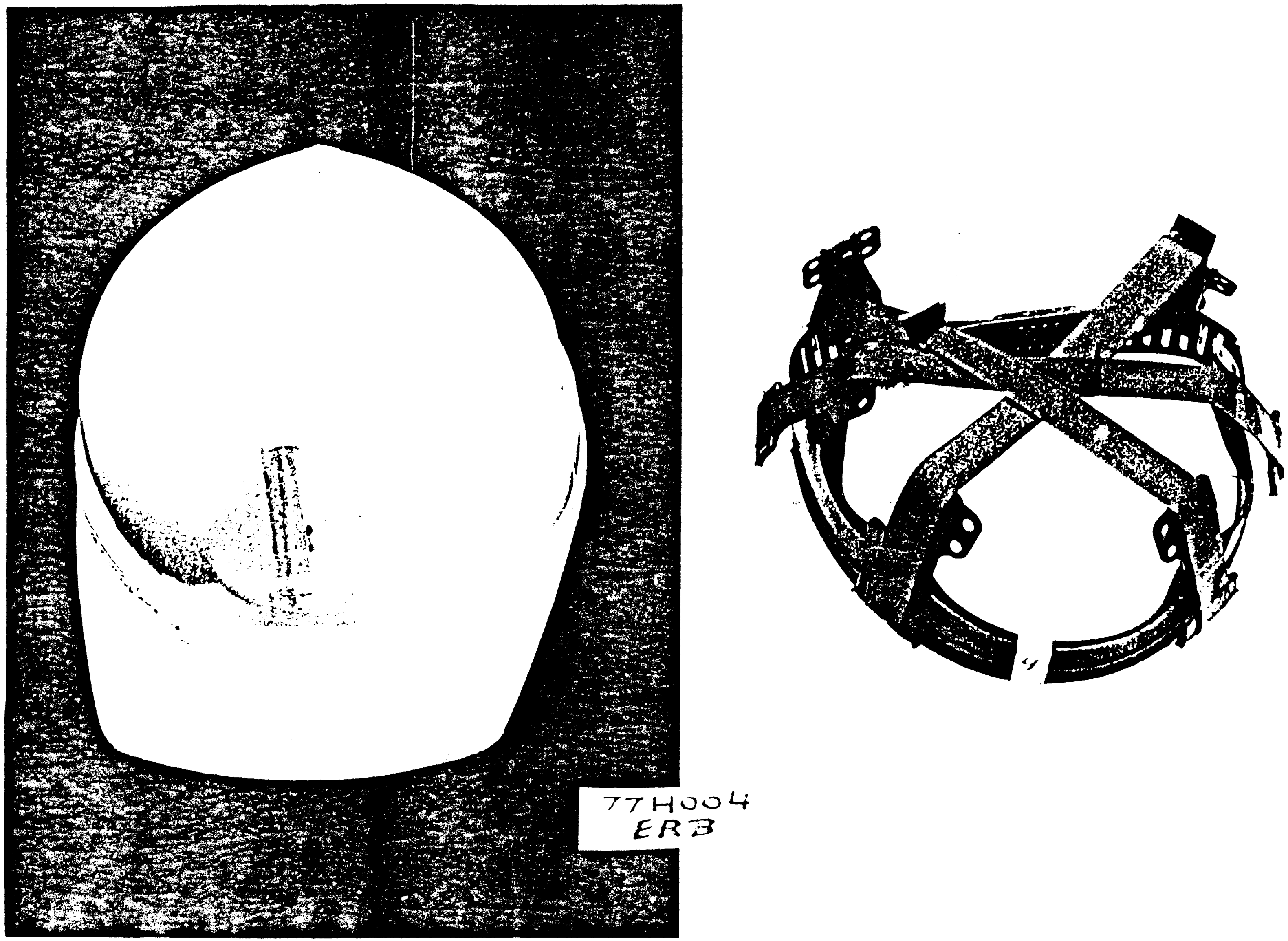

Figure 4. Helmet type ERB, shell and suspension.

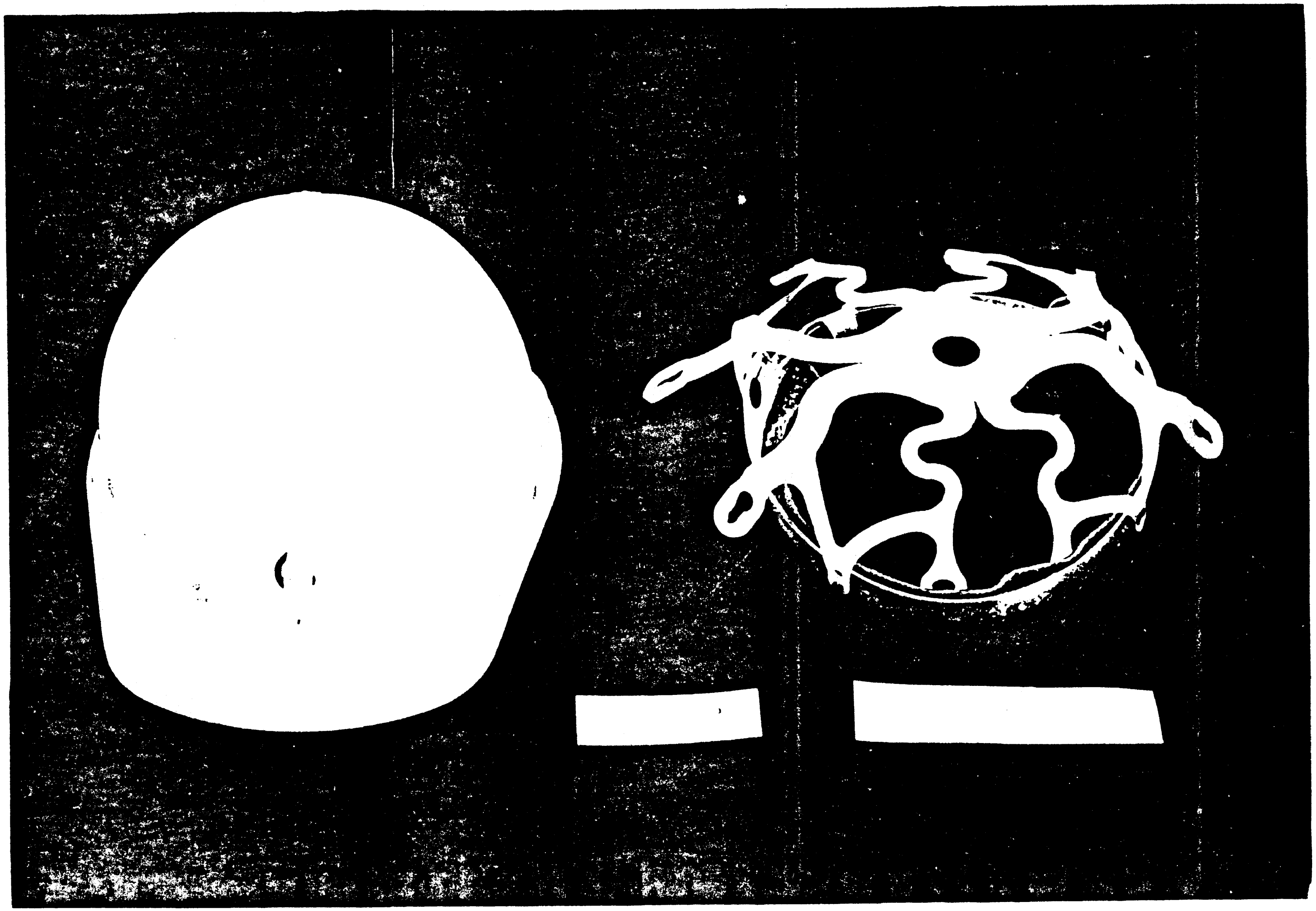

Figure 5. Helmet type FBM Superlectric, shell and suspension.

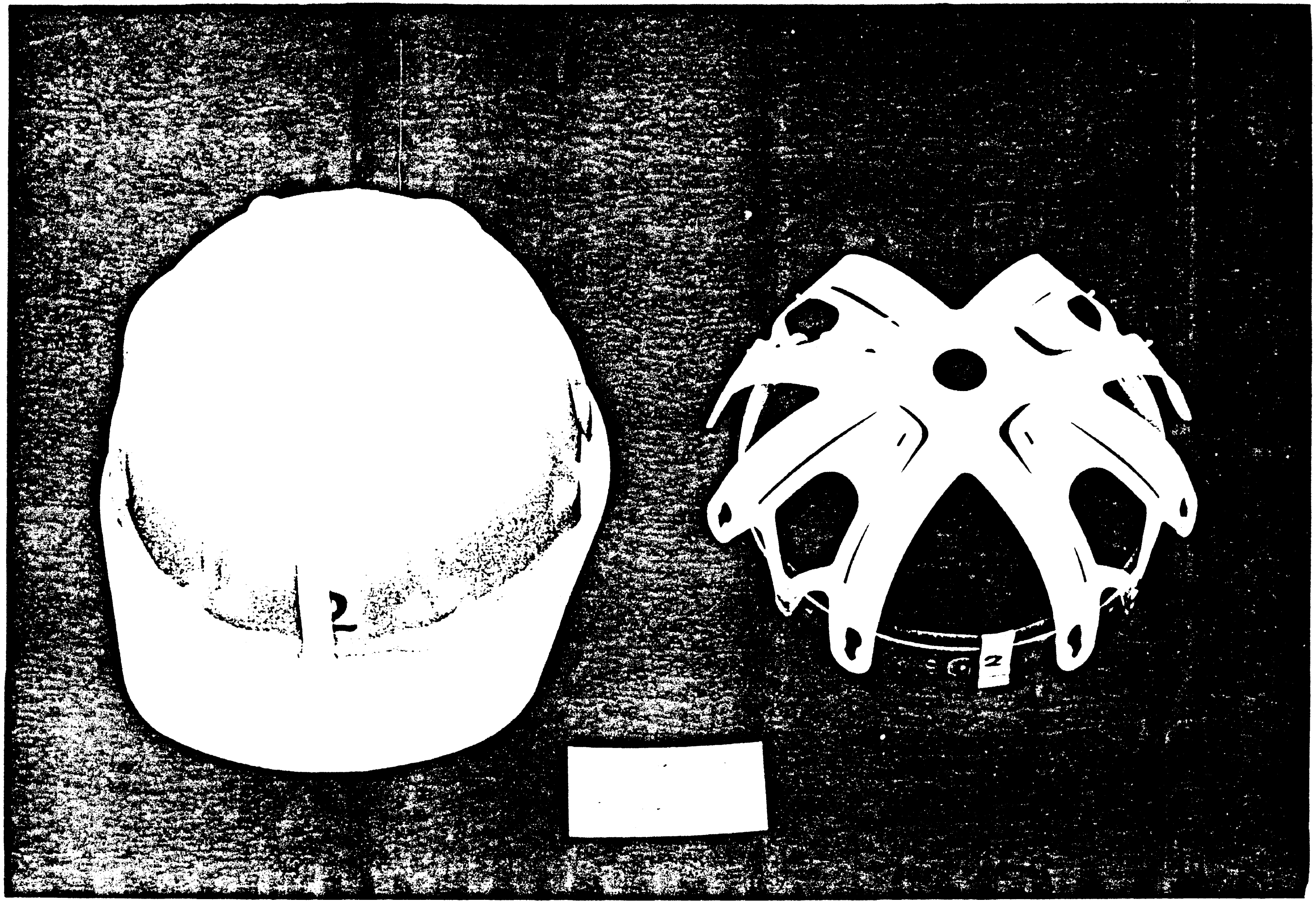

Figure 6. Helmet type FBM Tuf-ite, shell and suspension.

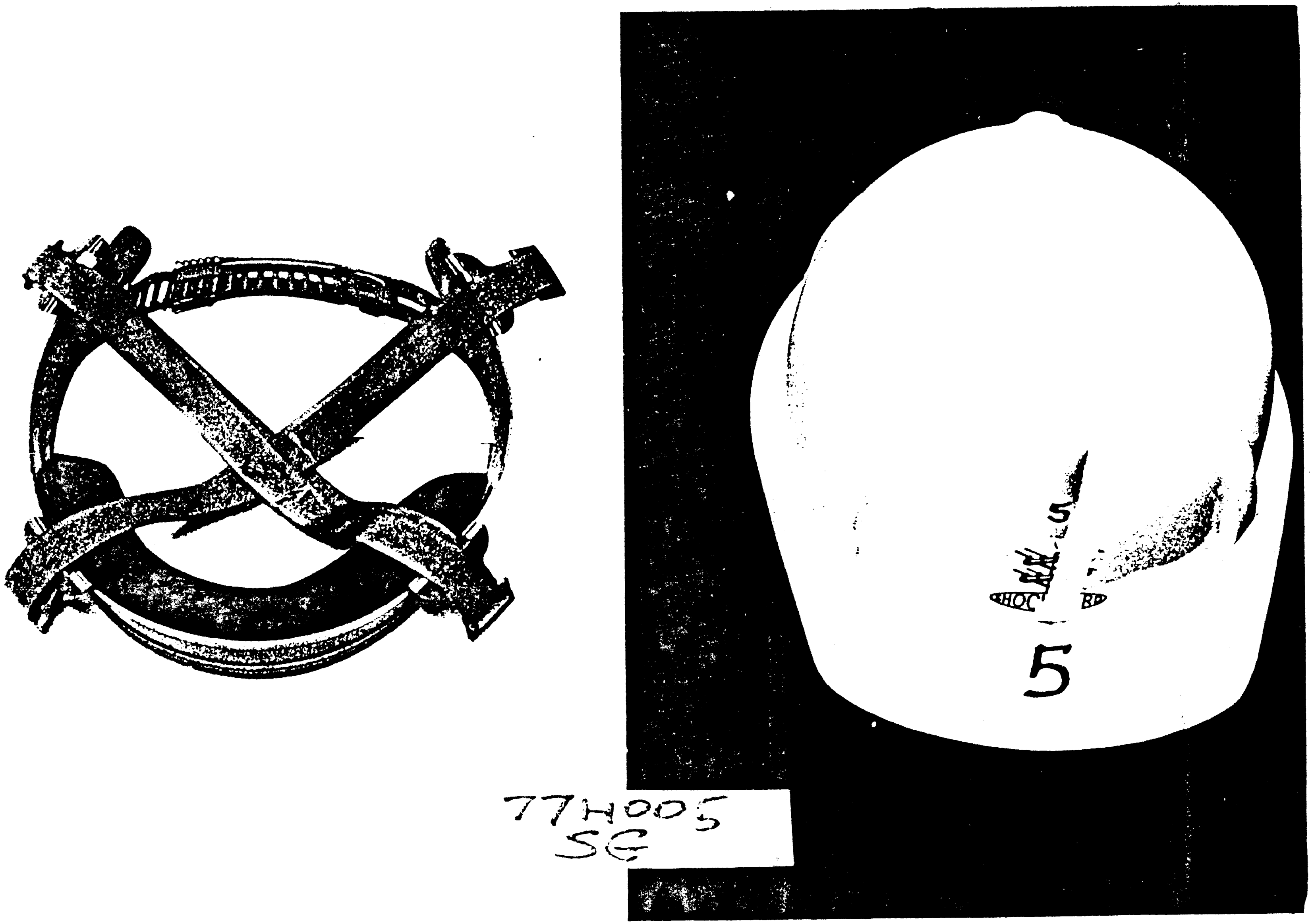

Figure 7. Helmet type SG, shell and suspension.

from the Setra 111 uniaxial accelerometer located in the impactor. Impactor velocity data were derived from time of impactor passage between two magnetic pick-up transducers spaced one inch apart, located 20 inches above the crown of the helmet. This height above the helmet was necessary for x-ray system timing requirements. Velocity data were corrected for this differential above the point of impact.

2.3 High-Speed Cineradiography

Specimen helmets positioned on the dummy head were radiographed during impact, laterally from left to right, at approximately 1000 frames per second. X-ray contrast of boundaries between the inner and outer surfaces of helmet shells, and the midsaggital plane of the dummy head, was enhanced by taping 0.040 inch diameter lead wire on these surfaces.

The dummy head and specimen helmets were positioned so that the test configuration filled a 12-inch diameter x-ray-to-light conversion screen. The midsaggital plane of the dummy head was located 4.5 inches from, and parallel to, the input screen. A 2-inch lead wire was placed on the screen for dimensional reference. X-ray tube focal spot to screen distance was 31.5 inches. Radiographic factors for each test were as follows: 125 kilovolts, peak, filtered through 0.080-inch steel, at 50-milliamperes, and 0.2 sec. x-ray on-time to cover impactor entrance into field-of-view, impact event, and subsequent motion of helmet, head, and impactor. High-speed radiographic images were filmed with a Photosonics 1-B high-speed, 16-mm motion picture camera using Eastman 7222 (Double-X) black and white film; these films were developed with Accufine developer at 69° F for 5 minutes.

Each x-ray motion-picture test sequence contains an image of a 2-inch lead wire marker visible on the motion-picture frames, for the purpose of dimensional scaling on a Vanguard motion-picture analyzer. X-ray magnification of the helmet-head system, due to the geometry of the x-ray focal spot-to-screen distance and the dummy head midsaggital plane distance to screen distance was taken into account in the derivation of the scale factor.

An overall view of the x-ray system showing the x-ray source and detector geometry is shown in Figure 8; a larger input field was used for these tests than is shown.

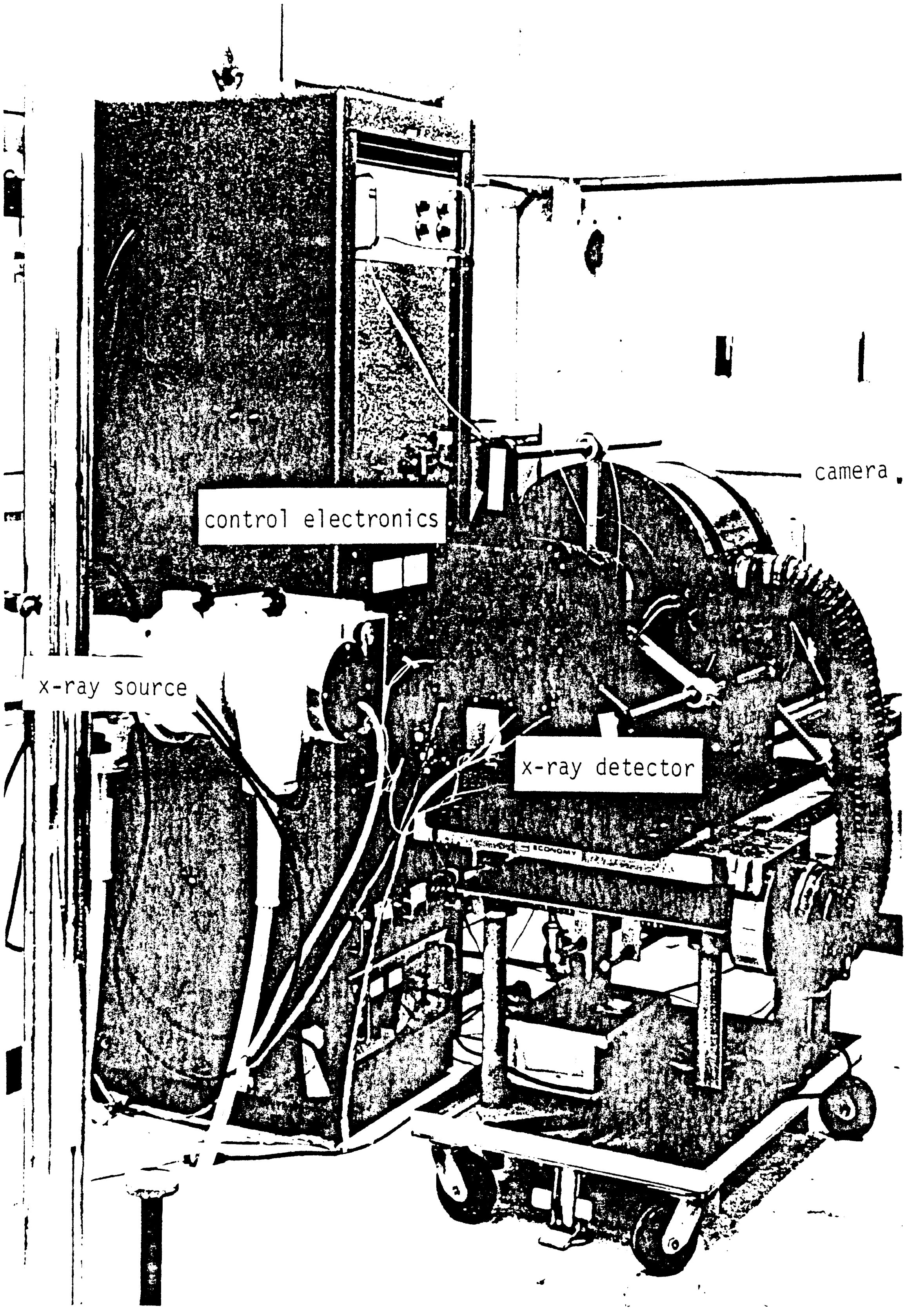

Figure 8. High-speed x-ray cinematographic system.

3.0 RESULTS

Primary test data were obtained in two formats: 1) filtered dynamics instrumentation outputs were recorded on a Gould Brush recorder, and 2) cineradiography was recorded on 16-mm, black and white, motion-picture film. Dynamics instrumentation outputs are given in the appendix, and each helmet type is identified with its corresponding impact force as a function of time, posterior-anterior head acceleration, lateral, or left-right, head acceleration, superior-inferior head acceleration, and resultant head acceleration, all as a function of time. Appropriate scale factors for each output are also given.

3.1 Dynamics Data from Instrumentation

Dynamics instrumentation data are summarized in Table 1, in English and metric system units, which gives average impact velocity, peak impact force, impact duration, average force, peak resultant head acceleration, and average resultant head acceleration for each helmet type. Average force and average resultant head acceleration were determined from the ratio of integrated force-time, and resultant acceleration-time, outputs to impact duration time interval, respectively.

3.2 Helmet-Head System Motion from Cineradiography

Motion of the helmet-head system during impact for each helmet type may be observed by projection of a 16-mm motion picture film, which accompanies this report, and comprises part of the primary data. An example of a test sequence obtained with the x-ray system is shown in Figure 9, which was reproduced from the motion-picture film.

Analysis of test sequences on a Vanguard analyzer yielded three quantities: 1) initial helmet-head clearance before impact; 2) final helmet-head clearance, taken at the frame where the energy absorption process appeared to be completed; and 3) deformation of the shell during impact. In each case, the inside surface of the shell was considered with respect to the line demarcating the crown of the dummy's head.

Table 2 contains a summary of these data, as well as maximum helmet deflection, together with some brief comments obtained from observing the impact sequences.

TABLE 1 SUMMARY OF DATA

TEST NO.	HELMET TYPE	AVERAGE IMPACT VELOCITY		PEAK IMPACT FORCE		IMPACT DURATION	AVERAGE FORCE		PEAK RESULTANT ACCELERATION	AVERAGE RESULTANT ACCELERATION
		ft/sec	m/sec	lb	N	millisec	lb	N	G's	G's
77H001	ESE	16.5	5.03	510	2269	17.5	182	810	33.5	8.3
77H003	SUR	16.9	5.15	660	2936	17.6	218	970	28.1	7.0
77H004	ERB	16.4	5.0	670	2980	25.8	180	801	17.5	4.7
77H006	FBM Superlectric	16.7	5.10	590	2624	20.0	180	801	15.1	4.9
77H007	FBM Tuf-Ite	16.2	4.94	620	2758	16.8	170	756	45.4	7.6
77H008	SG	17.0	5.18	610	2713	16.5	213	948	31.3	8.8
77H009	SG	22.4	6.83	810	3603	16.5	266	1183	34.6	10.4
77H010	No Helmet	16.3	4.97	1340	5961	3.7	400	1779	164.0	56.0

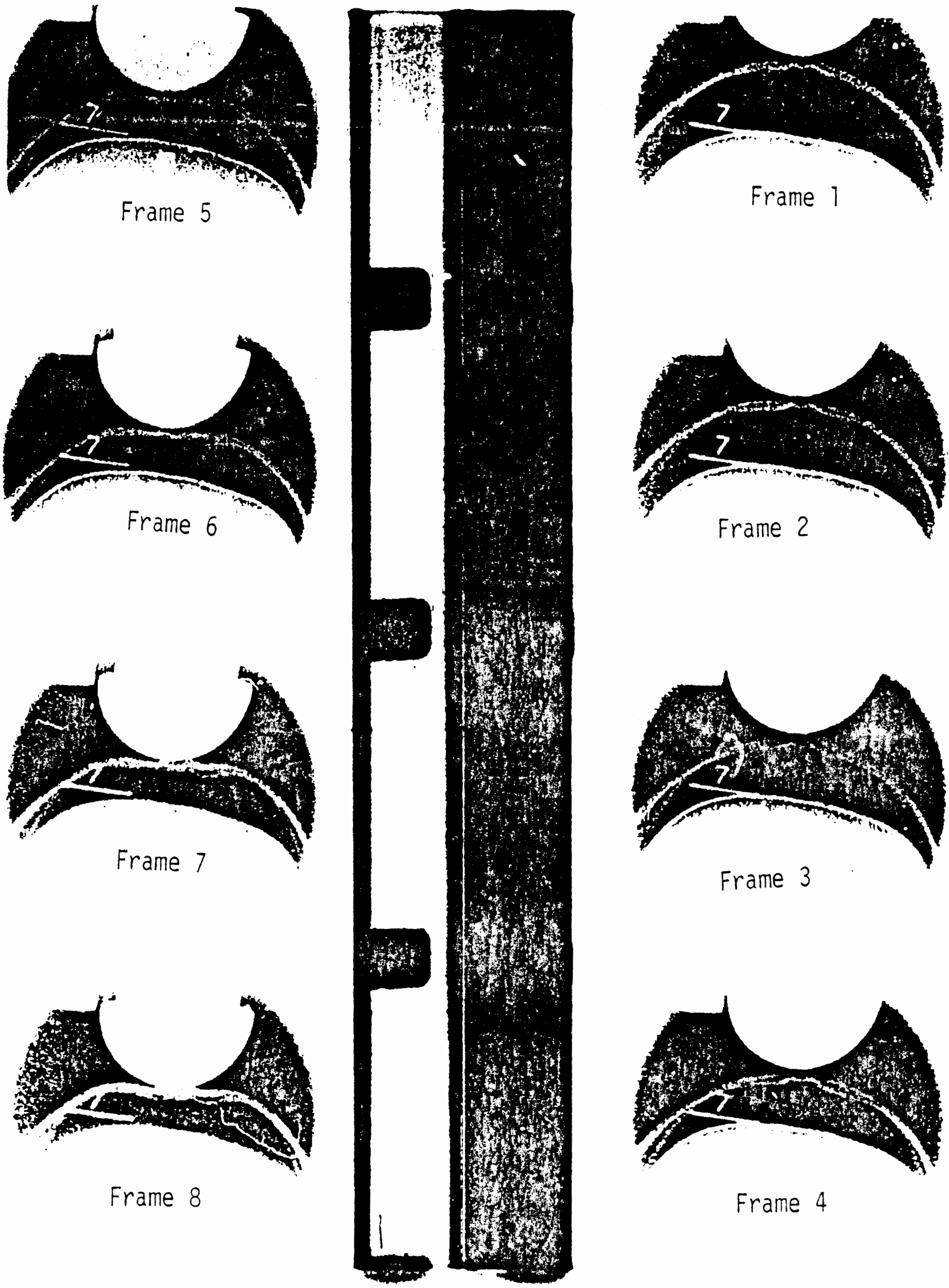

Figure 9. Example of test sequence obtained with x-ray system.

TABLE 2 SUMMARY OF HELMET-HEAD GEOMETRY

TEST NO.	HELMET TYPE	INITIAL HELMET-HEAD CLEARANCE		FINAL HELMET-HEAD CLEARANCE		MAXIMUM HELMET DEFLECTION		SHELL DEFORMATION UNDER IMPACT		COMMENTS
		in	cm	in	cm	in	cm	in	cm	
77H001	ESE	2.15	5.46	0.81	2.06	1.35	3.43	0.32	0.81	Left side of suspension detached; partial rotation of shell after impact.
77H003	SUR	2.41	6.12	1.50	3.81	0.93	2.36	0.22	0.56	System functioned properly.
77H004	ERB	2.45	6.22	0.91	2.31	1.54	3.91	0	0	Impact occurred toward shell posterior; shell displaced vertically, without deformation. Two of six suspension points detached.
77H006	FBM Superlectric	2.20	5.59	0.81	2.06	1.52	3.86	0.18	0.46	Two of eight suspension points detached; shell and suspension separated from head.
77H007	FBM Tuf-Ite	1.71	4.34	0.73	1.85	0.98	2.50	0.48	1.22	System functioned properly.
77H008	SG	2.00	5.08	0.97	2.46	1.04	2.64	0.17	0.43	Impact occurred toward shell posterior; system functioned properly.
77H009	SG	1.69	4.29	0.48	1.22	1.21	3.07	0.19	0.48	System functioned properly.
77H010	No Helmet	-	-	-	-	-	-	-	-	

4.0 DISCUSSION

The principal mechanical function of a helmet is to dissipate impact energy so that an impacting object will not come into contact the head. Observation of the high-speed x-ray motion pictures suggested that a convenient way to characterize helmet performance was by defining a helmet-head average stiffness parameter, or spring constant. It is recognized that a shell-suspension combination represents a rather complex mechanical system, and this, together with the neck, represents a total system that is not yet well understood. Hence, within the scope of these tests and data available from x-ray motion pictures and dynamics instrumentation, an average helmet-head stiffness was defined as the ratio of the average force to the maximum deflection distance of the inside surface of the helmet shell with respect to the top of the dummy head. The average force, rather than peak, was taken because it more closely represents the integrated force described in the ANSI Z 89.1 standard.

Table 3 lists this derived parameter for each helmet type, together with minimum percent helmet-head clearance and relative energy absorption of the helmet head system. Percent clearance was determined from analyzer measurements of distance of closest approach of the shell to the head and initial shell position with respect to the head; for example, if the shell did not deflect at all, percent clearance would be 100%. Range of this quantity for the specimen helmets is seen to vary from 62% to 31%, in Table 3.

Relative energy absorption by the helmet-head system was determined from the difference between initial impact kinetic energy and impactor rebound kinetic energy. The arithmetic mean of the values listed in Table 3 is 92%; range is between 97% and 87%.

Another important function of a helmet is to prevent or minimize occurrence of closed brain injury. It is possible to evaluate the helmets tested for this property on the basis of comparison of resultant head accelerations obtained with the Mean Strain Criterion (MSC), (4). Although several other head injury criteria models exist, MSC was selected because it was developed for various directions and average resultant accelerations. Also, the MSC average resultant accelerations as a function of impact pulse duration are known for various Abbreviated

TABLE 3. SUMMARY OF ANALYSIS

TEST NO.	HELMET TYPE	HELMET-HEAD SYSTEM STIFFNESS lb/in	HELMET-HEAD SYSTEM STIFFNESS N/cm	FINAL HELMET-HEAD CLEARANCES %	RELATIVE ENERGY ABSORPTION OF HELMET-HEAD SYSTEM %
77H001	ESE	135	236	38	90
77H003	SUR	234	411	62	92
77H004	ERB	117	205	37	96
77H006	FBM Superlectric	118	208	31	95
77H007	FBM Tuf-Ite	173	302	45	87
77H008	SG	205	359	48	97
77H009	SG	220	385	28	88
77H010	No Helmet	-	-	-	-

Injury Scale (AIS) levels (5). It was found in these tests that the largest average resultant head acceleration was 10.4 g's. This is substantially less than the approximately 30 g's required for a closed brain injury AIS level of one, the least injury. Therefore, under the conditions of these tests, the probability of closed head injury to a wearer of these helmets tested is minimal; whereas for no helmet worn, the probability of an AIS injury level of approximately three would be quite large, providing the load were distributed over the head so that skull fracture would not occur first. Average tolerance load for skull fracture is 1240 lb (5518 Newtons), (6). In the no helmet case in these tests, a maximum force of 1340 lb (5961 N) was obtained.

Since all of the head accelerations are low, helmets with the greatest stiffness are considered preferable over those with lesser stiffness.

5.0 CONCLUSIONS

On the basis of data obtained from high-speed x-ray cinematography and dynamics instrumentation and analysis of these data, it is concluded that:

1) high-speed x-ray cinematography gave good contrast and resolution image sequences during impact events, and yielded analysis of helmet-head motion;

2) a comparative basis for helmet performance was found through definition of a helmet-head stiffness parameter, and consideration of the Mean Strain Criterion for head injury;

3) under the test conditions, all of the helmets functioned properly with respect to head clearance, load distribution, and dissipation of impact kinetic energy;

4) no evaluation of potential neck injury could be made in this study due to lack of knowledge about the head-neck interaction;

5) the higher the stiffness parameter for a given helmet, the better the head protection, provided tolerable g levels are not exceeded, and it should be noted that potential neck injury is not yet considered.

6.0 REFERENCES

1. American National Standard: "Safety Requirements for Industrial Head Protection," ANSI Z89.1-1969, American National Standards Institute, Inc., New York, 1969.

2. J. H. McElhaney, et al., "A New Crash Test Device -- Repeatable Pete," Proceedings of the 17th Stapp Car Crash Conference, Society of Automotive Engineers, Warrendale, Pa., 1973.

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5. Joint Committee on Injury Scaling; The Abbreviated Injury Scale (AIS), 1976 Revised Ed., American Association for Automotive Medicine, Morton Grove, Illinois, 1976.

6. V. R. Hodgson, J. Brinn, L. M. Thomas and S. W. Greenberg, "Fracture Behavior of the Skull Frontal Bone Against Cylindrical Surfaces," Proceedings of the 14th Stapp Car Crash Conference, Society of Automotive Engineers, Warrendale, Pa., 1970.

APPENDIX A

DYNAMICS DATA

NIOSH HELMET-HEAD INTERACTION

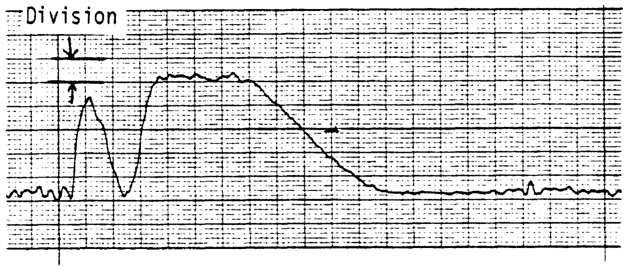
DATA SUMMARY

TEST NUMBER H-001

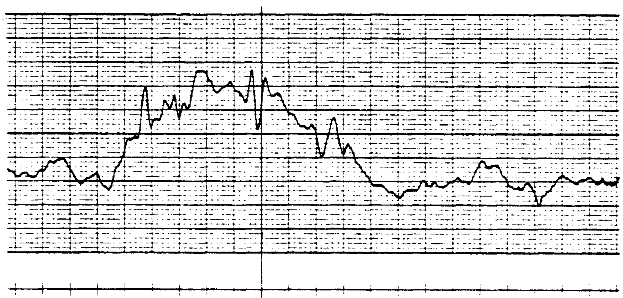
HELMET TYPE ESE

IMPACT VELOCITY 16.5 fps

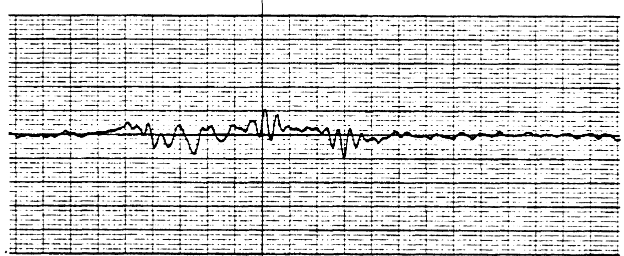
Compensated Force
100 lbs./Division
Filtered 1650 Hz



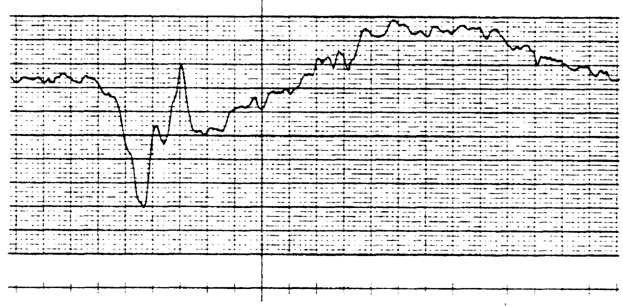
Posterior-Anterior
Head Acceleration
5 G's/Division
Filtered 1650 Hz



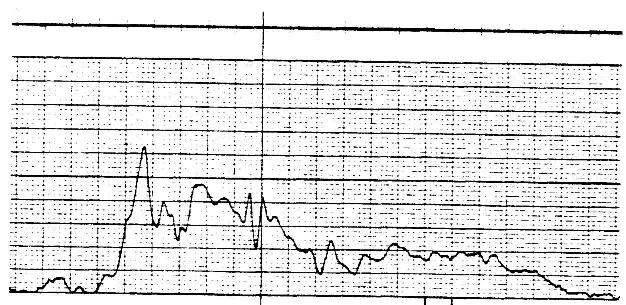
Left-Right
Head Acceleration
5 G's/Division
Filtered 1650 Hz



Inferior-Superior
Head Acceleration
5 G's/Division
Filtered 1650 Hz



Resultant
Head Acceleration
5.4 G's/Division
Filtered 1650 Hz



1.56 msec

NIOSH HELMET-HEAD INTERACTION

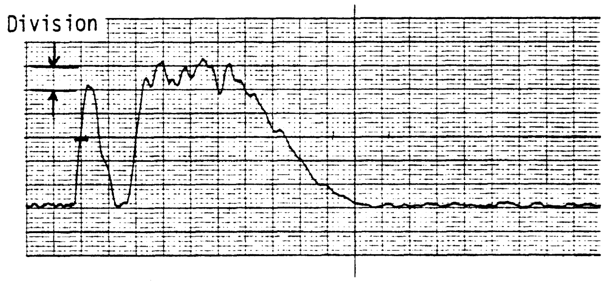
DATA SUMMARY

TEST NUMBER H-003

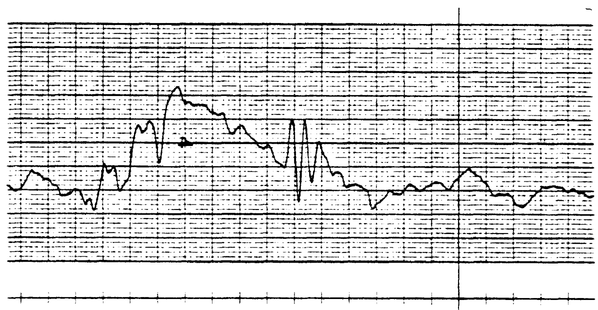
HELMET TYPE SUR

IMPACT VELOCITY 16.9 fps

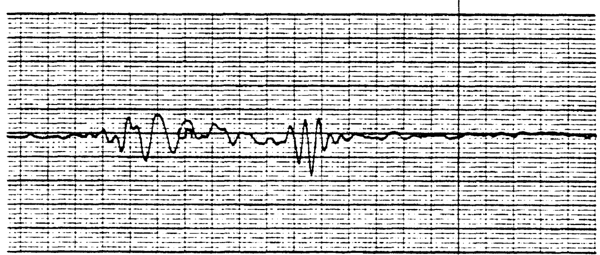
Compensated Force
100 lbs./Division
Filtered 1650 Hz



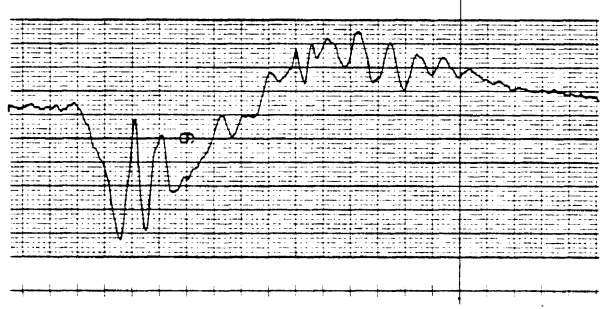
Posterior-Anterior
Head Acceleration
5 G's/Division
Filtered 1650 Hz



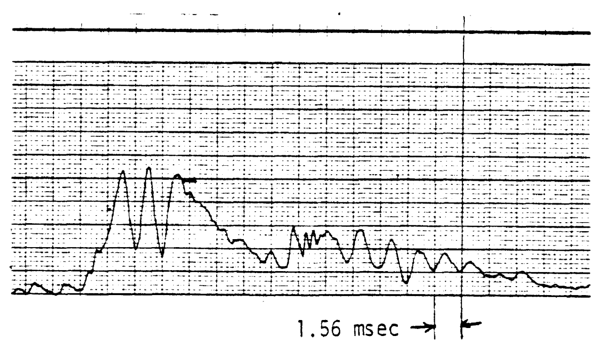
Left-Right
Head Acceleration
5 G's/Division
Filtered 1650 Hz



Inferior-Superior
Head Acceleration
5 G's/Division
Filtered 1650 Hz



Resultant
Head Acceleration
5.4 G's/Division
Filtered 1650 Hz



NIOSH HELMET-HEAD INTERACTION

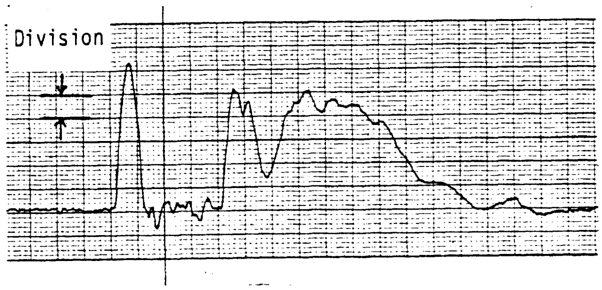
DATA SUMMARY

TEST NUMBER H-004

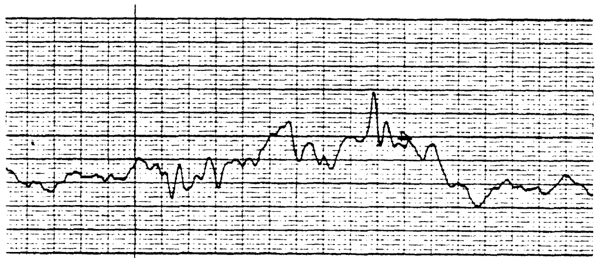
HELMET TYPE ERB

IMPACT VELOCITY 16.4 fps

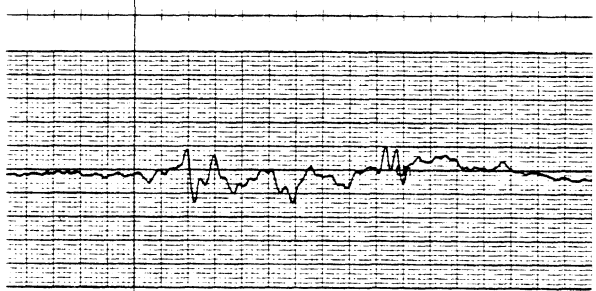
Compensated Force
100 lbs./Division
Filtered 1650 Hz



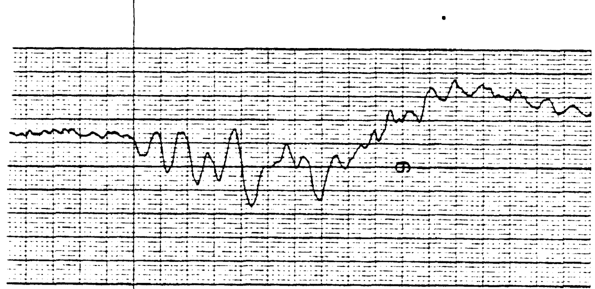
Posterior-Anterior
Head Acceleration
5 G's/Division
Filtered 1650 Hz



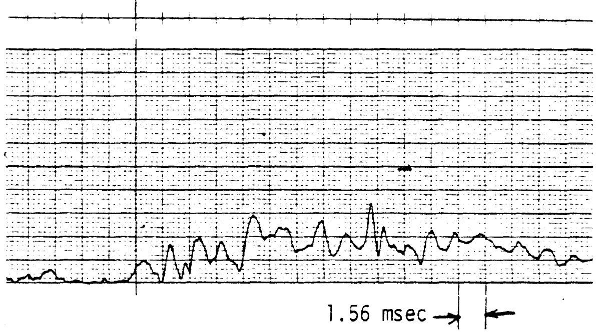
Left-Right
Head Acceleration
5 G's/Division
Filtered 1650 Hz



Inferior-Superior
Head Acceleration
5 G's/Division
Filtered 1650 Hz



Resultant
Head Acceleration
5.4 G's/Division
Filtered 1650 Hz



1.56 msec

NIOSH HELMET-HEAD INTERACTION

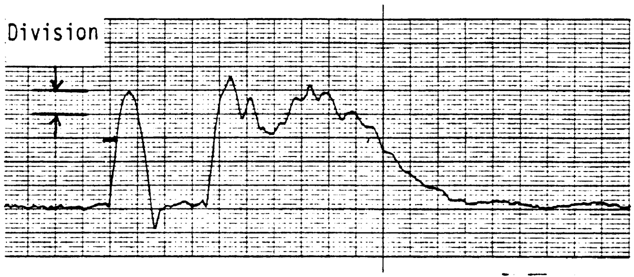
DATA SUMMARY

TEST NUMBER H-006

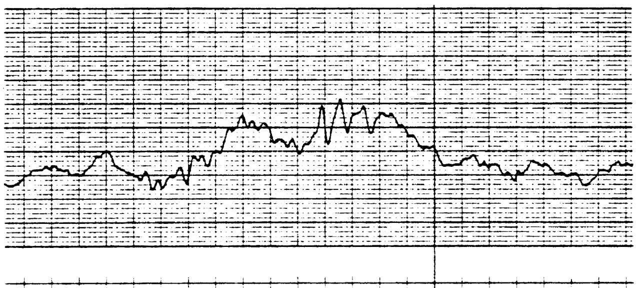
HELMET TYPE FBM-SUPERLECTRIC

IMPACT VELOCITY 16.7 fps

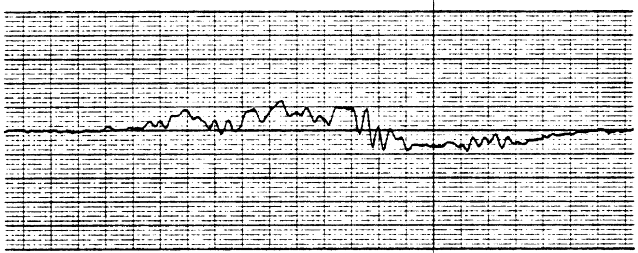
Compensated Force
100 lbs./Division
Filtered 1650 Hz



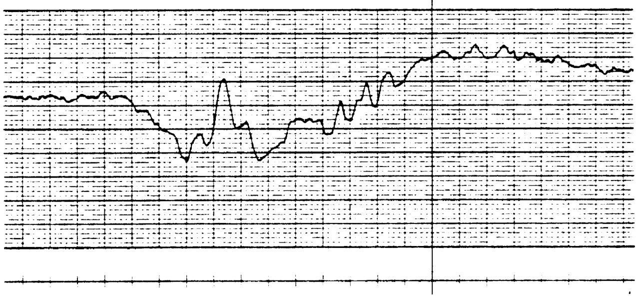
Posterior-Anterior
Head Acceleration
5 G's/Division
Filtered 1650 Hz



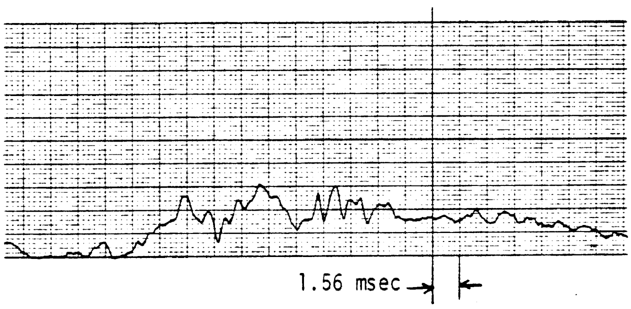
Left-Right
Head Acceleration
5 G's/Division
Filtered 1650 Hz



Inferior-Superior
Head Acceleration
5 G's/Division
Filtered 1650 Hz



Resultant
Head Acceleration
5.4 G's/Division
Filtered 1650 Hz



NIOSH HELMET-HEAD INTERACTION

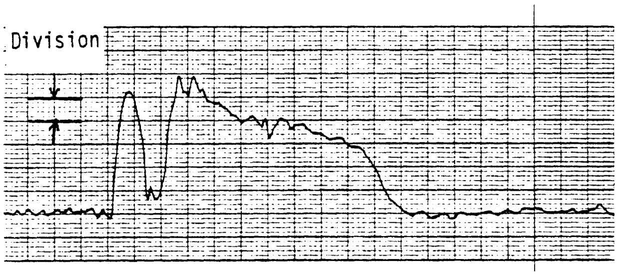
DATA SUMMARY

TEST NUMBER H-007

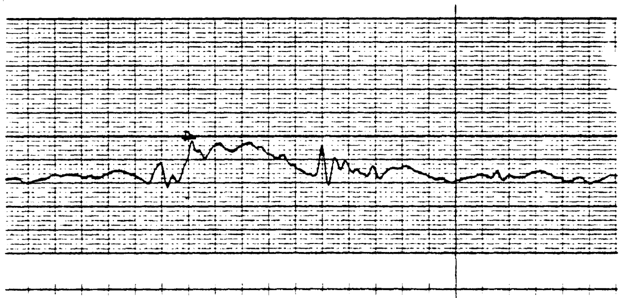
HELMET TYPE FBM TUF-ITE

IMPACT VELOCITY 16.2 fps

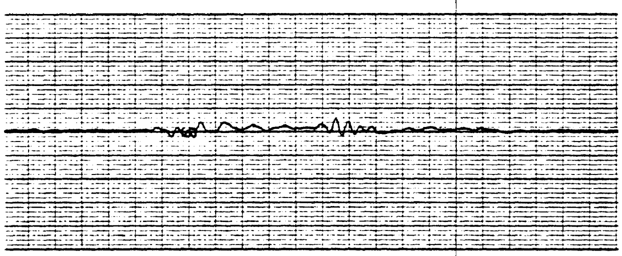
Compensated Force
100 lbs./Division
Filtered 1650 Hz



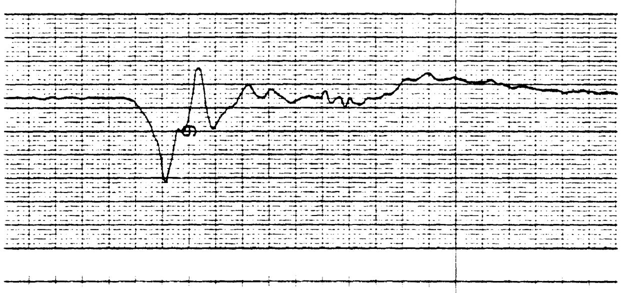
Posterior-Anterior
Head Acceleration
12.5 G's/Division
Filtered 1650 Hz



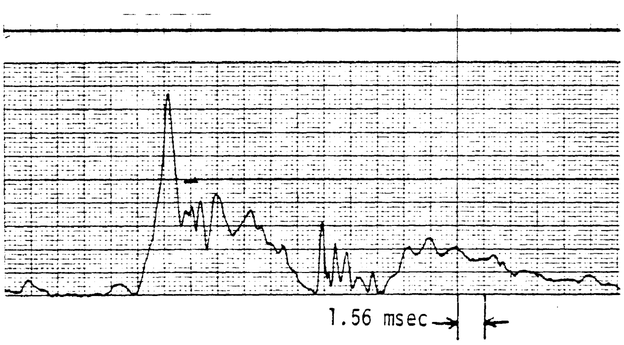
Left-Right
Head Acceleration
12.5 G's/Division
Filtered 1650 Hz



Inferior-Superior
Head Acceleration
12.5 G's/Division
Filtered 1650 Hz



Resultant
Head Acceleration
54 G's/Division
Filtered 1650 Hz



NIOSH HELMET-HEAD INTERACTION

DATA SUMMARY

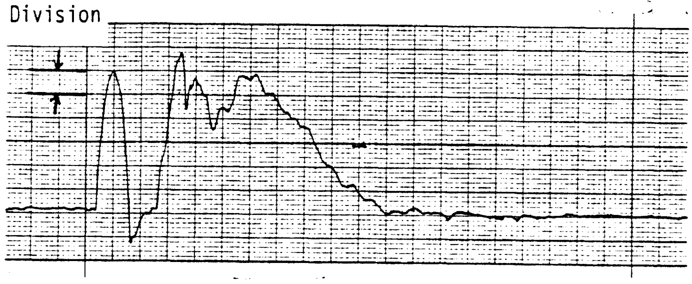
TEST NUMBER H-008

HELMET TYPE SG

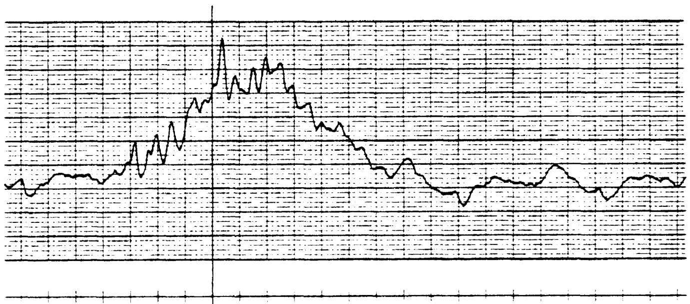
IMPACT VELOCITY 17.0 fps

Division

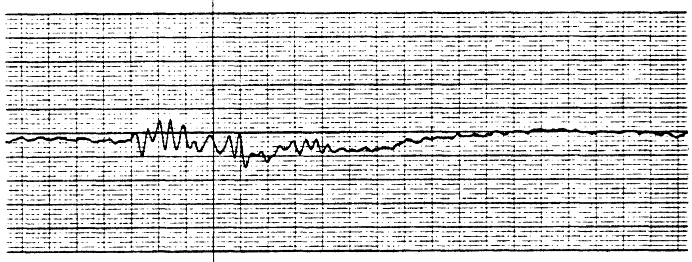
Compensated Force
100 lbs./Division
Filtered 1650 Hz



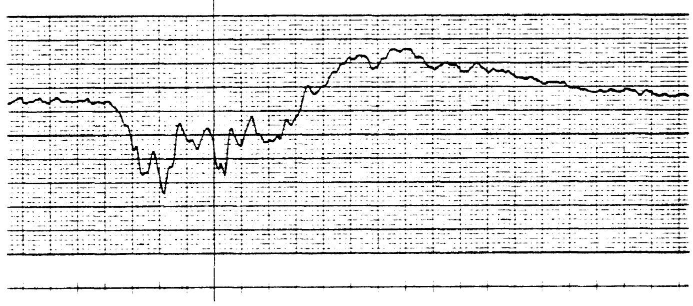
Posterior-Anterior
Head Acceleration
5 G's/Division
Filtered 1650 Hz



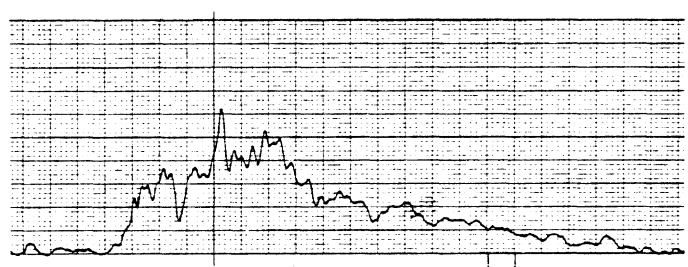
Left-Right
Head Acceleration
5 G's/Division
Filtered 1650 Hz



Inferior-Superior
Head Acceleration
5 G's/Division
Filtered 1650 Hz



Resultant
Head Acceleration
5.4 G's/Division
Filtered 1650 Hz



1.56 msec

NIOSH HELMET-HEAD INTERACTION

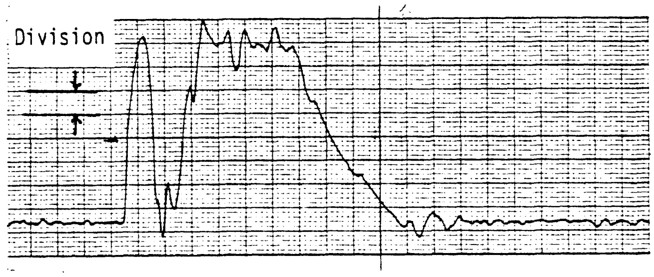
DATA SUMMARY

TEST NUMBER H-009

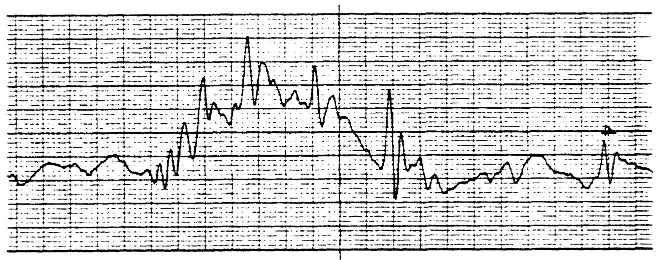
HELMET TYPE SG

IMPACT VELOCITY 22.4 fps

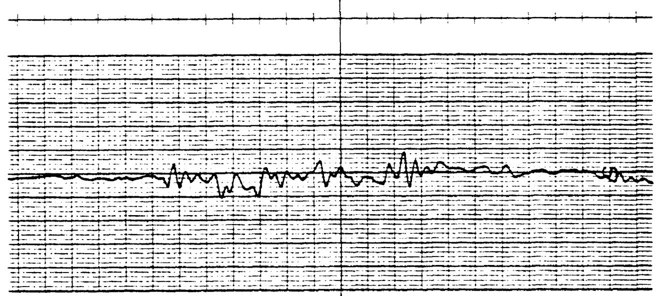
Compensated Force
100 lbs./Division
Filtered 1650 Hz



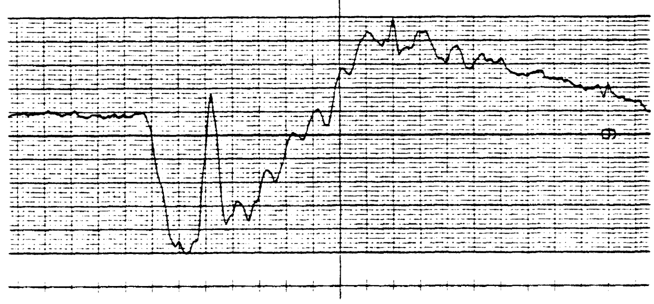
Posterior-Anterior
Head Acceleration
5 G's/Division
Filtered 1650 Hz



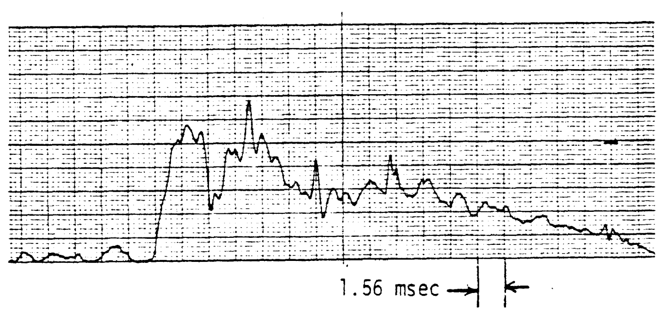
Left-Right
Head Acceleration
5 G's/Division
Filtered 1650 Hz



Inferior-Superior
Head Acceleration
5 G's/Division
Filtered 1650 Hz



Resultant
Head Acceleration
5.4 G's/Division
Filtered 1650 Hz



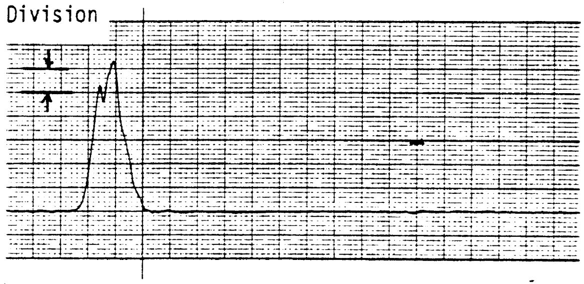
NIOSH HELMET-HEAD INTERACTION

DATA SUMMARY

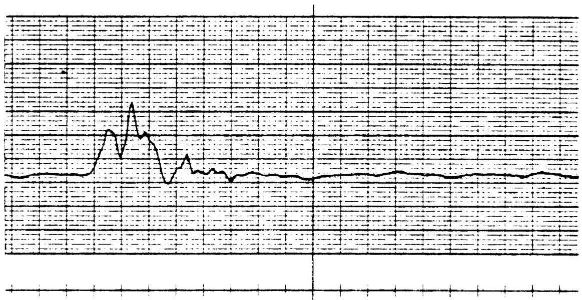
TEST NUMBER H-010 HELMET TYPE NO HELMET

IMPACT VELOCITY 16.3 fps

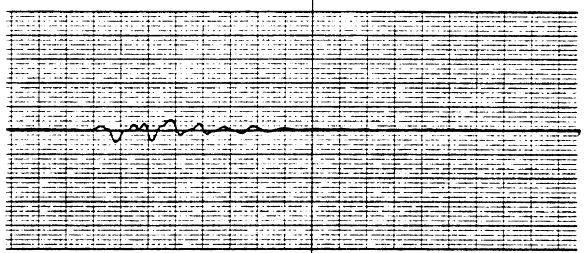
Compensated Force
400 lbs./Division
Filtered 1650 Hz



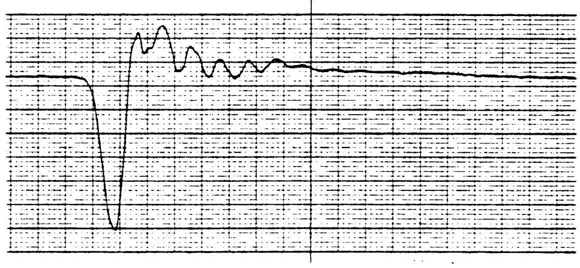
Posterior-Anterior
Head Acceleration
25 G's/Division
Filtered 1650 Hz



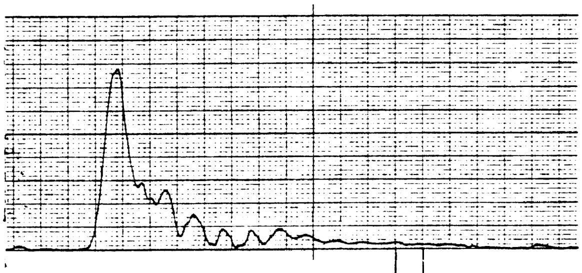
Left-Right
Head Acceleration
25 G's/Division
Filtered 1650 Hz



Inferior-Superior
Head Acceleration
25 G's/Division
Filtered 1650 Hz



Resultant
Head Acceleration
21.6 G's/Division
Filtered 1650 Hz



1.56 msec