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VALIDATION STUDIES FOR
HEAD IMPACT INJURY MODEL

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16. Abstract

The objective of this study was to perform experiments involving the heads of sub-human primates and fresh unembalmed cadavers with sufficient precision and reliability so that a validation of an analytical model can be made for the impact situation, and to determine the brain injury mechanisms in the primate test from the pathology and engineering data obtained from the experiments.

The static load-deflection response, and the resulting static principal strains on the skulls of two monkeys and one human cadaver, are reported.

Thirty-nine live primate head impacts and two human cadaver head impacts are reported in the texts. Techniques for measuring epidural pressure during impact, strains on the skull, and placement of six accelerometers on the skull were developed.

Analysis of the injuries produced in the test impacts to lower primates indicate a strong relationship between contre-coup injuries and the negative pressure levels produced near the contre-coup site. The data indicate that negative pressure magnitudes greater than 68 KPa can produce brain tissue damage. Injury-producing impact velocity levels are greater for padded impacts than for rigid impacts.

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1. INTRODUCTION

The design of much protective equipment for the head is often based on intuition because of the lack of reliable information about the mechanical behavior of the head.

In order to properly design devices aimed at minimizing head injury in the automotive crash environment, engineers require a means of predicting potential injury or so-called Head Injury Model. This model might be used in real accident reconstructions, car crash and sled test experiments, or mathematical simulations.

The automotive crash environment encompasses a wide range of impulse durations and directions. Thus, a viable head injury model must provide appropriate mechanisms that realistically account for the frequently observed, but poorly documented, relations of head impact tolerance and impulse duration and direction. In addition, two distinct types of loading are observed:

1. An impact or blow involving a collision of the head with another solid object at an appreciable velocity. This situation is generally characterized by large linear accelerations and small angular accelerations during the impact phase.

2. An impulsive loading including a sudden head motion without direct contact. The load is generally transmitted through the head-neck junction upon sudden changes in the motion of the torso and is associated with large angular accelerations of the head.

Research is currently being conducted by NHTSA to develop a comprehensive finite-element representation of the entire head and neck capable of simulating the role of skull deformation, skull geometry, gross head motions, and compression waves in the skull and brain. Such knowledge would be helpful in the treatment of injury by serving to identify the mechanism of trauma. Thus, both a rational design procedure for impact protection and a rational therapy for treatment of trauma cannot be developed until a quantitative description of the mechanical responses of the human body is obtained.

The objective of this study was to perform experiments involving the heads of animals and fresh cadavers with sufficient precision and reliability so that a validation of the analytical model can be made for the impact situation, and to determine the brain injury mechanisms in the animal tests from the pathology and engineering data obtained from the experiments.

A detailed description of the procedures used to obtain the validation data is outlined in the text. The computer routines for digitizing, filtering, and rigid body analysis program with validation are all given in Appendices A1, A2, and A3.

2.0 STATIC COMPRESSION TESTS OF SKULLS

These tests consist of the measurements and the recording of load, displacements, and strain-time/histories of various selected sites on two Rhesus monkey skulls and one human cadaver skull.

2.1 Method

Three skulls were used in this study. Two were obtained from Rhesus monkeys weighing 11.9 lbs. and 16.7 lbs., respectively, and one was obtained from an unembalmed human cadaver weighing 168 lbs.

Four rosette strain gage sites on each skull were chosen to best represent the state of strain on the surface of the loaded skull. The first location was on the frontal bone in the mid-sagittal plane, the second and third locations were on the right and left parietal bones at approximately mid-way between the external-auditory canal and the mid-sagittal plane, and the fourth location was on the occipital bone in the mid-sagittal plane. No strain gage rosette was placed on or within four rosette diameters of a suture because of the structural discontinuity of the suture construction.

Three loading directions were investigated for each skull. The skull to be tested was loaded in the anterior-posterior (A-P), the Superior-Inferior (S-I), and the Left-Right (L-R) directions. Skull deformation versus time data were recorded simultaneously in the A-P, S-I, and L-R directions for each loading direction. A loading rate of 0.2 inches per minute was used in all tests.

All of the skulls were cleaned of all tissues inside and out. The locations on the surface of the skull to be strain gaged were scraped clean and sanded smooth with 320 grit wet abrasive paper while flushing with 99% ethyl alcohol. Final skull cleaning and drying was done with gauze sponges and alcohol. The delta rosette strain gages and cable relief tabs were bonded to the skulls with Micro-Measurements M-Bond 100 (Methy-2-Cyanoacrylate) adhesive. The gage direction and position on the skull were then measured and recorded. The skulls were then stored in a moist environment at 37° F until time to be tested.

The skull to be tested was removed from the cooler and placed in the testing machine as shown in Figures 1 and 2. The strain gages, load cell, and extensometer were then connected to their respective amplifiers. The data were recorded on a light beam oscillograph. This procedure was repeated for each direction and for each skull.

The specifications for all transducers, amplifiers, and recorders are given in Appendix C.

2.2 Results

The results of these tests are given in Appendix B-1. The strain gage rosette analysis, the location and direction of each strain gage, as well as each loading location are given in the appendix. The skull cross-section dimensions are also presented in the results. The data are presented in tabular form, giving load, displacement, and principal strains for any given point in time.

The major source of error in these tests was skull rotation or settling during loading, and lack of symmetry in the skulls. These two sources of error account for most of the discrepancies in the tabular readings.

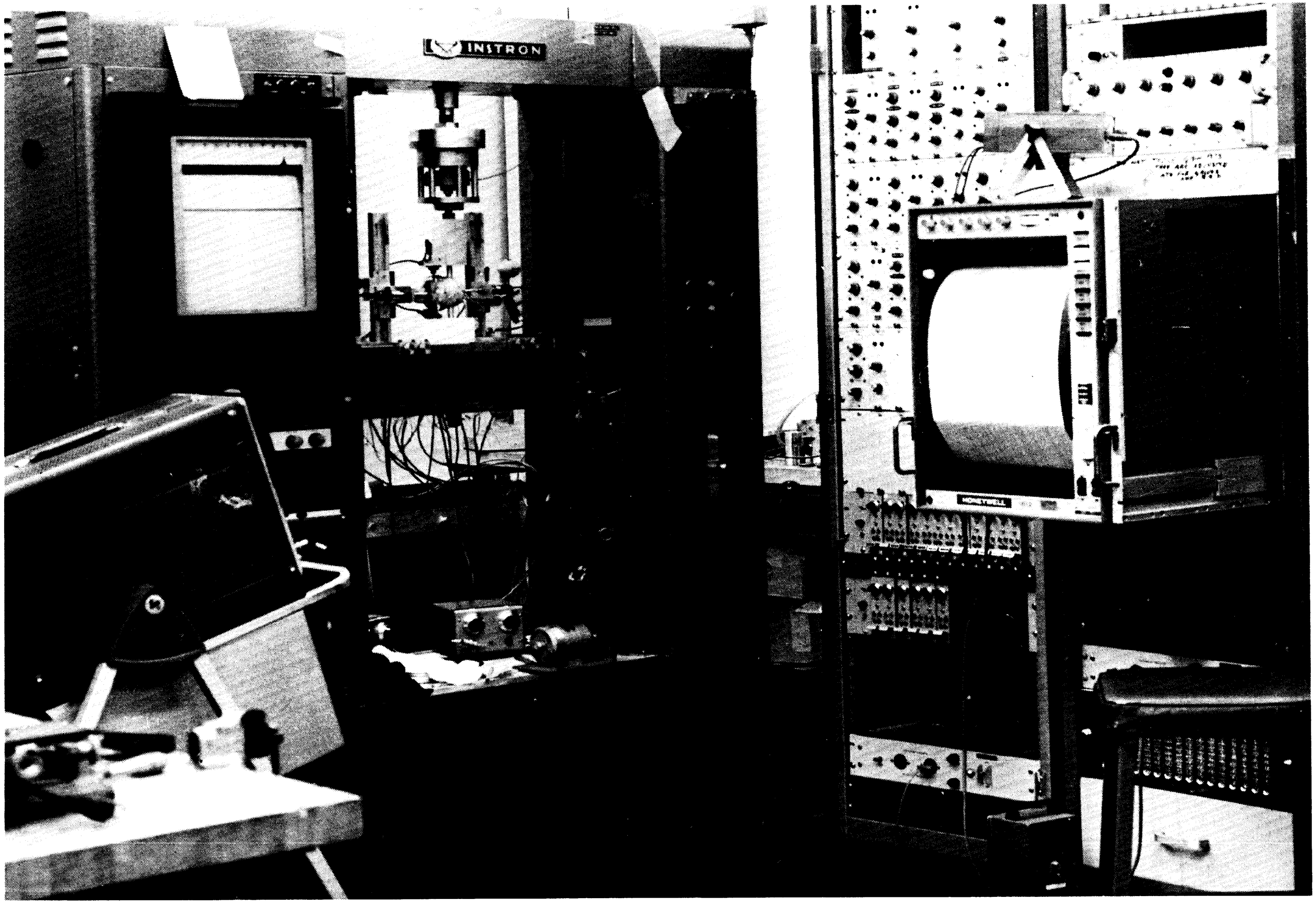

FIGURE 1. TEST SETUP FOR STATIC COMPRESSION

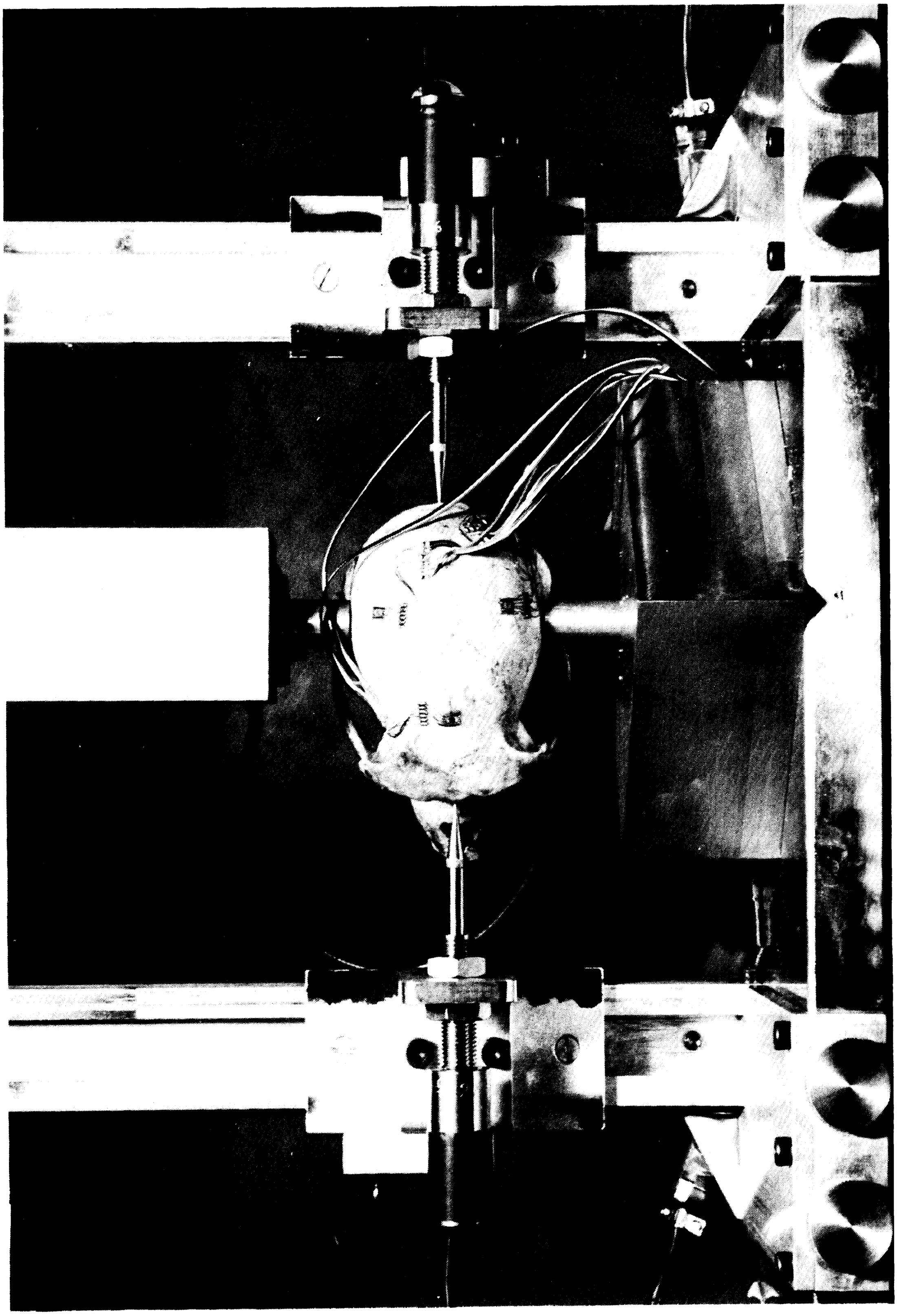

FIGURE 2. LOCATION OF EXTENSOMETERS

3.0 HEAD IMPACT TESTS

These tests consist of the measurements and recording of impact force, seven accelerations at the surface of the skull, two epidural pressures, and nine strains in three rosettes on the surface of the skull. Detailed autopsies were performed to obtain all injury data for correlation with the test parameters. High speed motion pictures, both front and side views, were also obtained. Eighteen Rhesus (Macaca mulatta), sixteen Cynomolgus (Macaca fascicularis), five baboons (Papio cynocephalus), and two human cadavers were used in this study. There were sixteen back-of-the-head and sixteen side-of-the-head impacts. The specification for all transducers, amplifiers, and recorders are given in Appendix C. The weight of the impactor for all tests was 44 pounds.

3.1 Type I - Monkey Head Impacts

In Type-I tests, epidural pressure and skull surface accelerations were measured at the point of impact and the point opposite impact. The principal strains were determined at the same locations as in Section 2.0, except for the occipital bone location, which was dropped from the tests. The back-of-the-head and side-of-the-head impacts were carried out on five Rhesus and four Cynomolgus.

3.1.1 Method. The delivery of monkeys was scheduled for the day prior to the start of a test series. Upon arrival, they were immediately transferred from the shipping crates to individual steel cages in the vivarium and inspected for injury or abnormalities. The monkeys selected for testing on the next day were provided only with water, while the others were given monkey chow and fresh fruit.

The morning of the test, the monkey was transferred to the catch cage and initially sedated with Ketamine [dL-2-(O-Chlorophenyl)-2-(Methylamino) Cyclohexanone Hydrochloride] at a dosage of 50 mg/kg for Rhesus and Cynomolgus, and 20 mg/kg for baboons. The monkey was then placed on a table in the vivarium and its left lower leg shaved. The saphena parva vein was located and a catheter inserted. A three-way valve was connected to the catheter and the assembly taped securely at the ankle. The monkey was given an intravenous injection of sodium pentobarbitol through the catheter valve, at a dosage of 20 mg/kg for Rhesus, Cynomolgus, and baboons. The monkey's head and shoulders were shaved to facilitate surgery, a disposable surgeon's mask was placed around its müzzle for sanitation purposes, and it was taken to the surgery room.

Surgery for a Type I test began with removal of the scalp with a cauterizing scalpel. Two holes were drilled and tapped in the skull for the pressure transducer mounting bases at sites near and opposite the impact point. Two holes were drilled and tapped for installation of Wilcoxon accelerometers, one at the point of impact and the other opposite impact. The locations on the skull to be strain gaged were scraped clean and sanded smooth with 320 grit wet or dry abrasive paper while flushing with 99% ethyl alcohol. Final skull cleaning and drying were done with gauze sponges and alcohol. The strain gages and cable relief tabs were bonded to the skull with Micro-Measurements M-Bond 100 (Methy-2-Cyanoacrylic) adhesive, and the actual gage position on the skull was measured and recorded. A flat six-wire cable was used for each strain rosette and was soldered to the cable relief tabs. Finally, the pressure transducer mounting bases were screwed into the tapped holes in the skull and fastened in place with epoxy adhesive (Figure 3).

The monkey was immediately set up at the impact cannon, and its head held upright with loops of surgical thread through the ears. The pressure transducer cups were filled with a silicone fluid to provide pressure coupling with the brain cavity, and the pressure transducers were installed, taking care to prevent trapped air bubbles.

All the transducer cables were connected to the instrumentation and the transducers checked for continuity and function. Photo targets were placed on the skull and accelerometers. The monkey's head was then positioned in front of the impactor. The Hycam high-speed camera (3000 fps) was positioned for a side view, bore sighted, and focused. The instrumentation was then zeroed and calibrated.

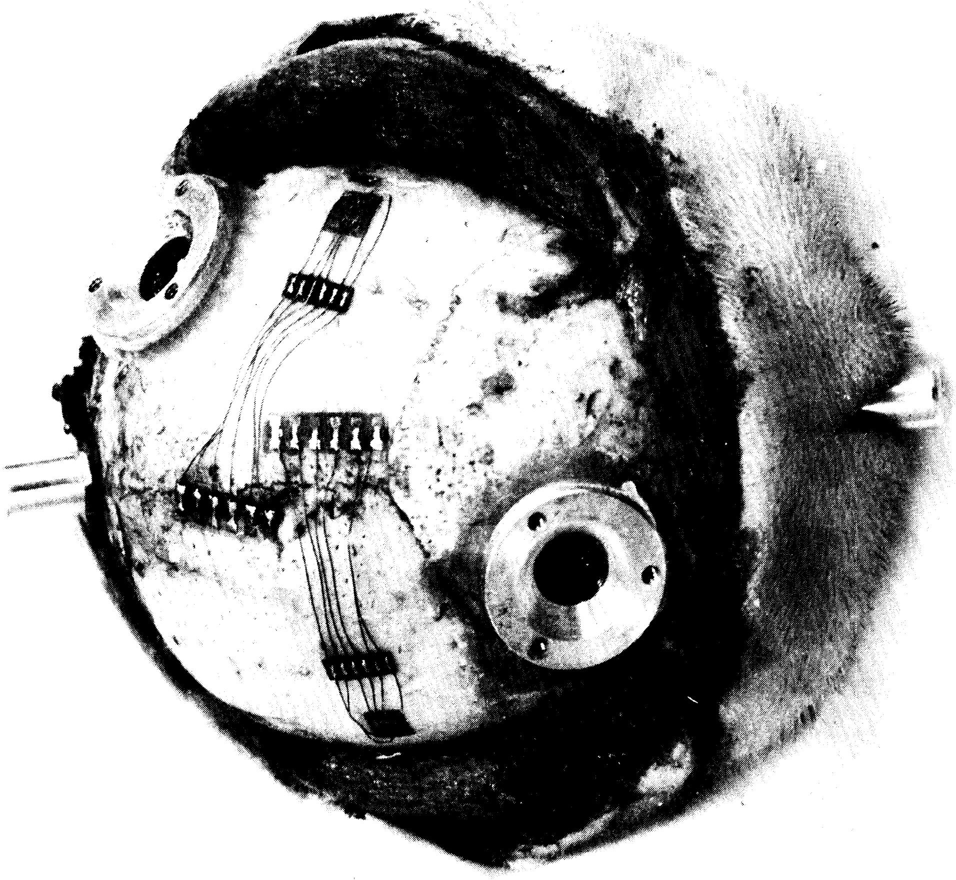

FIGURE 3. PRESSURE TRANSDUCER LOCATIONS

Just before the monkey was set up at the impact cannon, the anaesthetic was changed from Sodium Pentobarbitol to Sodium Thiamalal, which has a much shorter lasting effect. The monkey was impacted when it had come out of the anaesthetic sufficiently to exhibit an eye blink reflex and arm muscle tone (Figure 4). After impact, the monkey was observed closely and a detailed time history of its condition recorded until it recovered to its pre-impact state. The monkey was then removed to surgery and terminated.

Gross autopsy was conducted in the Autopsy Laboratory, specially equipped for dissection. Careful anatomical dissection of the head, face, and neck tissues where head impacts occurred allowed discrete identification of many sites of vascular failure. When gross trauma was found, it was photographically recorded, using a specially modified Pentax camera with close-up lens, either <u>in situ</u> or as an isolated entity, to provide a permanent record of the injury.

The injuries were evaluated using the Abbreviated Injury Scale (AIS). Each individual injury was assigned an AIS value and the overall AIS injury was assigned by summing the cubes of the individual AIS numbers and then taking the cube root.[1] These detailed injuries were recorded on the summary sheets. Only injuries directly related to the impact are used for overall injury. Any injury related to instrumentation installation was ignored, where possible, in injury assessments.

3.1.2 <u>Results</u>. The results of these tests are given in Appendix B-2. The subject's anthropometry, impact location and conditions, plots of force, principal strains, epidural pressure and skull accelerations versus time, as well as autopsy summary and injury ratings are all presented in the Appendix.

The results of the Type-I monkey dynamic tests are shown in Table 1. The pressure data are presented in the form of two peaks,

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1. Stalnaker, R. L., Mohan, D., and Melvin, J. W., "Head Injury Evaluation: Criteria for Assessment of Field, Clinical, and Laboratory Data," Proceedings of the 19th Conference of the American Association for Automotive Medicine, San Diego, California, November 17-21, 1975.

MONKEY HEAD IMPACTS - TYPE 1
Table 1

Run No.	Test Subject: Species*	Test Subject: Wt(kg)	Test Conditions: Dir. of Impact	Test Conditions: Impact Velocity (M/Sec)	Test Conditions: Impact Force (Newtons)	Test Conditions: Peak Head Accl. (G's)	Test Conditions: Impact Dur. (MSec)	Peak Pressures (kPa): Side of Impact: Initial	Peak Pressures (kPa): Side of Impact: Secondary	Peak Pressures (kPa): Side Opposite Impact: Initial	Peak Pressures (kPa): Side Opposite Impact: Secondary	Overall* Head Injuries (AIS)	Injury Comments
002	RH	5.2	Rear R	9.53	3026	1560	5.6	LOD	LOD	-35.30	+47.85	6	AIS Compound & Simple Fracture of occipital 3+1 Simple Fractures of Lt. Parietal Bone 2+1 Simple Fracture of Rt. Parietal Bone 2 Simple Fracture of Rt. Temporal Bone 2 Simple Fracture of Lt. Temporal Bone 2 Subdural Hemorrhage over back of parietal lobe (Massive) 4+1 Tear of Major Vessel (Lt. Cerebral Arterie) DEAD AT IMPACT
003	RH	5.3	Rear R	6.44	3204	1122	2.6	LOD	LOD	-87.70	+122.80	6	Simple Fracture of occipital Bone 3 Simple Fracture of Lt. Parietal Bone 2 Simple Fracture of Lt. Temporal Bone 2 Subdural Hemorrhage Rt. Tip of Frontal Lobe 4 Highly Localized Coutre-Coup Injury Forward of Front Pressure Gauge 3 Unconscious with Severe Neurological Signs Greater than 15 min. 4 UNCONSCIOUS ONE HOUR AFTER IMPACT (TERMINATED)
010	RH	5.2	Rear R	4.43	2092	209	3.2	+11.10	-11.24	-43.30	LOD	0	No Loss of Consciousness

MONKEY HEAD IMPACTS - TYPE 1
Table 1 (Continued)

Run No.	Test Subject		TEST CONDITIONS					PEAK PRESSURES (KPa)				Overall* Head Injuries (AIS)	INJURY COMMENTS	AIS
								Side of Impact		Side Opposite Impact				
	Species*	Wt(kg)	Dir. of Impact	Impact Velocity(M/Sec.)	Impact Force (Newtons)	Peak Head Accl. (G's)	Impact Dur. (MSec)	Initial	Secondary	Initial	Secondary			
028	RH	6.5	Right P	9.80	3115	LOD	3.5	NI	NI	-54.19	+97.22	4	Dazzed One Minute Diffuses Subdural Hemorrhage Over Lt. Temporal Lobe AWAKE IN 20 MINUTES (TERMINATED)	1 4
082	CY	4.0	Left R	11.61	2670	NI	2.3	NI	NI	-42.06	+52.61	3	Contusion On Left Cheek Comminuted Fracture Left Zygoma Unconscious Less Than 15 Minutes UNCONSCIOUS 8 MINUTES AWAKE IN 20 MINUTES (TERMINATED)	1 3 2
083	CY	4.7	Left P	12.97	912	391	2.9	NI	NI	-31.72	+28.68	0	No Loss of Consciousness	
084	CY	3.2	Rear P	13.27	681	270	4.0	+28.41	-8.89	-28.27	_67.98	2	Unconscious Less Than 15 Minutes UNCONSCIOUS 4 MINUTES AWAKE IN 25 MINUTES (TERMINATED)	2

MONKEY HEAD IMPACTS - TYPE 1
Table 1 (Continued)

Run. No.	Test Subject		TEST CONDITIONS					PEAK PRESSURES (KPa)				Overall* Head Injuries (AIS)	INJURY COMMENTS	
								Side of Impact		Side Opposite Impact				
	Species*	Wt(kg)	Dir. of Impact	Impact Velocity (M/Sec)	Impact Force (Newtons)	Peak Head Accl. (G's)	Impact Dur. (Msec)	Initial	Secondary	Initial	Secondary			AIS
085	CY	4.2	Rear R	10.72	1397	335	3.3	+59.71	-15.72	-68.26	+25.17	6	Scalp Laceration Back of Head (Deep) Neck Muscle Torn From Skull Simple Fracture of Occipital Bone Highly Localized Contre-Coup Injury Forward of Front Pressure Gauge Subdural Hemorrhage Right Side of Frontal and Parietal Lobe Unconscious For More Than 15 Minutes with Severe Neurological Signs NO RESPIRATION FOR TWO MINUTES AFTER IMPACT - UNCONSCIOUS FOR 18 MINUTES AWAKE IN 45 MINUTES (TERMINATED)	2 2 3 3 4 4

*RH - Rhesus
CY - Cynomolgus
LOD - Loss of Data
NI - Not Instrumented
R - Rigid Impactor
P - Padded Impactor

** See Reference 1
Head Injury Evaluation: Criteria for Assessment of Field, Clinical, and Laboratory Data

Stalnaker, R.L. Etal.,
To Be Published AAAM Conference,
November 17-21, 1975,
San Diego, California

an initial peak followed by a secondary peak. In every test, the initial spike was negative at the point opposite impact and positive nearest impact.

In two tests contre-coup injuries were obtained. The pressure-time curve and the resulting injury for one of the tests are given in Figures 5 and 6, respectively.

3.2 Type II - Monkey Head Impacts

In Type-II tests, rigid-body motion of the head was measured with accelerometers along with high speed motion pictures from orthogonal views. Back-of-the-head and side-of-the-head impacts were carried out on thirteen Rhesus, twelve Cynomolgus and five baboons.

3.2.1 Method. The monkey preparation for Type II head impacts was the same as for the Type I. Surgery for a Type II test requires only local scalp removal with a cauterizing scalpel at the mounting site for the accelerometer cups and impact direction accelerometers. Accelerometer cups for mounting the three biaxial headsets were positioned to provide maximum separation of accelerometers and to avoid interference with the impactor. Three 6 mm holes were drilled with a Stryker trephine, the two-piece collets inserted through the holes, and the accelerometer cups threaded onto the collets with Loctite on the threads to prevent loosening (Figure 7). Two holes were drilled and tapped in the skull for the impact direction accelerometers, as in the Type I surgery.

The accelerometer mounting blocks were fastened to the installation fixture and the fixture was adjusted to position the base of each block into one of the cups attached to the skull. The fixture was locked in this adjustment and the cups filled with a freshly mixed paste of acrylic. The blocks, still attached to the fixture, were reinserted in the cups and the acrylic was molded around the block bases to entrap the blocks when set. The fixture was measured to determine accelerometer axis dimensions and then

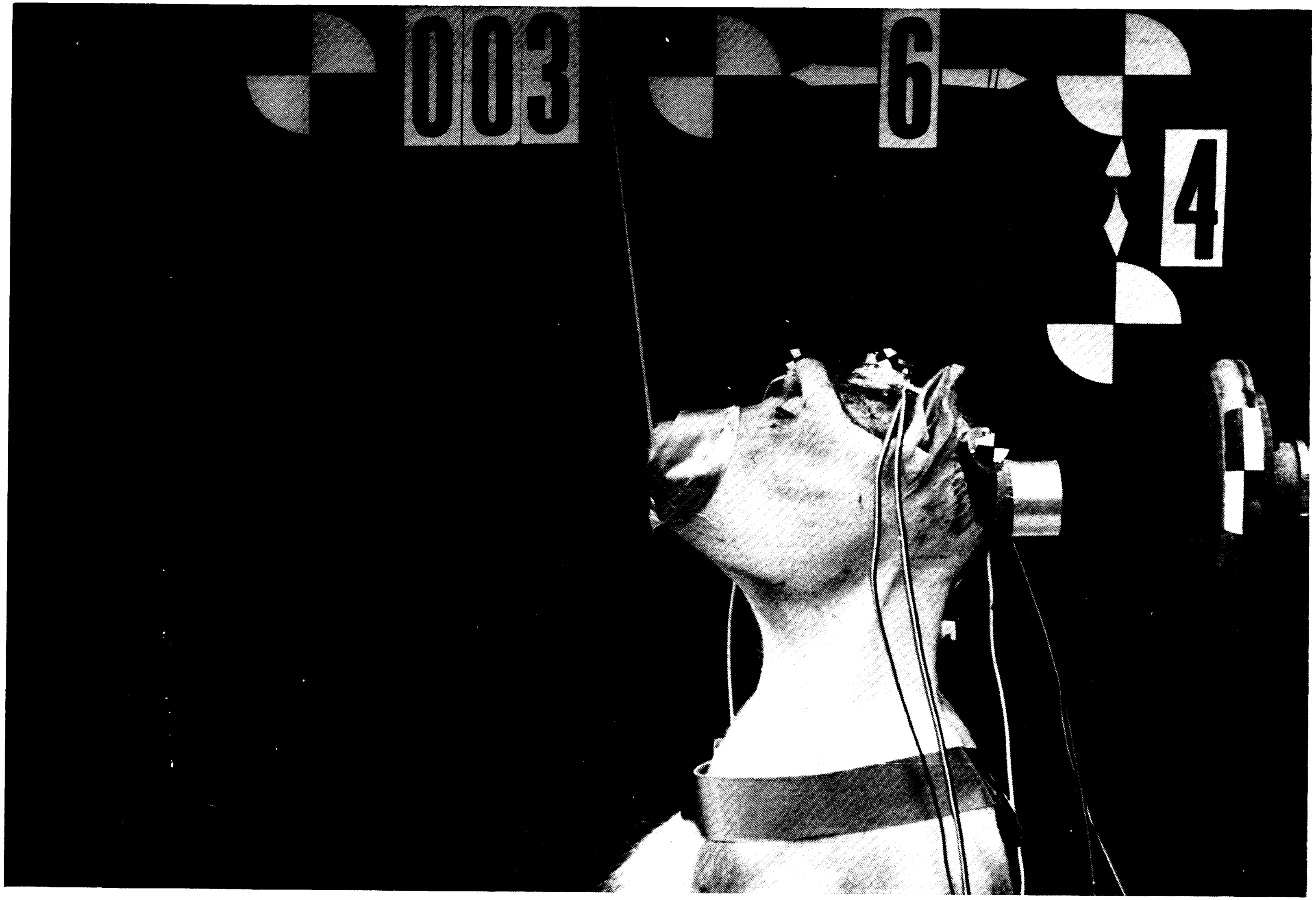


FIGURE 4. TEST SETUP FOR TYPE-1 IMPACTS

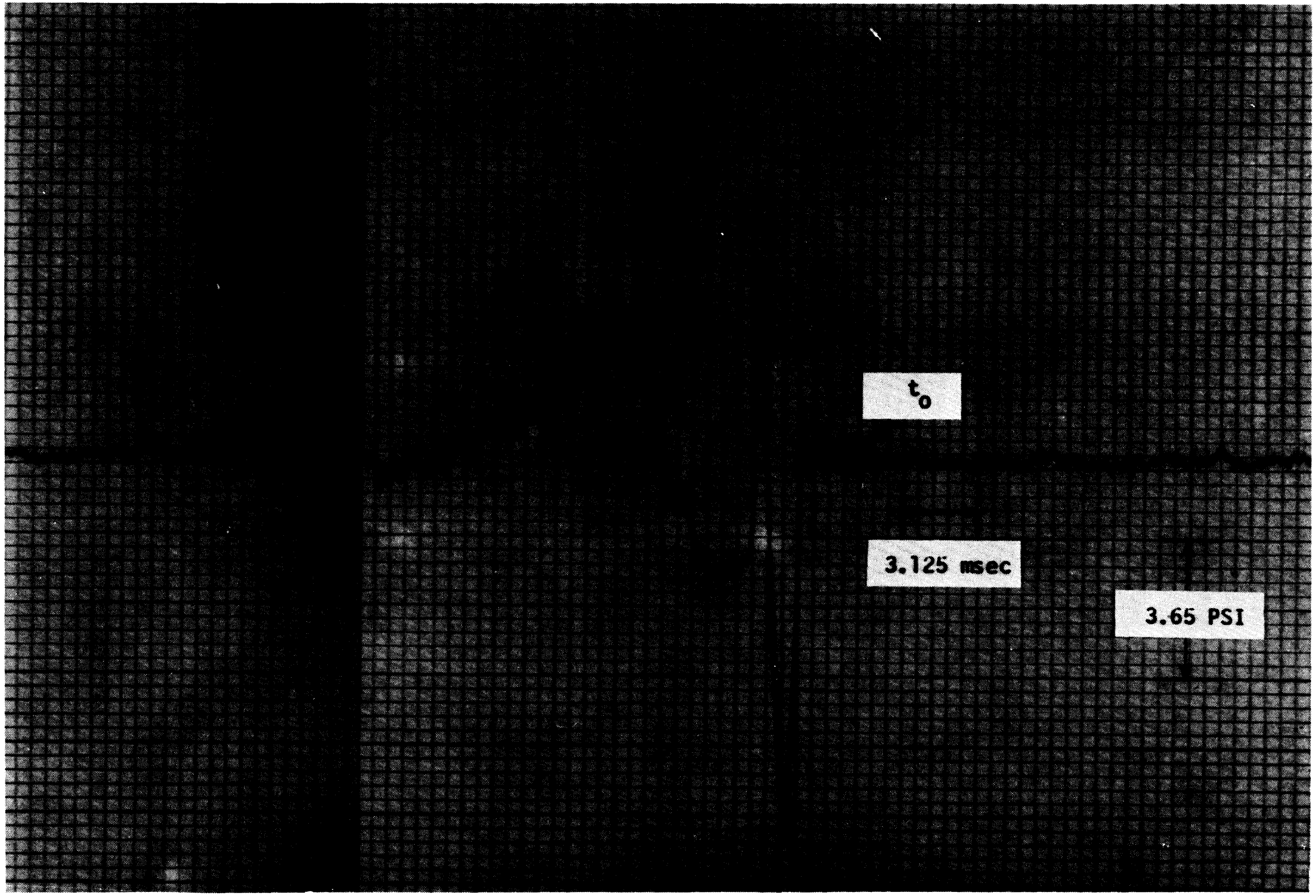


FIGURE 5. PRESSURE-TIME CURVE FOR TEST 085 AT THE POINT OF CONTRE-COUP INJURY

FIGURE 6. CONTRE-COUP INJURY IN TEST 085

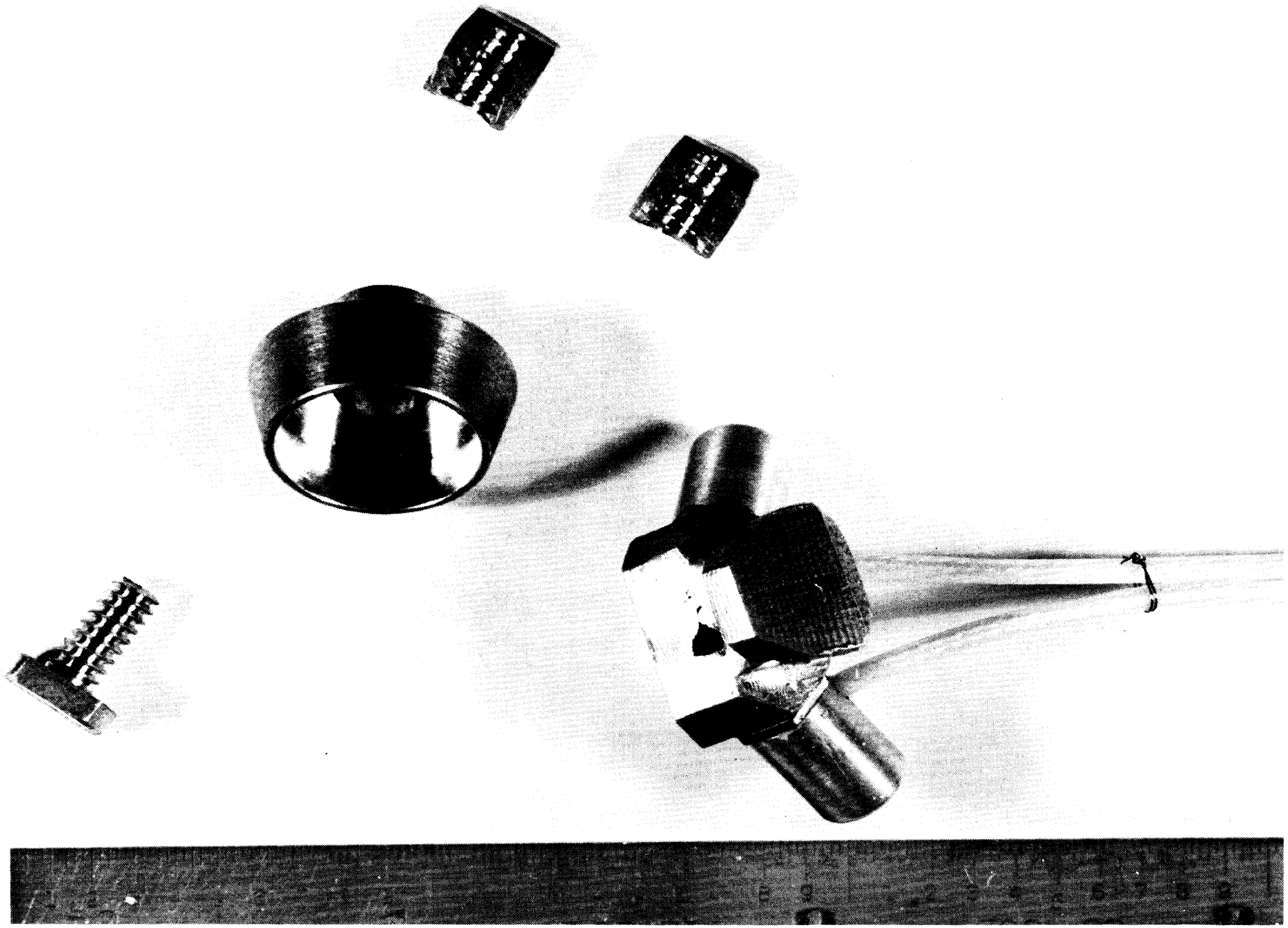


FIGURE 7. ACCELEROMETER MOUNT LOCATIONS

the fixture was removed when the acrylic had set, leaving the blocks bonded into the cups in an orthogonal relationship at precisely known positions. A theoretical description of accelerometer motion analysis is given in Appendix A-1.

Lead pellets were installed at the eyes and ears to define the physiological axes; for identification on the x-ray, each pellet was a different configuration. The two Wilcoxon or Endevco accelerometers used for direction of impact readings were threaded into the tapped holes in the skull and a directional marker with two incline lead pellets placed on each one. For Type II tests, an additional lead target must be fastened to each of the three accelerometer mounting blocks to define the c.g. position of each biax. The targeted monkey was placed in a prone position on the x-ray platform with its head elevated so all the lead targets were raised above its body. The head was taped in position to prevent movement.

The x-ray procedure requires two orthogonal views identified as the Z-X and Z-Y exposures. A lead wire was hung as a plumb line down the center of the x-ray table to provide a prime vertical reference on each exposure. The x-ray platform the monkey was placed on pivots to provide the 90° rotation required for the two x-ray views. Each view requires two exposures, one of the targeted monkey, and one of a target ring that identifies the focal center of the x-ray beam on each exposure. Distances from the x-ray table to each lead target were measured for each view. The theoretical description of the x-ray analysis is given in Appendix A-2.

The monkey was taken into the impact area for Type II tests. The anaesthetic was changed to sodium thiamalal just prior to this step. Then the monkey was set up in front of the impact cannon, and the six Endevco or Wilcoxon accelerometers were installed on the mounting blocks (Figure 8). The accelerometers were connected to the instrumentation and tested for function. Targeting, positioning, and calibration were performed as in Type-I testing.

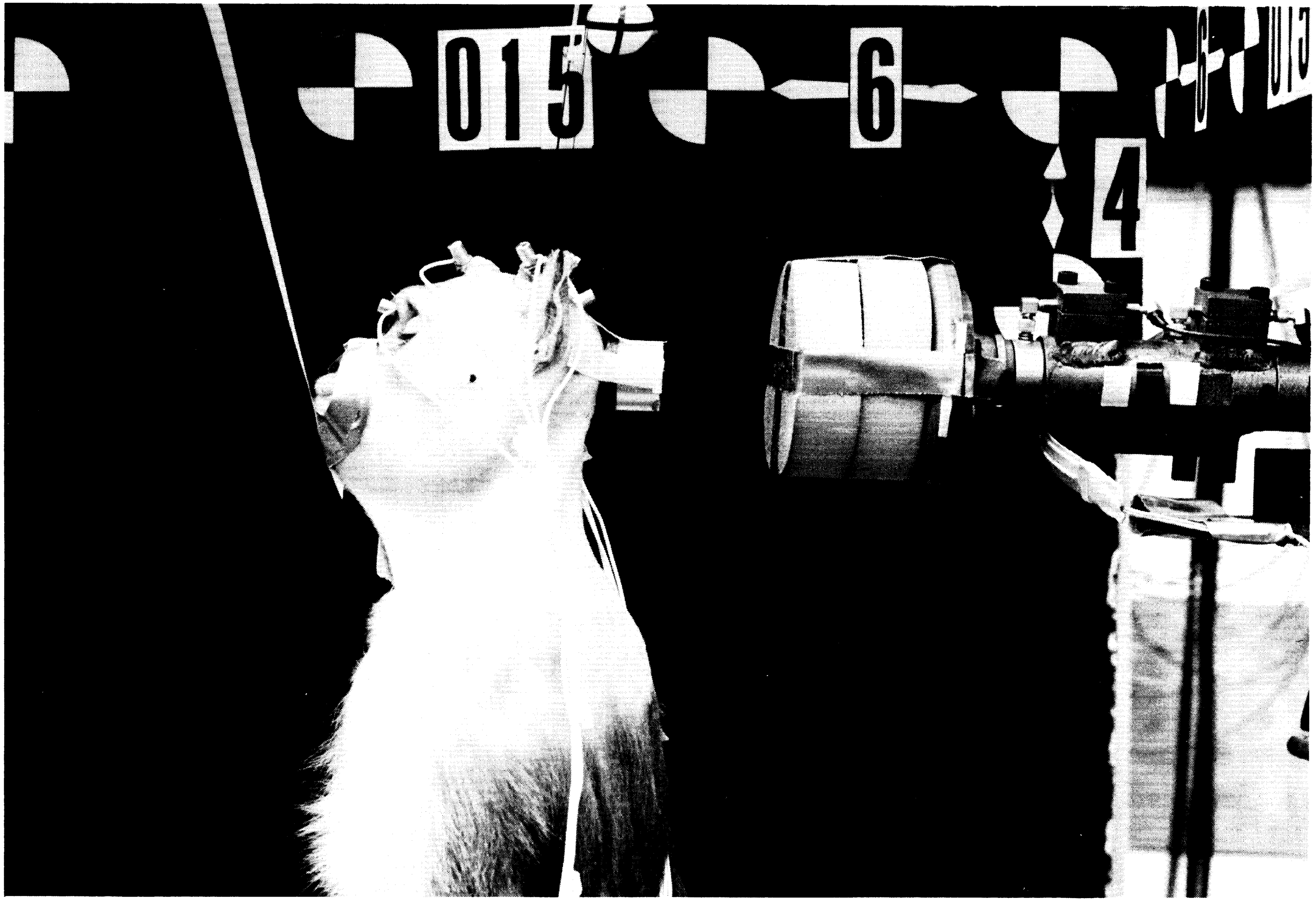


FIGURE 8. TEST SETUP FOR TYPE-II IMPACTS

Two orthogonally positioned high-speed movie cameras were required for the three-dimensional motion analysis of the Type-II test. The ideal placement of all three biaxial accelerometer sets gave an unimpaired view for each camera. The monkey was brought to the same level of consciousness as for a Type-I test before impacting. A written record was also kept on the monkey's condition as in Type-I tests. The monkey was then removed to surgery and terminated. A gross autopsy was conducted in the same manner as discussed in Section 3.2.1.

3.2.2 Results. The results of these tests are given in Appendix B-3. The subject's anthropometry, impact location and condition, plots of the force, skull accelerations, and rigid body head motion, both angular and linear, are all given in the summaries in the appendix. Autopsy summary and injury ratings are also given in the appendix.

3.3 Type III - Human Cadaver Head Impacts

In Type-III tests, epidural pressure and skull surface accelerations were measured at the point of impact and a point opposite impact. The principal strains were determined on the right and left parietal bone and the frontal bone. One frontal and one side head impact were carried out on two human cadavers.

3.3.1 Method. The specimens used in this study were fresh, unembalmed cadavers obtained from the Anatomy Department of the University of Michigan Medical School. They were stored at 37° F for two of the three days between time of death and impact. The cadavers were allowed to reach room temperature before testing. These procedures ensured that the effects of rigor mortis have disappeared.

The axis of the impactor was in the mid-sagittal plane for the back of the head impact, and was normal to the surface of the skull at the point of initial impact. The impact site was at the most rearward point of the occipital bone.

The installation of the pressure transducer, strain gage rosettes, and skull surface accelerometers was the same as detailed in Section 3.1. After being targeted and equipped with accelerometers, the cadaver was placed in a specially designed chair. All surfaces against which the cadaver might come into contact in its post-impact movements were thickly padded with styrofoam to prevent damage to the cadaver.

The cadaver was carefully positioned so that its head was in the correct position relative to the impactor and at the same time the whole cadaver acted as a relatively free body. The head was suspended and held in place by four strands of 000 thickness surgical thread. This thread supports only the weight of the head, and breaks easily on impact (Figure 9).

The side impact was on the left temporal region, two inches superior to the external acoustic meatus. All other details of the test setup were the same as above.

Gross autopsy was conducted in the autopsy laboratory and an overall injury assessment made using the Abbreviated Injury Scale, as outlined in Section 3.1.

3.3.2 Results. The results of the Type-III tests are given in Appendix B-4. The subject's anthropometry, impact location and conditions, plots of force, principal strains, epidural pressures and skull accelerations versus time, as well as autopsy summary and injury ratings, are all presented in the Appendix.

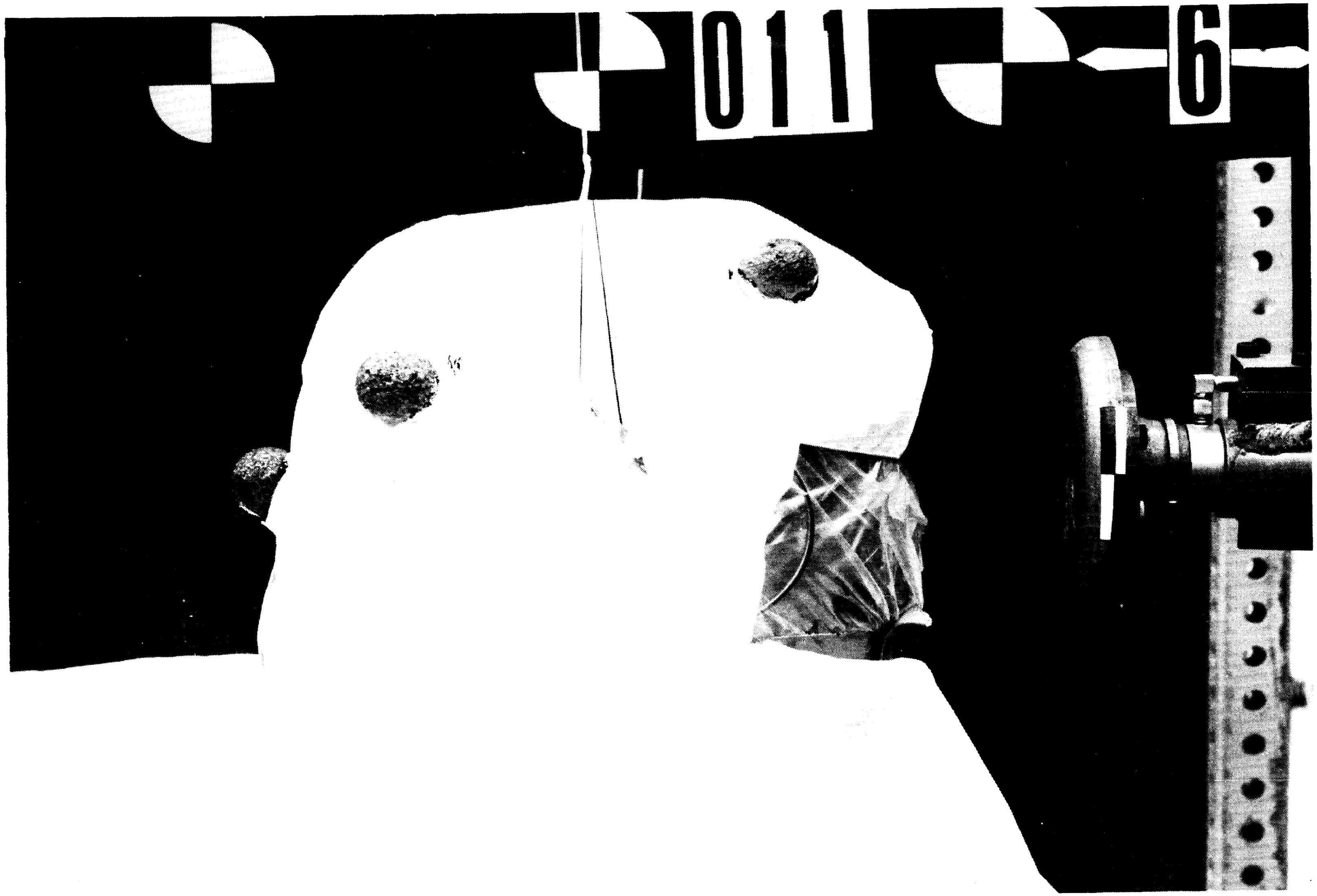


FIGURE 9. TEST SETUP FOR TYPE-III IMPACTS

4.0 PROGRAM SUMMARY, DISCUSSION, AND CONCLUSIONS

4.1 Program Summary

In this study, static load-deflection response and the resulting static principal strains on the skulls of two monkeys and one human cadaver were obtained. Techniques for attaching strain gages to moist bone and measuring small skull deflection were developed, along with a method for referencing loading points, gage locations, and deflection locations.

Thirty-nine live sub-human primate head impacts and two human cadaver head impacts were conducted. Techniques for measuring epidural pressure during impact, strains on the skull, and placement of six accelerometers on the skull were developed. Computer routines for obtaining three linear accelerations and three rotational accelerations of the skull during impact were developed along with digitizing and filtering routines. All of the details of these routines along with validation of the program are given in Appendix A.

Detailed autopsy on the head for each test was obtained; also, injury scaling, using the AIS, was given for all head impacts.

4.2 Discussion

4.2.1 3-D Motion Analysis. It was shown that the 6-accelerometer technique used in this study was useful and accurate when physical limitations are imposed on an experiment.

The method is accurate enough for many short- and long-duration applications but the stability of the method depends largely on the accuracy of the measurements made and the type of motion being analyzed. The truncation errors due to the finite length of a computer word, and the round-off errors in evaluating numerical integrals and natural function, were found to be negligible compared to other errors. Other errors which were found to be significant were experimental uncertainties such as the resolution of the accelerometers, their cross-axis sensitivities, mounting and orientation errors.

Additional (redundant) measurement is recommended to minimize the errors of computation and measurement, and to counteract the instability of the integration. The most appropriate method would appear to be one using nine accelerometers.

4.2.2 Epidural Pressures and Brain Injury. For many years the mechanism for the contre-coup injury has been debated (See References 2-7). Many researchers feel that the injury is caused by either the brain rotating in the skull and impacting one of the many protrusions on the interior surface of the skull or the brain being slapped by a bending wave in the skull. Others postulate the injury is caused by cavitation. Although brain rotation and skull bending may cause some injuries, it does not account for many contre-coup injuries observed. In the tests reported here, two contre-coup injuries were observed. Tests 003 and 085 both produced contre-coup injuries on the top tip of the frontal lobe. Rotation of this tip downward is virtually impossible because of the orbital plate, and bending of the skull at this point would be extremely difficult because of the very thick forehead bones of the monkey. Many of the cavitation theories speculate that the injuries occur by the collapse of tissue from vaporization of that tissue. The negative pressure levels necessary to vaporize water are in the thousands of KPa. From our tests, severe injuries occur when pressures of only 70 to 90 KPa are encountered. This type of injury is highly localized with small petechiae (hemorrhages) radiating from the center of the injury. From sections and slides, the petechial injuries appear to be closed spherical eruptions.

Dissolved gases in the brain would be relatively easy to expand at very low values of negative pressure. That is, at negative pressures at or close to one atmosphere (~ 100 KPa) the gas bubbles in the brain would expand their size, rupture the tissue, and then shrink away after the impact. This phenomenon can be readily seen on the walls of a syringe when filling it with a viscous fluid and a small-gage needle.

Pressure pulses in head impacts are the results of two major components. The first is strain waves in the skull bone and brain tissue. This effect is of very short time duration (10^{-5} sec.). All impacts consist of both components. In rigid impacts the former mechanisms may play a relatively greater role in producing contre-coup injury, while in padded impacts the latter effect may predominate. Higher velocity levels are associated with padded-injury-producing impacts.

4.2.3 Error Analysis There were many possible sources of errors in this study. The skulls were found to be assymetrical, leading to variations in strain gage readings. The inability to conduct perfect axial impacts due to skull surface irregularities led to skull accelerations which were not always perfectly correlated with the direction of impacts.

In some tests air may have been entrapped between the pressure transducers and the brain, causing loss of a conducting medium. This happened during or after impact. The major cause of errors in the rigid-body motion analysis was vibration, both of the skull and the mounts. This vibration was filtered but still influenced the rigid-body motion analysis.

Significant brain injuries were introduced by the surgical techniques in some cases. And just the presence of the instrumentation during impact did lead to artificial injuries. These artifacts were not used in the injury scaling where possible. But in most cases, instrumentation injuries were in the scaling.

All of the possible errors were minimized as much as possible, and it is believed that the results of these tests are meaningful for most analytical work if the user understands the possible errors and their origins.

4.3 Conclusions and Recommendations

This project has shown that:

1. Epidural pressure during impact can be measured.
2. Rigid-body head motion can be obtained using six accelerometers.
3. The skull can be strain gaged for live head impacts and principal strains obtained during impact.

4. The skull of most primates is not symmetrical.

Based on the results of this project, the following recommendations are made:

1. More development is needed on techniques for measurement of impact parameters without causing skull or brain damage.

2. Nine head accelerometers instead of six for rigid-body analysis is desirable.

3. More impacts with more epidural pressure measurement points are needed to obtain a better understanding of the pressure field in the skull during impact.

4. More detailed medical data before and after impact (blood chemistry, EEG's, EKG's, etc.) would be desirable.

5.0 REFERENCES

1. Stalnaker, R. L., Mohan, D. and Melvin, J. W., "A Head Injury Evaluation: Criteria for Assessment of Field, Clinical, and Laboratory Data," Proceedings of the 19th Conference of the American Association for Automotive Medicine, San Diego, California, November 17-21, 1975.

2. Ommaya, A. K., Crubb, R. L., Jr. and Naumann, R. A., "Observation on the Mechanics of Visible Brain Injuries in the Rhesus Monkey," J. Neurosurgery 35, 503-516, 1971.

3. Unterharnscheidt, F. and Sellier, K., "Head Injury Conference Proceedings," edited by W. F. Caveness and A. E. Walker, p. 321, Lippencott, Philadelphia, 1966.

4. Unterharnscheidt, F. J. and Ripperger, E. A., "Dynamic Response of Biomechanical Systems," edited by N. Perrone, p. 46, ASME, New York.

5. Gross, A. G., "A New Theory on the Dynamics of Concussion and Brain Injury," J. Neurosurgery, 15: 548-561, 1958.

6. Gross, A. G., "Impact Thresholds of Brain Concussion," Aviation Med. 29, 548-561, 1958.

7. Kenner, V. H., Goldsmith, W., "Impact on a Simple Physical Model of the Head," J. Biomechanics, 6: 1-11, 1973.

APPENDIX A

DATA PROCESSING

APPENDIX A-1

THREE DIMENSIONAL MOTION MEASUREMENT

A.1 VALIDATION OF MINIMUM-INPUT 3-D MOTION MEASUREMENT

The six-accelerometer method for measuring a general three-dimensional motion is validated using hypothetical and experimental acceleration readings. Results show that the 2-2-2 combination of accelerometers prove to be stable for the durations of the tested motions. Small deviations result from truncation and round-off errors, but considerably larger errors result from the calibration of accelerometers and from the uncertainties in measuring other physical quantities required for the analysis. The effect of both types of errors is cumulative, increasing the instability of integration. The use of additional (redundant) measures is therefore recommended.

A.1.1 3-D Rigid Body Motion Measurement

A.1.1.1 Kinematic Equations - The general 3-D motion of the rigid body, shown in Figure 1, can be described with kinematic equations which determine its six degrees of freedom at any instant of time.

Let P be the origin of an instrumentation frame $(\hat{e}_1,\hat{e}_2,\hat{e}_3)$ which is embedded in the rigid body. Let O be a fixed point in space and the origin of an inertial reference frame $(\hat{I},\hat{J},\hat{K})$.

Consider a body-point Q_1, embedded in the rigid body such that $\vec{\rho}_1 = \overrightarrow{PQ_1}$ and let $\vec{R} = \overrightarrow{OP}$ be the position vector of the moving origin P. The position vector of point Q_1 with respect to the inertial space is then:

$$\vec{r}_1 = \overrightarrow{OQ_1} = \vec{R} + \vec{\rho}_1 \qquad (1)$$

the velocity and acceleration vectors of Q_1 are

$$\dot{\vec{r}} = \dot{\vec{R}} + \vec{\omega} \times \vec{\rho}_1 \qquad (2)$$

and

$$\ddot{\vec{r}} = \ddot{\vec{R}} + \dot{\vec{\omega}} \times \vec{\rho}_1 + \vec{\omega} \times (\vec{\omega} \times \vec{\rho}_1) \qquad (3)$$

Equation (3) may be rewritten as 3 scalar equations by expressing each vector in any desired cartesian frame. The most convenient one is the moving reference frame $(\hat{e}_1,\hat{e}_2,\hat{e}_3)$. Thus,

$$\ddot{\vec{r}}_1 = a_{11}\,\hat{e}_1 + a_{21}\,\hat{e}_2 + a_{31}\,\hat{e}_3 \tag{4}$$

$$\ddot{R} = A_1\,\hat{e}_1 + A_2\,\hat{e}_2 + A_3\,\hat{e}_3 \tag{5}$$

$$\vec{\rho}_1 = \rho_{11}\,\hat{e}_1 + \rho_{21}\,\hat{e}_2 + \rho_{31}\,\hat{e}_3 \tag{6}$$

$$\vec{\omega} = \omega_1\,\hat{e}_1 + \omega_2\,\hat{e}_2 + \omega_3\,\hat{e}_3 \tag{7}$$

$$\dot{\vec{\omega}} = \dot{\omega}_1\,\hat{e}_1 + \dot{\omega}_2\,\hat{e}_2 + \dot{\omega}_3\,\hat{e}_3 \tag{8}$$

Two additional points Q_2 and Q_3 such that:

$$\ddot{\vec{r}}_2 = a_{12}\,\hat{e}_1 + a_{22}\,\hat{e}_2 + a_{32}\,\hat{e}_3 \tag{9}$$

$$\ddot{\vec{r}}_3 = a_{13}\,\hat{e}_1 + a_{23}\,\hat{e}_1 + a_{33}\,\hat{e}_3 \tag{10}$$

and

$$\vec{\rho}_2 = \rho_{21}\,\hat{e}_1 + \rho_{22}\,\hat{e}_2 + \rho_{32}\,\hat{e}_3 \tag{11}$$

$$\vec{\rho}_3 = \rho_{13}\,\hat{e}_1 + \rho_{23}\,\hat{e}_2 + \rho_{33}\,\hat{e}_3 \tag{12}$$

may be added to the rigid body so that equation (3) may be written for Q_2 and Q_3 as:

$$\ddot{\vec{r}}_2 = \ddot{R} + \dot{\vec{\omega}} \times \vec{\rho}_2 + \vec{\omega} \times (\vec{\omega} \times \vec{\rho}_2) \tag{13}$$

$$\ddot{\vec{r}}_3 = \ddot{R} + \dot{\vec{\omega}} \times \vec{\rho}_3 + \vec{\omega} \times (\vec{\omega} \times \vec{\rho}_3) \tag{14}$$

Using equations (4) through (12), equations (3), (13) and (14) may be broken down into 9 scalar equations which contain 9 accelerations (which can be measured with linear accelerometers) and 3 unknown components of each of $\vec{R}$, $\dot{\vec{\omega}}$ and $\vec{\omega}$.

These equations are generally simplified if the 3 points, Q_1, Q_2, Q_3 are chosen on the instrumentation axes $\hat{e}_1$, $\hat{e}_2$, $\hat{e}_3$, respectively. Thus the expressions for $\vec{\rho}_1$, $\vec{\rho}_2$ and $\vec{\rho}_3$ become:

$$\vec{\rho}_1 = \rho_1\,\hat{e}_1 \tag{15}$$

$$\vec{\rho}_2 = \rho_2\,\hat{e}_2 \tag{16}$$

$$\vec{\rho}_3 = \rho_3\,\hat{e}_3 \tag{17}$$

and the 9 scalar equations become:

$$a_{11} = A_1 - \rho_1(\omega_2^2 + \omega_3^2) \tag{18}$$

$$a_{21} = A_2 + \rho_1(\dot{\omega}_3 + \omega_1\omega_2) \tag{19}$$

$$a_{31} = A_3 - \rho_1(\dot{\omega}_2 - \omega_3\omega_1) \tag{20}$$

$$a_{12} = A_1 - \rho_2(\dot{\omega}_3 - \omega_1\omega_2) \tag{21}$$

$$a_{22} = A_2 - \rho_2(\omega_3^2 + \omega_1^2) \tag{22}$$

$$a_{32} = A_3 + \rho_2(\dot{\omega}_1 + \omega_2\omega_3) \tag{23}$$

$$a_{13} = A_1 + \rho_3(\dot{\omega}_2 + \omega_3\omega_1) \tag{24}$$

$$a_{23} = A_2 + \rho_3(\dot{\omega}_1 - \omega_2\omega_3) \tag{25}$$

$$a_{33} = A_3 + \rho_3(\omega_1^2 + \omega_2^2) \tag{26}$$

A.1.1.2 Minimum-Input Method - There are several methods which have been suggested to deal with the 9 equations (18) through (26). A method which has been adopted at HSRI requires a minimum number of input acceleration readings. Although all the minimum-input methods are proven to be mathematically unstable, the HSRI method presented here has shown a limited successful applicability.

To simplify the problem, equations (18), (22) and (26) are disregarded because they are redundant, and because they do not contain components of the angular acceleration vector. This result in 6 equations and 6 unknowns which are the components of $\ddot{R}$ and $\dot{\vec{\omega}}$, ($\vec{\omega}$ is not an unknown since it is the integral of $\dot{\vec{\omega}}$.) The required acceleration readings become what is termed the 2-2-2 combination of uniaxial accelerometers.

After some lengthy manipulations, the remaining six equations (19, 20, 21, 23, 24, 25) are partially uncoupled to yield the two sets of equations. The first is a set of 3 coupled, nonlinear, simultaneous, first order differential equations in $\dot{\omega}_1$, $\dot{\omega}_2$ and $\dot{\omega}_3$:

$$\begin{Bmatrix} \dot{\omega}_1 \\ \dot{\omega}_2 \\ \dot{\omega}_3 \end{Bmatrix} = [S] \begin{Bmatrix} \frac{a_{12}-a_{13}}{2} \\ \frac{a_{23}-a_{21}}{2} \\ \frac{a_{31}-a_{32}}{2} \end{Bmatrix} + [T] \begin{Bmatrix} \omega_2\omega_3 \\ \omega_3\omega_1 \\ \omega_1\omega_2 \end{Bmatrix} \tag{27}$$

where

$$[S] = \begin{bmatrix} \frac{\rho_1}{\rho_2\rho_2} & -\frac{1}{\rho_3} & -\frac{1}{\rho_2} \\ -\frac{1}{\rho_3} & \frac{\rho_2}{\rho_1\rho_3} & -\frac{1}{\rho_1} \\ -\frac{1}{\rho_2} & -\frac{1}{\rho_1} & \frac{\rho_3}{\rho_1\rho_2} \end{bmatrix} \quad (28)$$

and

$$[T] = \begin{bmatrix} 0 & \frac{\rho_1}{\rho_2} & -\frac{\rho_1}{\rho_3} \\ -\frac{\rho_2}{\rho_1} & 0 & \frac{\rho_2}{\rho_3} \\ \frac{\rho_3}{\rho_1} & -\frac{\rho_3}{\rho_2} & 0 \end{bmatrix} \quad (29)$$

The other is a set of 3 uncoupled algebraic equations in the 3 components of R:

$$\begin{Bmatrix} A_1 \\ A_2 \\ A_3 \end{Bmatrix} = \begin{Bmatrix} \frac{a_{12}+a_{13}}{2} \\ \frac{a_{21}+a_{23}}{2} \\ \frac{a_{32}+a_{31}}{2} \end{Bmatrix} + [F] \begin{Bmatrix} \frac{a_{12}-a_{13}}{2} \\ \frac{a_{23}-a_{21}}{2} \\ \frac{a_{31}-a_{32}}{2} \end{Bmatrix} + [G] \begin{Bmatrix} \omega_2\omega_3 \\ \omega_3\omega_1 \\ \omega_1\omega_2 \end{Bmatrix} \quad (30)$$

where

$$[F] = \begin{bmatrix} 0 & -\frac{\rho_2}{\rho_1} & \frac{\rho_3}{\rho_1} \\ \frac{\rho_1}{\rho_2} & 0 & -\frac{\rho_3}{\rho_2} \\ -\frac{\rho_1}{\rho_3} & \frac{\rho_2}{\rho_3} & 0 \end{bmatrix} \quad (31)$$

and

$$[G] = \begin{bmatrix} \frac{\rho_2\rho_3}{\rho_1} & -\rho_3 & -\rho_2 \\ -\rho_3 & \frac{\rho_3\rho_1}{\rho_2} & -\rho_1 \\ -\rho_2 & -\rho_1 & \frac{\rho_1\rho_2}{\rho_3} \end{bmatrix} \qquad (32)$$

The forms of equations (27) and (30) are readily programmable since the matrices [S], [T], [F], and [G] are constant throughout the integration period. It can be shown mathematically that equations (27) are unstable. However, limited success was encountered where the integration is carried out up to a certain point, after which errors grow exponentially causing the integration to "blow up."

The integration is the first step toward a complete solution, after which equations (30) may be solved, then subsequent integrations and transformations lead to the final step of obtaining the three rotations- and three translations- time histories in inertial space.

A.1.1.3 Motion in Inertial Space

The angular acceleration and velocity vectors expressed in the anatomical frame are:

$$\dot{\vec{\omega}} = \dot{\omega}_1 \hat{i} + \dot{\omega}_2 \hat{j} + \dot{\omega}_3 \hat{k} \qquad (33)$$

$$\vec{\omega} = \omega_1 \hat{i} + \omega_2 \hat{j} + \omega_3 \hat{k} \qquad (34)$$

Since the acceleration readings were directly employed in the solution, $\dot{\vec{\omega}}$ and $\vec{\omega}$ are expressed in the instrumentation frame $(\hat{e}_1, \hat{e}_2, \hat{e}_3)$, and must be transformed to anatomical frame $(\hat{i}, \hat{j}, \hat{k})$.

$$[\dot{\omega}] = [\dot{\omega}] \ [E] \qquad (35)$$

$$[\omega] = [\omega] \ [E] \qquad (36)$$

where [E] is defined by

$$\begin{Bmatrix} \hat{e}_1 \\ \hat{e}_2 \\ \hat{e}_3 \end{Bmatrix} = [E] \begin{Bmatrix} \hat{i} \\ \hat{j} \\ \hat{k} \end{Bmatrix} \qquad (37)$$

The constant transformation matrix [E] must be known. A technique was developed to obtain [E] using two orthogonal x-rays of the head and is described in detail in Appendix A2.

The next step in obtaining a complete solution is to determine the orientation of the rigid body in inertial frame. This is defined by the Euler matrix [D]:

$$[D] = \begin{bmatrix} \cos\psi\cos\theta & \sin\psi\cos\theta & -\sin\theta \\ \cos\psi\sin\theta\sin\phi - \sin\psi\cos\phi & \cos\psi\cos\phi + \sin\psi\sin\theta\sin\phi & \cos\theta\sin\phi \\ \sin\psi\sin\phi + \cos\psi\sin\theta\cos\phi & -\cos\psi\sin\phi + \sin\psi\sin\theta\cos\phi & \cos\theta\cos\phi \end{bmatrix} \quad (38)$$

The three Euler angles, yaw (ψ), pitch (θ) and roll (ϕ) are defined as follows. Assume that initially, the rigid body's anatomical axes ($\hat{i},\hat{j},\hat{k}$) coincides with the inertial frame ($\hat{I},\hat{J},\hat{K}$). Then, yaw is defined as a positive rotation of magnitude ψ about the $\hat{k}$-axis, resulting in an intermediate frame ($\hat{i}^*,\hat{j}^*,\hat{k}^*$). Next is pitch which is defined as a positive rotation of magnitude θ about the new $\hat{j}^*$-axis, resulting in a second intermediate frame ($\hat{i}^{**},\hat{j}^{**},\hat{k}^{**}$). Finally, the roll is defined as a positive rotation ϕ about the newest $\hat{i}^{**}$-axis, resulting in the desired frame ($\hat{i},\hat{j},\hat{k}$). Therefore, the orientation of the anatomical frame in inertial space can completely be defined by specifying 3 ordered independent rotations called the Euler angles.

It can be shown from the definition of the Euler angles that the angular velocity vector is the sum of three angular rates:

$$\vec{\omega} = \vec{\dot{\psi}} + \vec{\dot{\theta}} + \vec{\dot{\phi}} \quad (39)$$

This is true even though the 3 vectors $\vec{\dot{\psi}}$, $\vec{\dot{\theta}}$, and $\vec{\dot{\phi}}$ are not, in general, mutually orthogonal. Equation 39 may be projected on each of the anatomical axes so that

$$\omega_1 = \text{proj}[\vec{\dot{\psi}} + \vec{\dot{\theta}} + \vec{\dot{\phi}}] \text{ on } \hat{i} \qquad (40)$$

$$\omega_2 = \text{proj}[\vec{\dot{\psi}} + \vec{\dot{\theta}} + \vec{\dot{\phi}}] \text{ on } \hat{j} \qquad (41)$$

$$\omega_3 = \text{proj}[\vec{\dot{\psi}} + \vec{\dot{\theta}} + \vec{\dot{\phi}}] \text{ on } \hat{k}$$

or

$$\omega_1 = \dot{\phi} - \dot{\psi}\sin\theta \qquad (43)$$

$$\omega_2 = \dot{\theta}\cos\phi + \dot{\psi}\cos\theta\sin\phi \qquad (44)$$

$$\omega_3 = \dot{\psi}\cos\theta\cos\phi - \dot{\theta}\sin\phi \qquad (45)$$

Since ω_1, ω_2 and ω_3 are known at this stage, equations (43),(44), and (45) may be solved for the Euler angular rates:

$$\begin{Bmatrix} \dot{\psi} \\ \dot{\theta} \\ \dot{\phi} \end{Bmatrix} = \frac{1}{\cos\theta} \begin{bmatrix} 0 & \sin\phi & \cos\phi \\ 0 & \cos\phi & -\sin\phi \\ 1 & \sin\phi\sin\theta & \cos\phi\sin\theta \end{bmatrix} \begin{Bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{Bmatrix} \qquad (46)$$

The Euler angular rates are therefore defined except when $\theta = \pm 90°$. This case, known as the "Gimbal lock," can be avoided by switching to another set of Euler angles. However, a numerical procedure was improvised for this case to deal with this problem without switching Euler set, and has been satisfactory.

Equation (46) can be integrated to obtain the Euler angles as functions of time, which are used in determining the transformation matrix [D] at each instant of time.

After determining the 3 rotational degrees of freedom, the 3 translational degrees of freedom are to be computed. These are defined as the acceleration, velocity and position vectors of a body-point in inertial frame. To this end, the motion of a convenient reference point must be known. Depending on the method used, this point may the the origin C of the anatomical frame, or the centroid Q_0 of Q_1, Q_2, Q_3, whose location in the anatomical frame is known. Also, the location of the body-point in the body-frame is assumed to be known. This may be the center of mass of the head, or any other point of interest. Then,

$$\ddot{\vec{r}}_B = \ddot{R} + \dot{\vec{\omega}} \times \vec{\rho}_B + \vec{\omega} \times (\vec{\omega} \times \vec{\rho}_B) \tag{47}$$

where $\vec{\rho}_B$ is the position vector of B (body-point) in the anatomical frame, $\ddot{R}$ is the acceleration vector of the reference point obtained as the algebraic average of the 3 triaxial readings (if Q_0 is used) or obtained with equation (30) if the origin C is used.

Now given the acceleration of B in anatomical $(\hat{i},\hat{j},\hat{k})$, and given the Euler transformation matrix, the absolute acceleration vector of B may be expressed in the inertial frame:

$$\ddot{\vec{r}}_B = \ddot{X}\,\hat{I} + \ddot{Y}\,\hat{J} + \ddot{Z}\,\hat{K} \tag{48}$$

Finally, $\ddot{X}(t)$, $\ddot{Y}(t)$, $\ddot{Z}(t)$ are integrated independently to yield the velocities $\dot{X}(t)$, $\dot{Y}(t)$ and $\dot{Z}(t)$, then integrated again to obtain the three translational degrees of freedom X(t), Y(t), Z(t).

A computer program was written to analyze the 3-D motion under these conditions. It requires the knowledge of the following:

1. three distances ρ_1, ρ_2 and ρ_3,
2. six acceleration readings a_{21}, a_{31}, a_{32}, a_{12}, a_{13}, a_{23},
3. the Euler matrix of $(\hat{e}_1,\hat{e}_2,\hat{e}_3)$ relative to $(\hat{i},\hat{j},\hat{k})$,
4. the location of P in the $(\hat{i},\hat{j},\hat{k})$ frame,
5. the location of a body point (e.g., center of mass) in the $(\hat{i},\hat{j},\hat{k})$ frame,
6. four sets of initial conditions: initial angular velocities along $(\hat{e}_1,\hat{e}_2,\hat{e}_3)$, initial Euler angles, initial velocity, initial position of the body point.

The program produces then the following outputs:

1. Angular accelerations and velocity in the $(\hat{i},\hat{j},\hat{k})$,
2. the Euler angular rates and Euler angles relative to the inertial frame $(\hat{I},\hat{J},\hat{K})$,
3. the translational acceleration vector, of the given body-point expressed in the anatomical $(\hat{i},\hat{j},\hat{k})$ and the inertial $(\hat{I},\hat{J},\hat{K})$ frames,
4. the velocity and position vectors of the given body point in the inertial frame.

A.1.2 Hypothetical Motion

The six degrees of freedom of motion are prescribed with the mathematical function:

$$S(t) = S_m[\sin 2\pi f_1 t - \sin 2\pi f_2 t]$$

which has a velocity (1st time-derivative):

$$\dot{S}(t) = 2\pi S_m[f_1 \cos 2\pi f_1 t - f_2 \cos 2\pi f_2 t]$$

and an acceleration (2nd time-derivative)

$$\ddot{S}(t) = -4\pi^2 S_m[f_1^2 \sin 2\pi f_1 t - f_2^2 \sin 2\pi f_2 t]$$

by selecting (S_m, f_1,f_2) for each of the degrees of freedom, and by specifying the location of Q_1, Q_2, Q_3, the acceleration "readings" at these points may be computed, along with the intermediate motion variables which will later be compared to the various output of the 3-D analysis program.

Several tests were conducted successfully, but only test HYP-81 will be presented. The duration of the test was 11.56 milliseconds, and data was sampled at the rate of 25 KHz resulting in 288 reading samples.

The six degrees of freedom for the motion were specified according to the following table:

	S_m	f_1(Hz)	f_2(Hz)
x(t):	0.5 inches	250.	20.
y(t):	0.1 inches	100.	300.
z(t):	1.25 inches	0.	150.
ψ(t):	2.0 degrees	80.	100.
θ(t):	40.0 degrees	40.	5.
ϕ(t):	5.0 degrees	50.	150.

In addition,

$$PQ_1 = \rho_1 = 2.0 \text{ inches}$$

$$PQ_2 = \rho_2 = 1.6 \text{ inches}$$

$$PQ_3 = \rho_3 = 2.5 \text{ inches}$$

and without loss of generality, the instrumentation frame $(\hat{e}_1, \hat{e}_2, \hat{e}_3)$ was selected to coincide with the "anatomical" frame $(\hat{i}, \hat{j}, \hat{k})$, and the body point for which the translational vectors will be computed, was selected to be the origin of the anatomical frame.

A.1.3 Comparison of Theoretical and Computed Motion

The 6 acceleration "readings" shown in Figure 3 were analyzed. The results, shown in figures 4, 6, 8, and 10, were compared to the theoretical values and the deviations plotted in figures 5, 7, 9, and 11.

The deviations of the angular accelerations were of the order of 5.0 rad/sec^2 over magnitudes of the order of 5.0 x 10^4 rad/sec^2. Therefore, the accuracy of angular accelerations is of the order of 0.01%. Similar reasoning leads to determine an accuracy of 0.01% for angular velocities.

The Euler angles and rates had a relative error, or accuracy of 0.001% for rates and 0.01% for angles.

The translational accelerations had an accuracy of 0.001%, whereas both velocity and positions were accurate to within 0.1%.

From a qualitative point of view, it may be observed that the error on most of the variables increase as the integration is prolonged. This may be attributed to truncation errors in the readings that were inputted and to the round-off errors of the evaluation of natural functions and the integrals. This aggrevates the inherent instability of the system of equations being integrated.

A.1.4 Experimental Motion

The motion was experimentally generated with an electromagnetic shaker. A monkey's skull (figure 12 and 13) was instrumented with 6 accelerometers (2-2-2) combination at 3 points.

The relationship between the instrumentation origin P and reference frame $(\hat{e}_1, \hat{e}_2, \hat{e}_3)$ on one hand and the anatomical center C and reference frame $(\hat{i}, \hat{j}, \hat{k})$ on the other hand, as well as the initial orientation of the anatomical frame relative to the inertial (shaker) reference frame, were all determined with an x-ray technique developed for this purpose, and described in section A.2.

The following measurements were found:

$$\rho_1 = 2.552 \qquad \rho_2 = 2.427 \qquad \rho_3 = 2.505$$

$$CP = 0.623\,\hat{i} - 0.459\,\hat{j} + 3.172\,\hat{k}$$

$$\begin{Bmatrix} \hat{e}_1 \\ \hat{e}_2 \\ \hat{e}_3 \end{Bmatrix} = \begin{bmatrix} -.48080 & -.59844 & -.64086 \\ -.36301 & 0.80116 & -.47578 \\ 0.79816 & 0.00389 & -.60243 \end{bmatrix} \times \begin{matrix} \hat{i} \\ \hat{j} \\ \hat{k} \end{matrix}$$

and the initial orientation of the anatomical frame with respect to inertial [shaker] frame:

$$\psi(0) = 2. \qquad \theta(0) = -12. \qquad \phi = -25. \text{ degrees}$$

The six accelerometers were all ENDEVCO uniaxial ones, and their signals were calibrated and amplified properly then recorded on a Honeywell 7600 FM tape recorder. The only motion variable which was directly recorded was the vertical (inertial $\hat{K}$) acceleration of the skull. This signal was to be compared to the computed component of the inertial translational acceleration of the anatomical center.

The unfiltered data, shown in Figure 14, was digitized then digitially filtered using a low-pass filter. The digital filter had a pass-band from 0 to 200 Hz (gain ripple under 0.50 dB), a gain drop of -6 dB at 275 Hz, and a stop-band from 500 Hz and up, with a gain of -120 dB. The filtered data is shown in figures 15, and 16.

The rigid-body motion analysis was carried out for the 6-acceleration input and results are shown in figures 17, 18, 19 and 20.

A.1.5 Comparison of Experimental and Computed Motions

The only direct measurement which was made was the acceleration along the shaker vertical axis (inertial $\hat{K}$), shown in Figure 18. This should be identical to the top graph of figure 19. Results show that the error in this computation was about 1.5%. It is worth noting that although no motion in the lateral (inertial $\hat{I}$ and $\hat{J}$) directions was supposed to be taking place, the computed non-zero accelerations in these directions may be attributed to small lateral vibrations of the shaker in these directions, and to unequal accuracies of calibrations of each pair of accelerometers pointing in the same direction. This error in calibration results in slightly different readings of the same acceleration, which leads to an apparent rotation. This, in turn, adds a "rotational" component to the various quantities during the computational procedure.

A.1.6 Conclusions

It was shown that in many cases, two of which were presented in this paper, that a 6-accelerometer technique would be useful and accurate and could be successfully used when physical limitations are imposed on the experimental set-up.

The method is accurate enough for many short- and long-duration applications but the success of the method depends largely on the accuracy of the measurements made and the duration and type of motion being analyzed.

The truncation errors due to the finite length of a computer word and the round-off errors in evaluating numerical integrals and natural functions, were found to be negligible compared to other errors.

Other significant sources of errors were found to be experimental uncertainties such as the resolution of accelerometers, their cross-axis sensitivities, mounting and orientation errors.

Additional (redundant) measurement is recommended to minimize the errors of computation and measurement, and to circumvent the instability of the integration.

A.1.7 References

1. Melvin, J. W., J. B. Benson, and N. M. Alem, "Whole Body Response Research Program," First Year Final Report, Highway Safety Research Institute, Ann Arbor, 1975.

2. Padgaonkar, A. J., K. N. Krieger and A. I. King, "Measurement of Acceleration of Rigid Body Using Linear Accelerometers," ASME Paper No. 75-APMB-3, 1975.

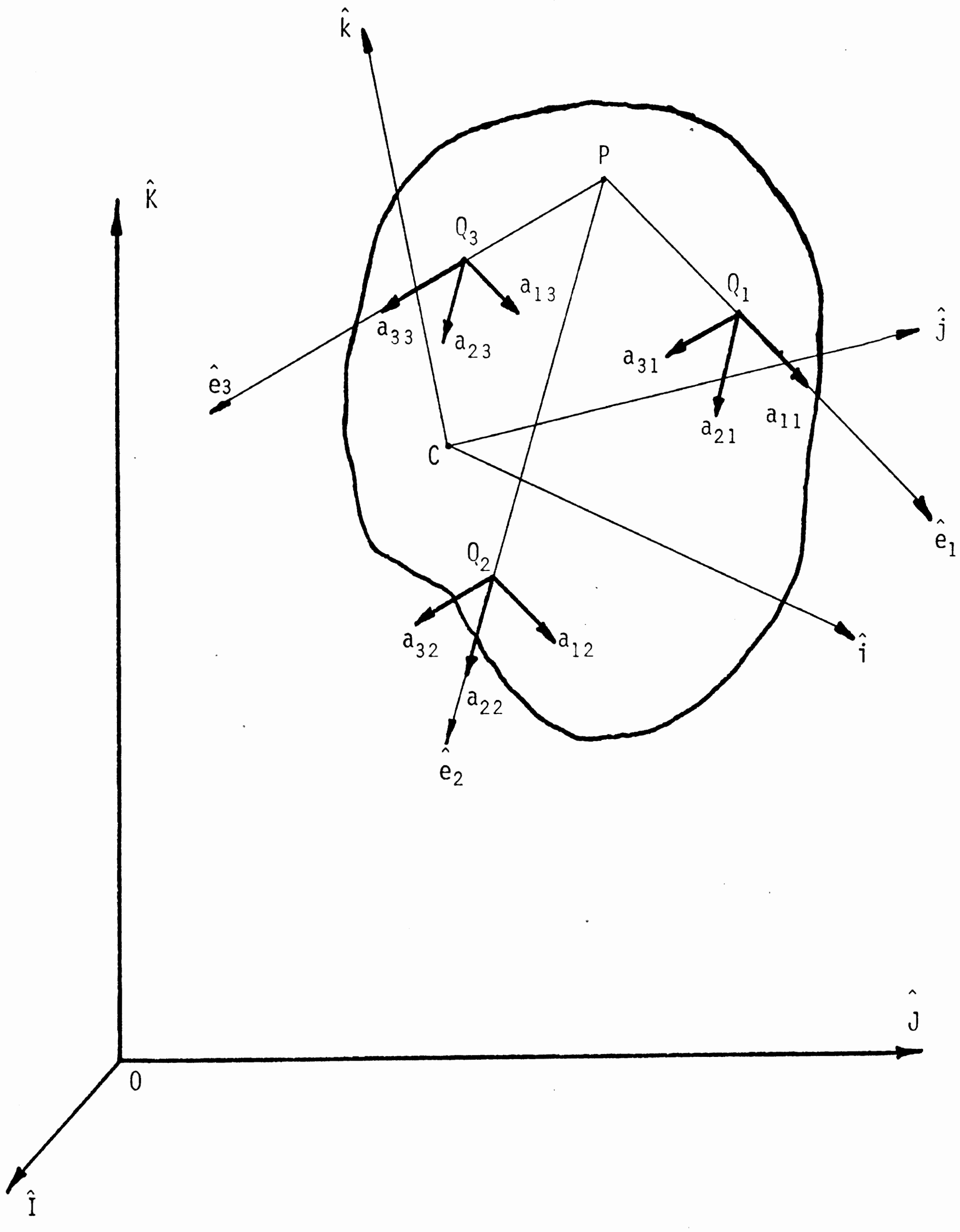
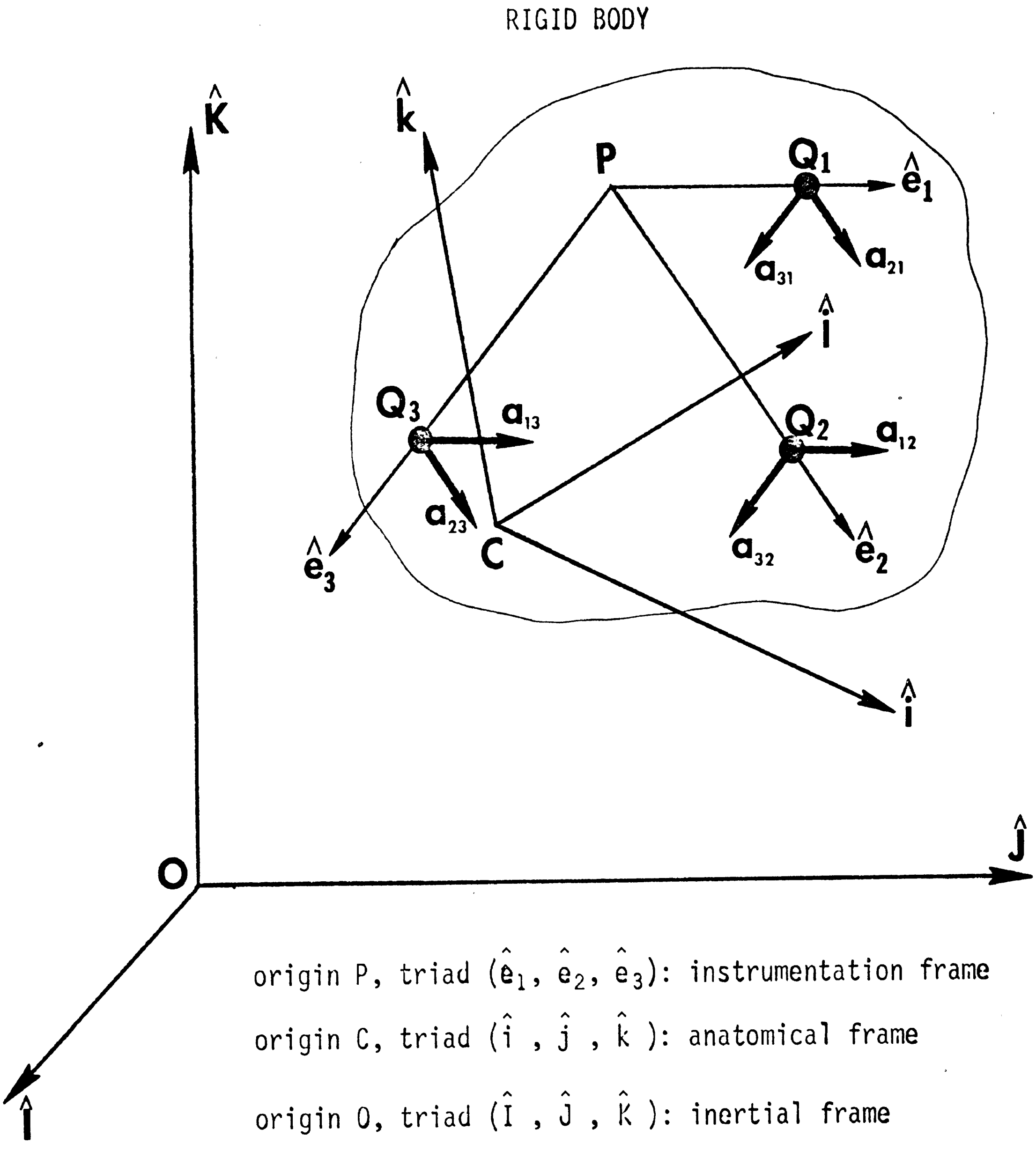


FIGURE 1. RIGID BODY COORDINATE SYSTEMS



origin P, triad ($\hat{e}_1$, $\hat{e}_2$, $\hat{e}_3$): instrumentation frame

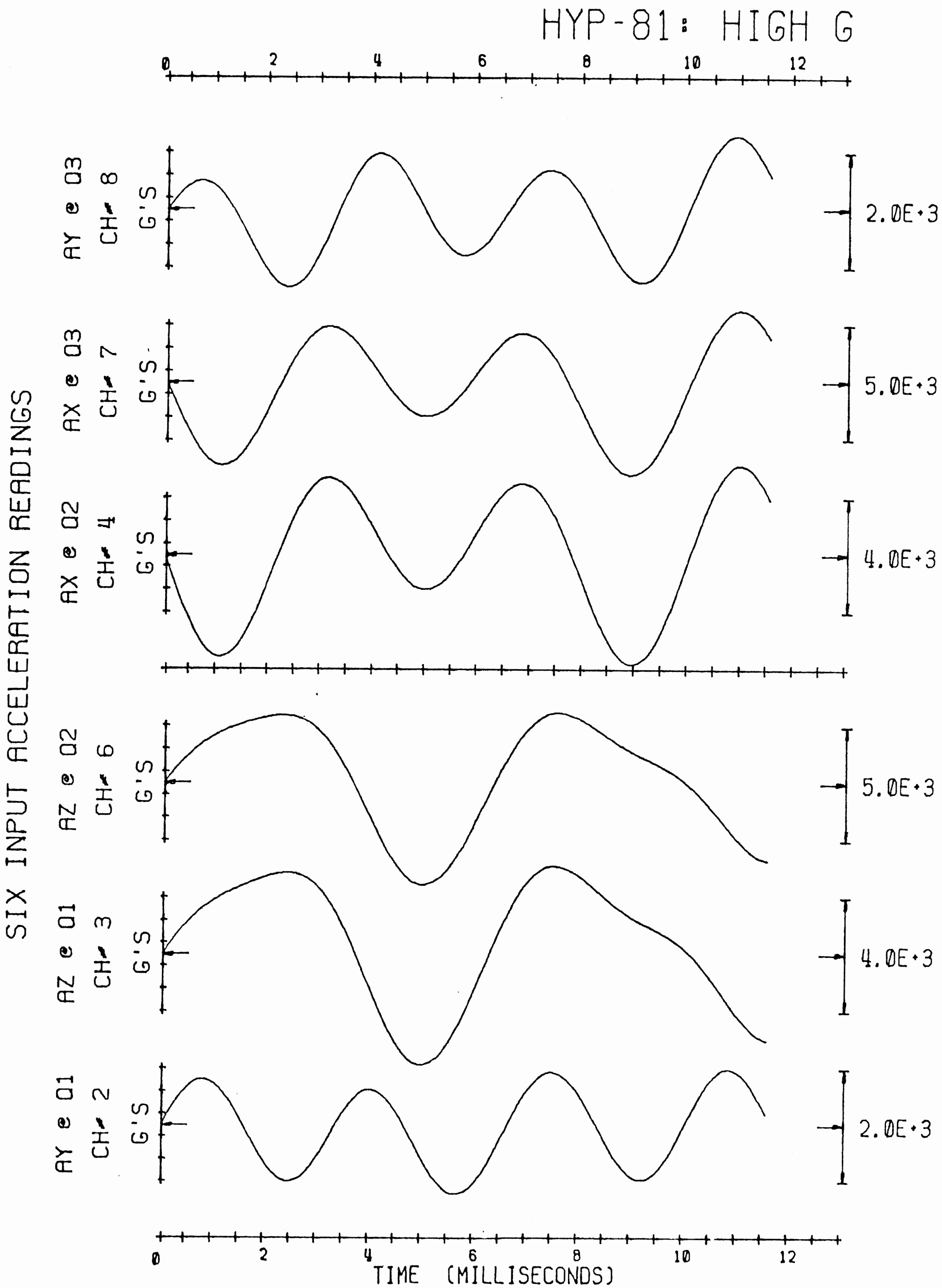
origin C, triad ($\hat{i}$, $\hat{j}$, $\hat{k}$): anatomical frame

origin O, triad ($\hat{I}$, $\hat{J}$, $\hat{K}$): inertial frame

Q_1, Q_2, Q_3: Location of three biaxial accelerometers

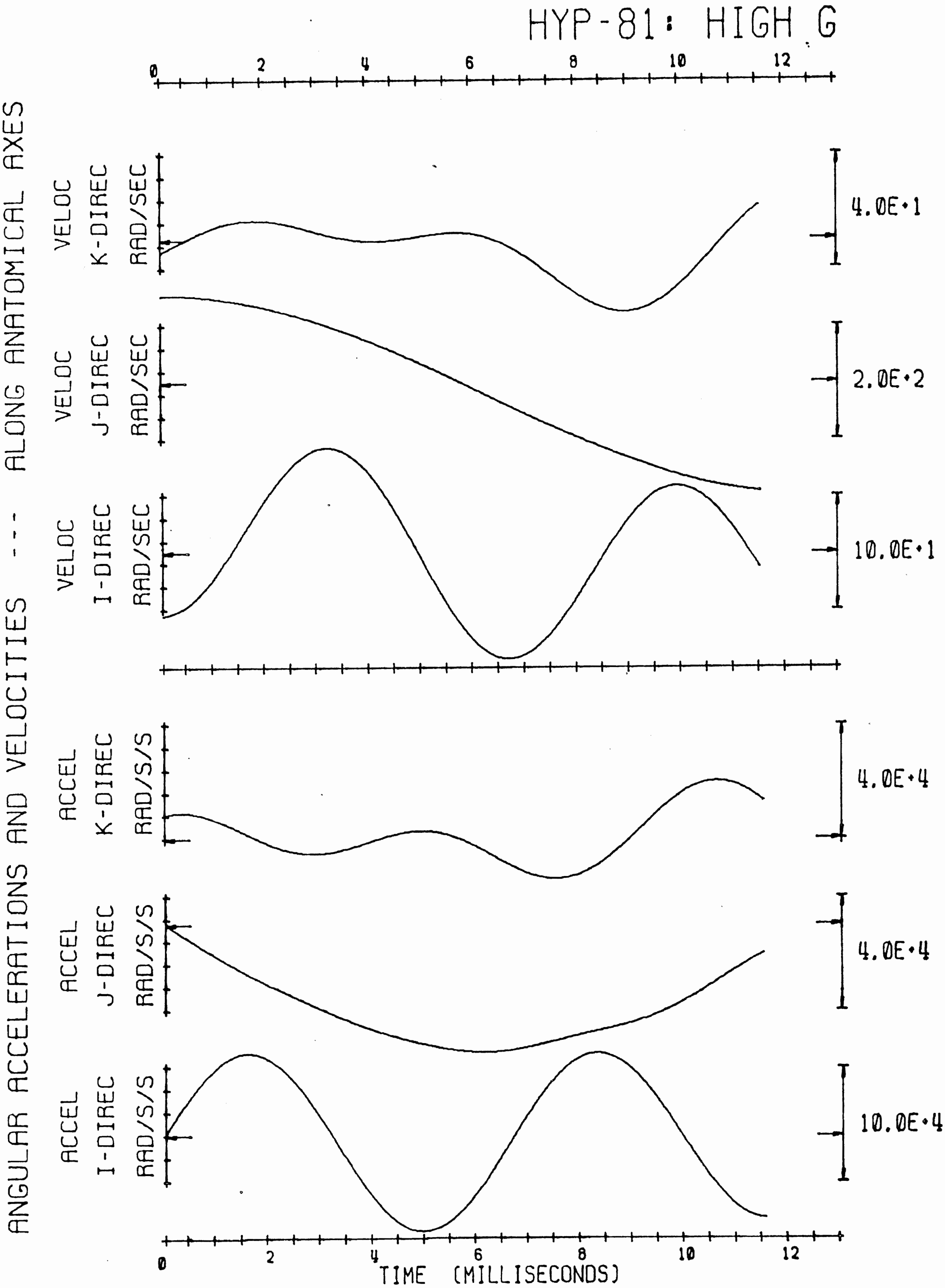
DEFINITION OF COORDINATES FRAMES FOR 3-D RIGID-BODY MOTION

Figure 2



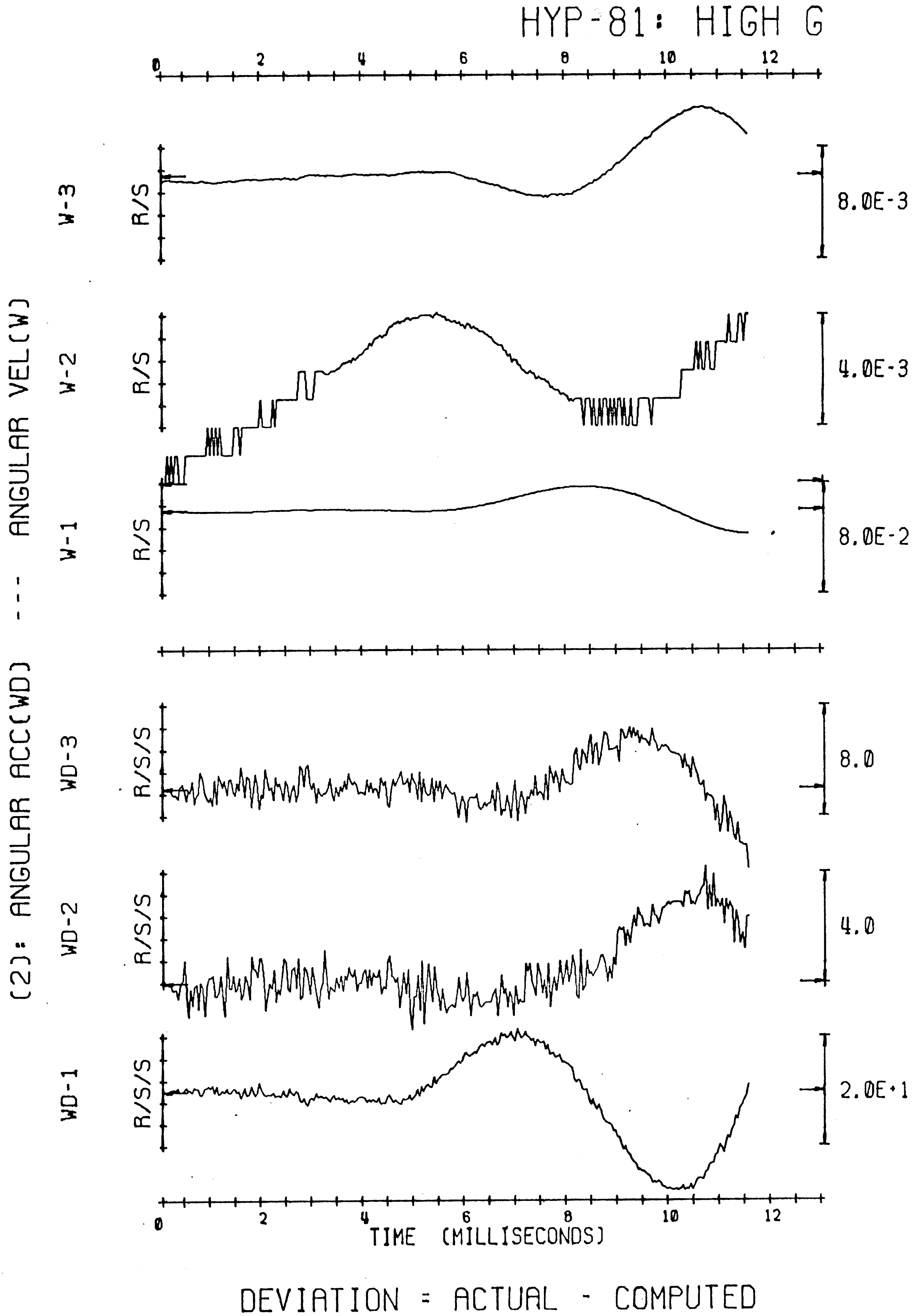
3-D RIGID BODY MOTION ANALYSIS

Figure 3



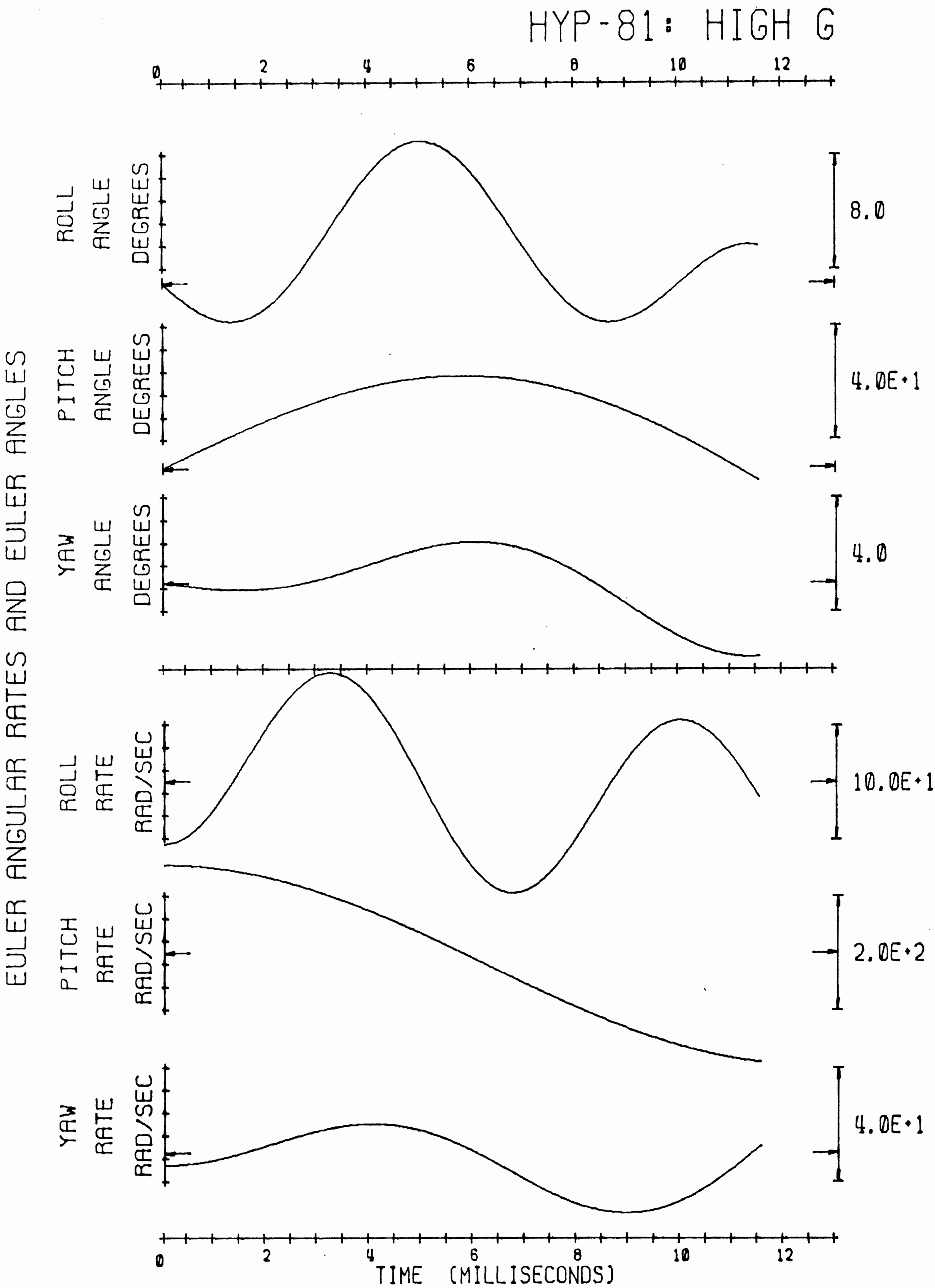
3-D RIGID BODY MOTION ANALYSIS

Figure 4



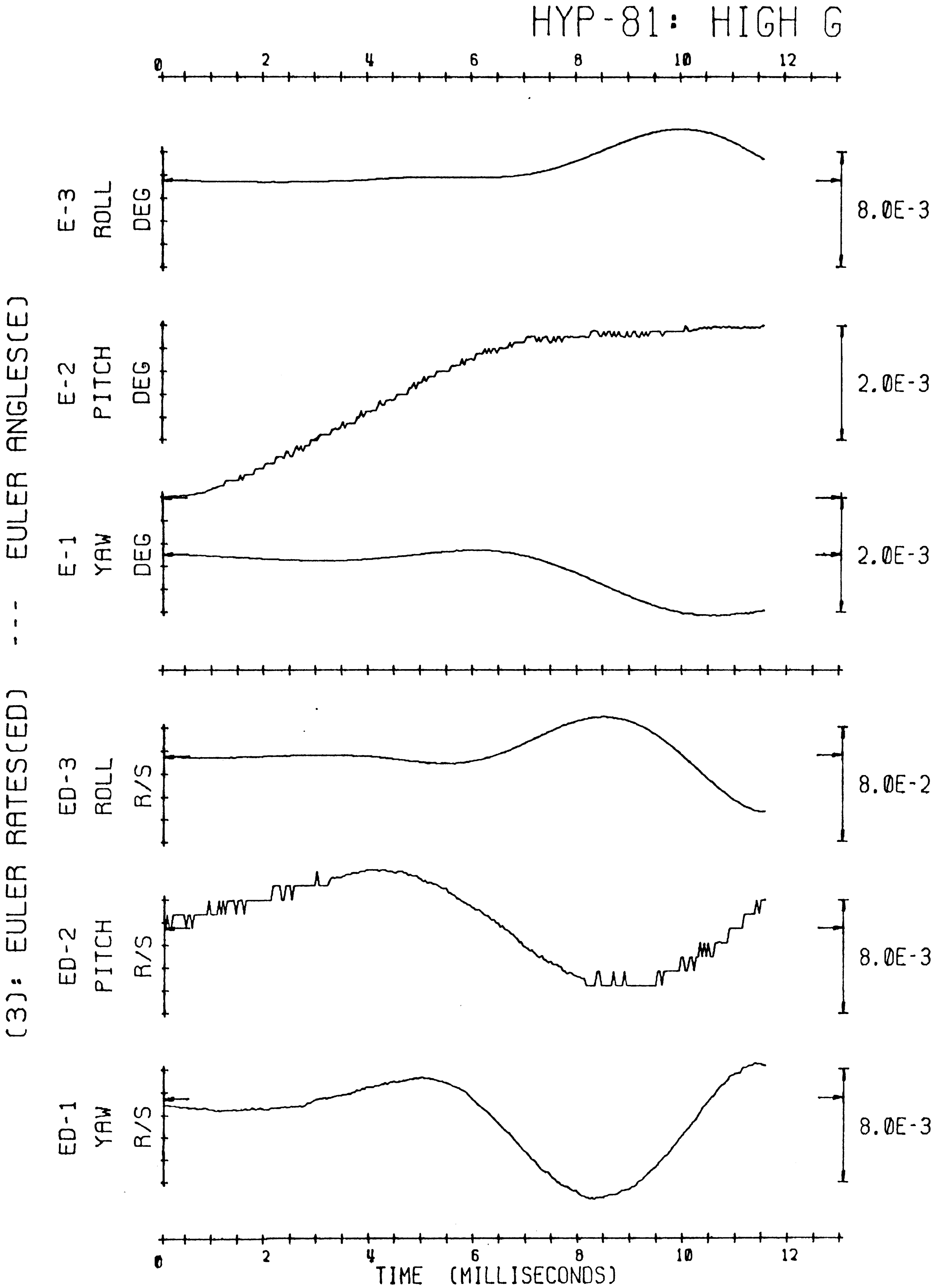
DEVIATION = ACTUAL - COMPUTED

Figure 5



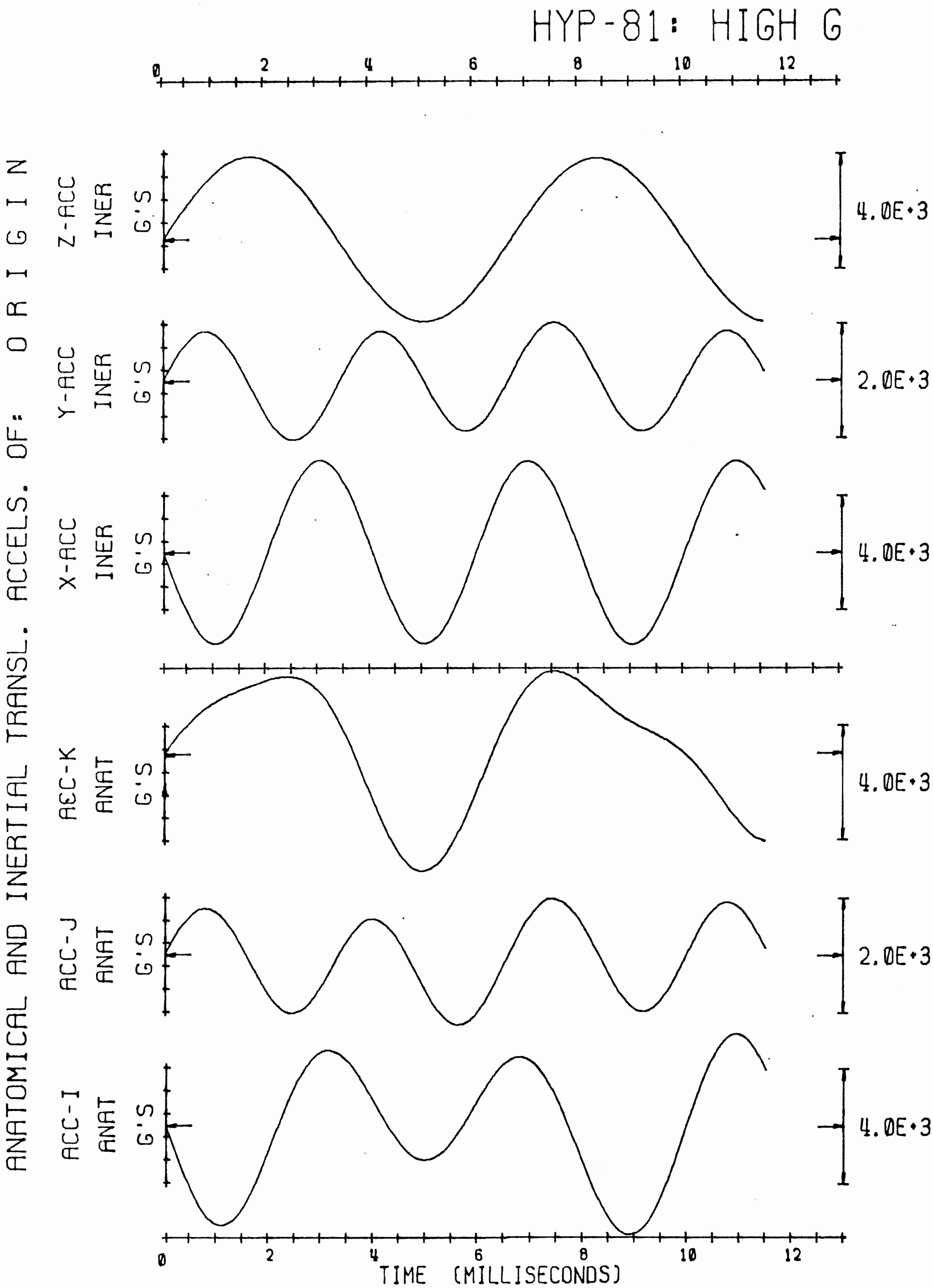
3-D RIGID BODY MOTION ANALYSIS

Figure 6



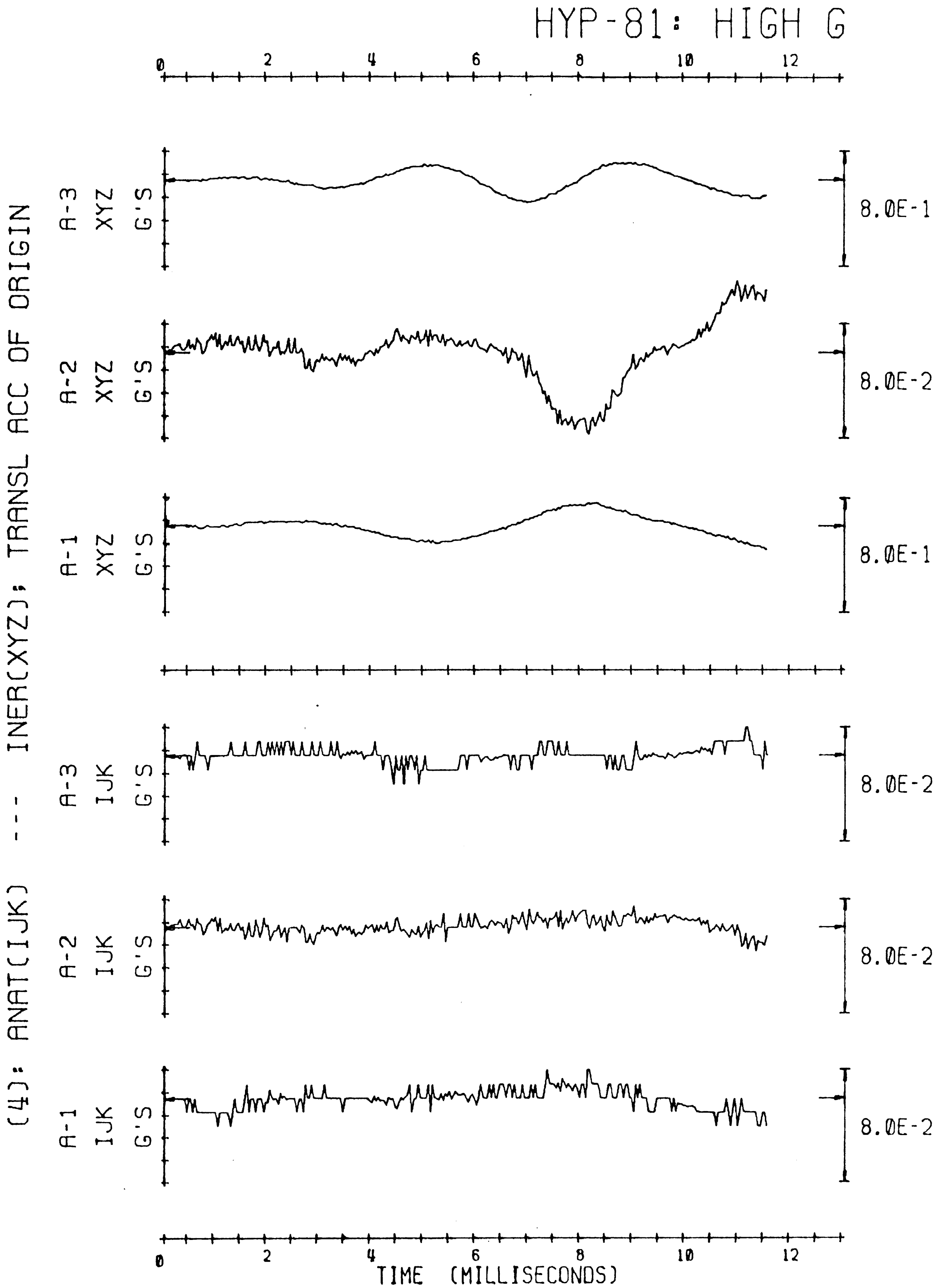
DEVIATION = ACTUAL - COMPUTED

Figure 7



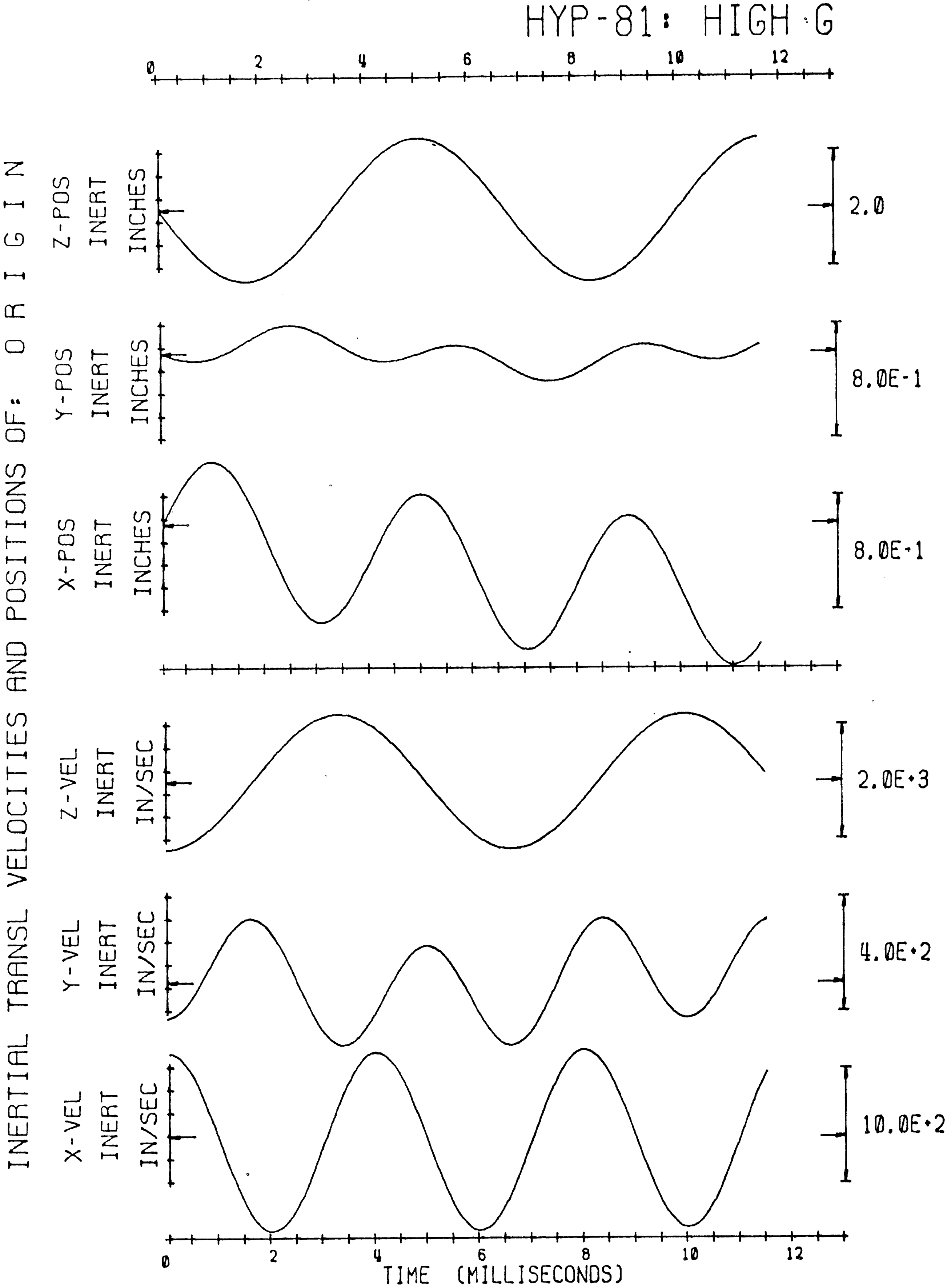
3-D RIGID BODY MOTION ANALYSIS

Figure 8



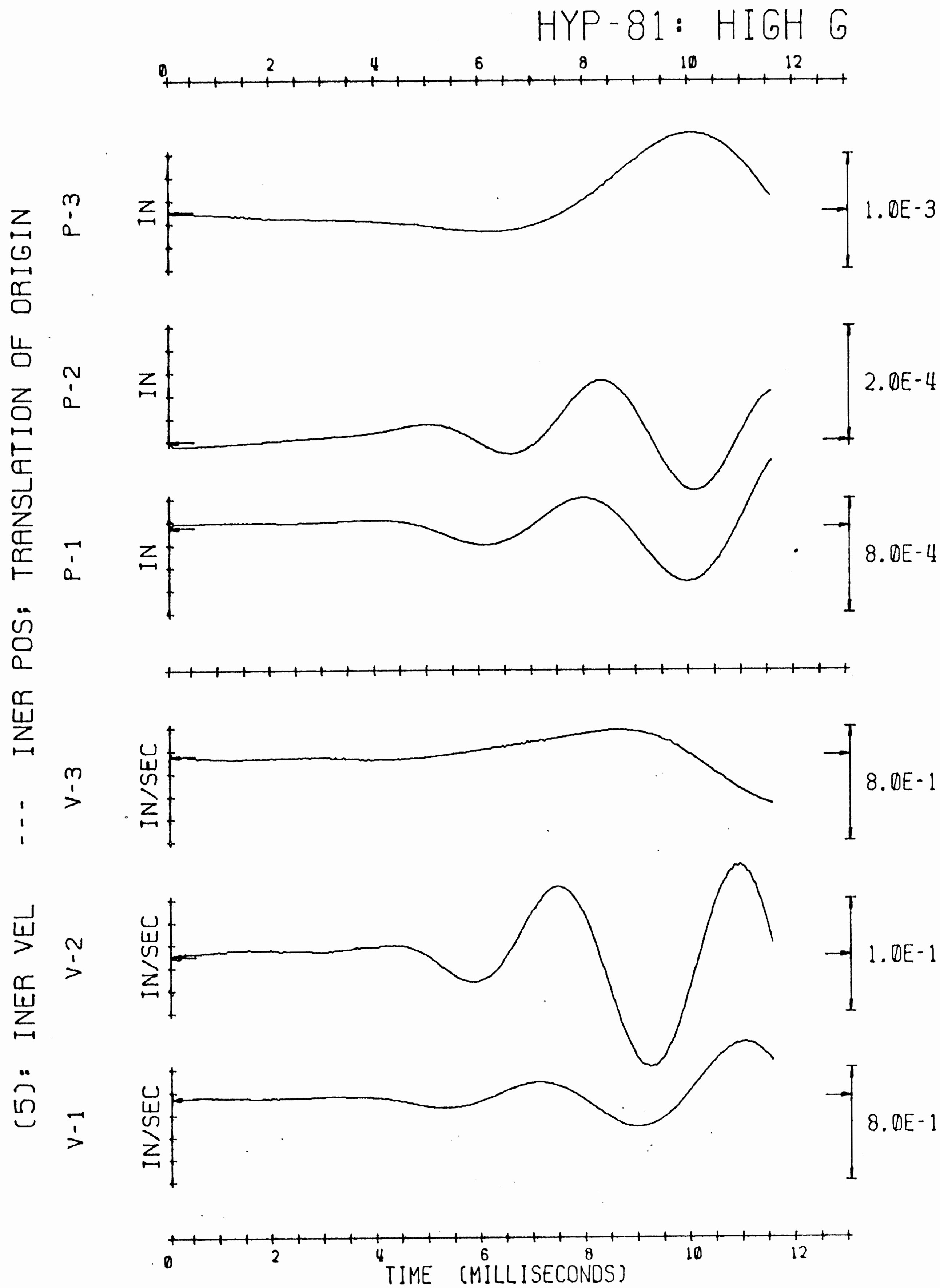
DEVIATION = ACTUAL - COMPUTED

Figure 9



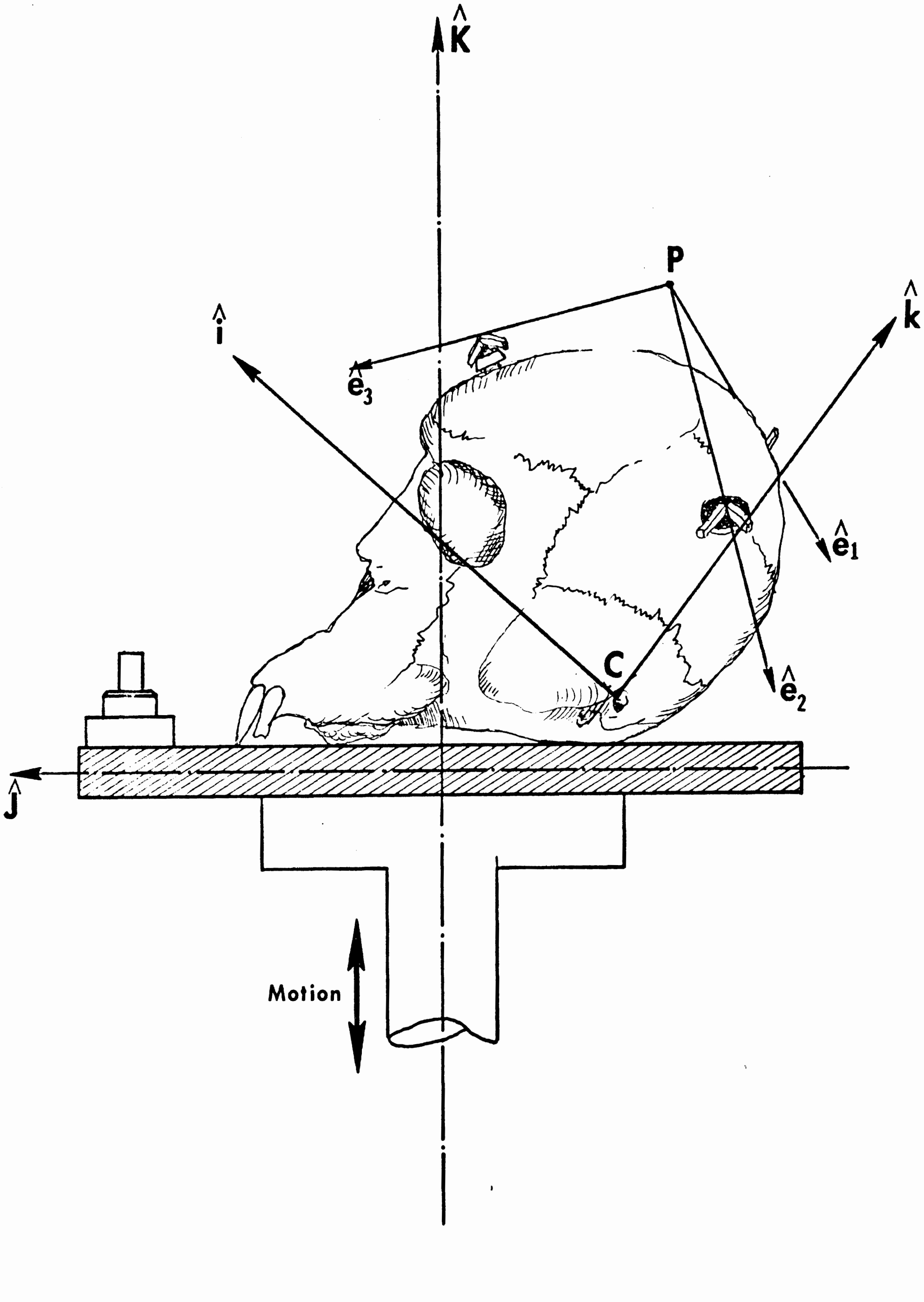
3-D RIGID BODY MOTION ANALYSIS

Figure 10



DEVIATION = ACTUAL - COMPUTED

Figure 11



SCHEMATIC DIAGRAM OF EXPERIMENTAL SET-UP FOR SKULL SHAKING.

Figure 12

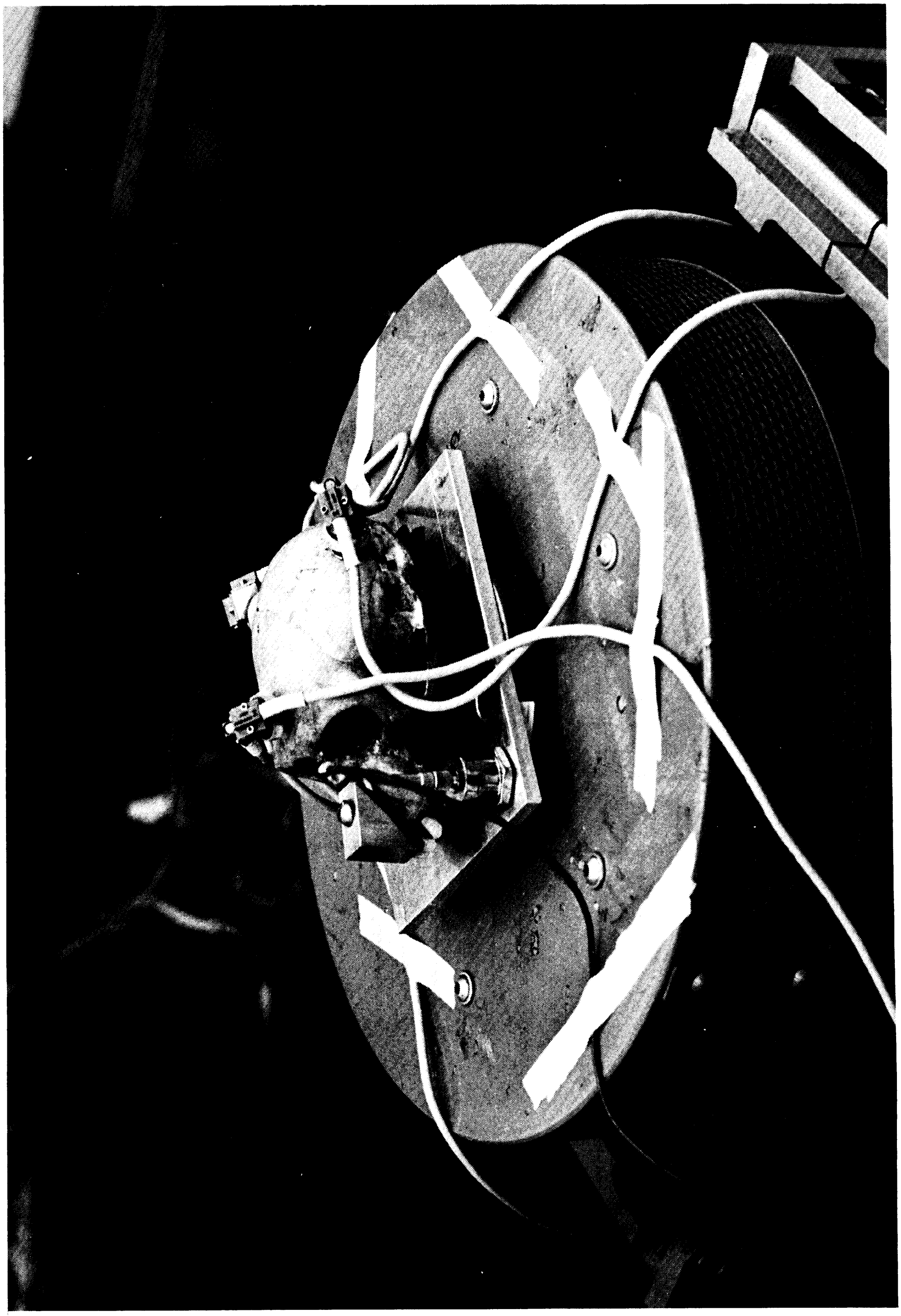
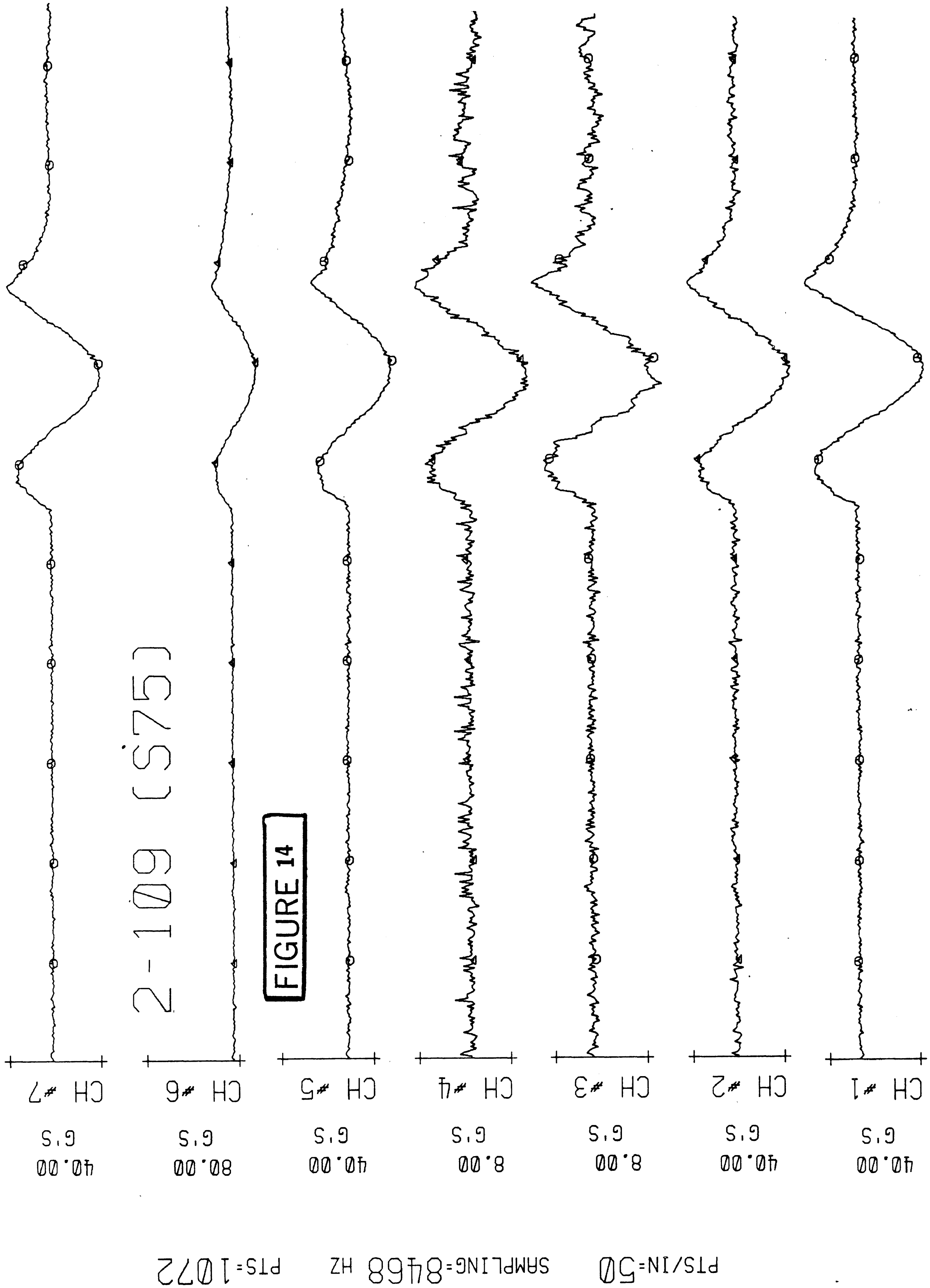


Figure 13


2-109 (S75)
FIGURE 14
CH #7
G'S
40.00
CH #6
G'S
80.00
CH #5
G'S
40.00
CH #4
G'S
8.00
CH #3
G'S
8.00
CH #2
G'S
40.00
CH #1
G'S
40.00
PTS/IN=50
SAMPLING=8468 HZ
PTS=1072

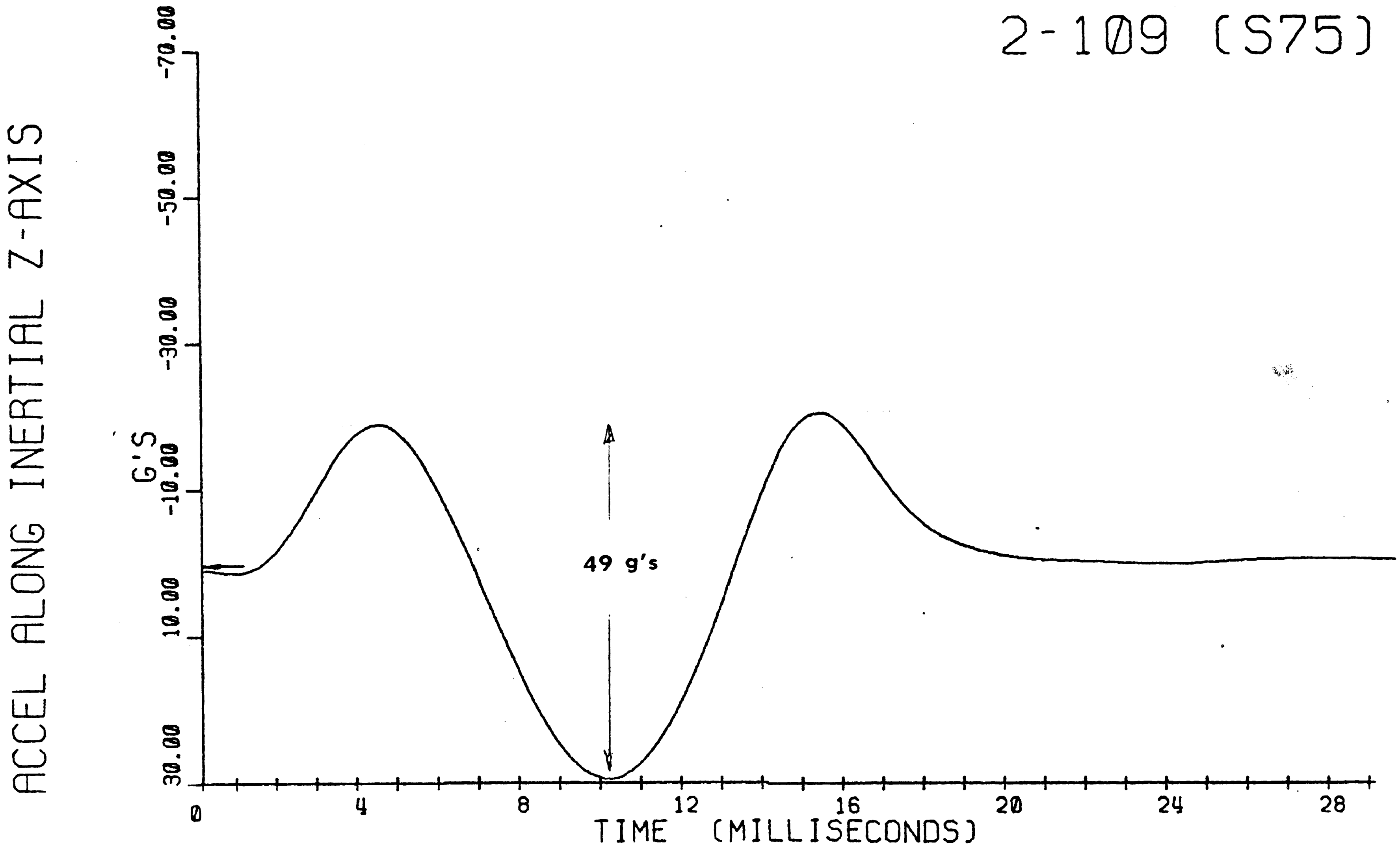
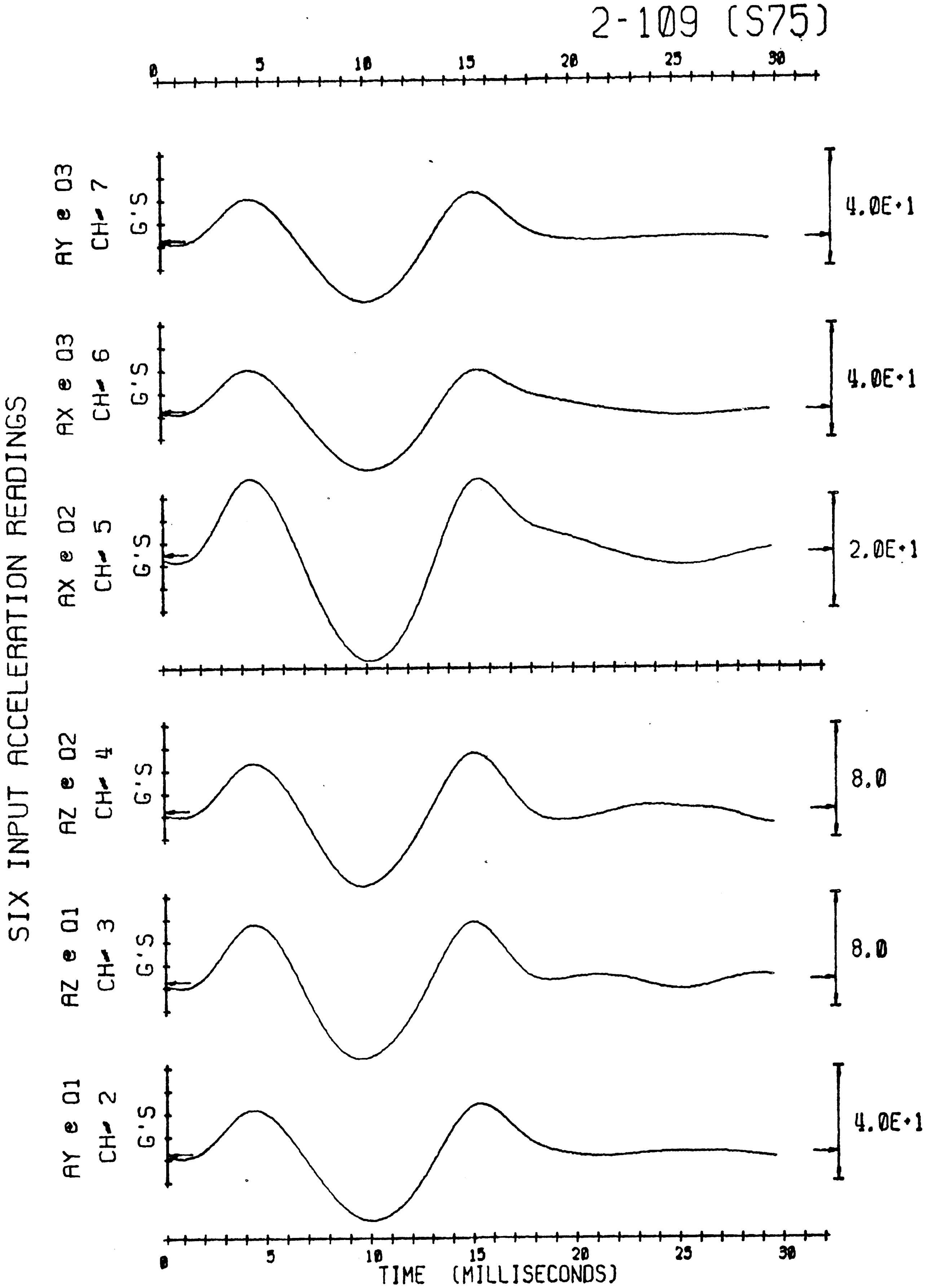
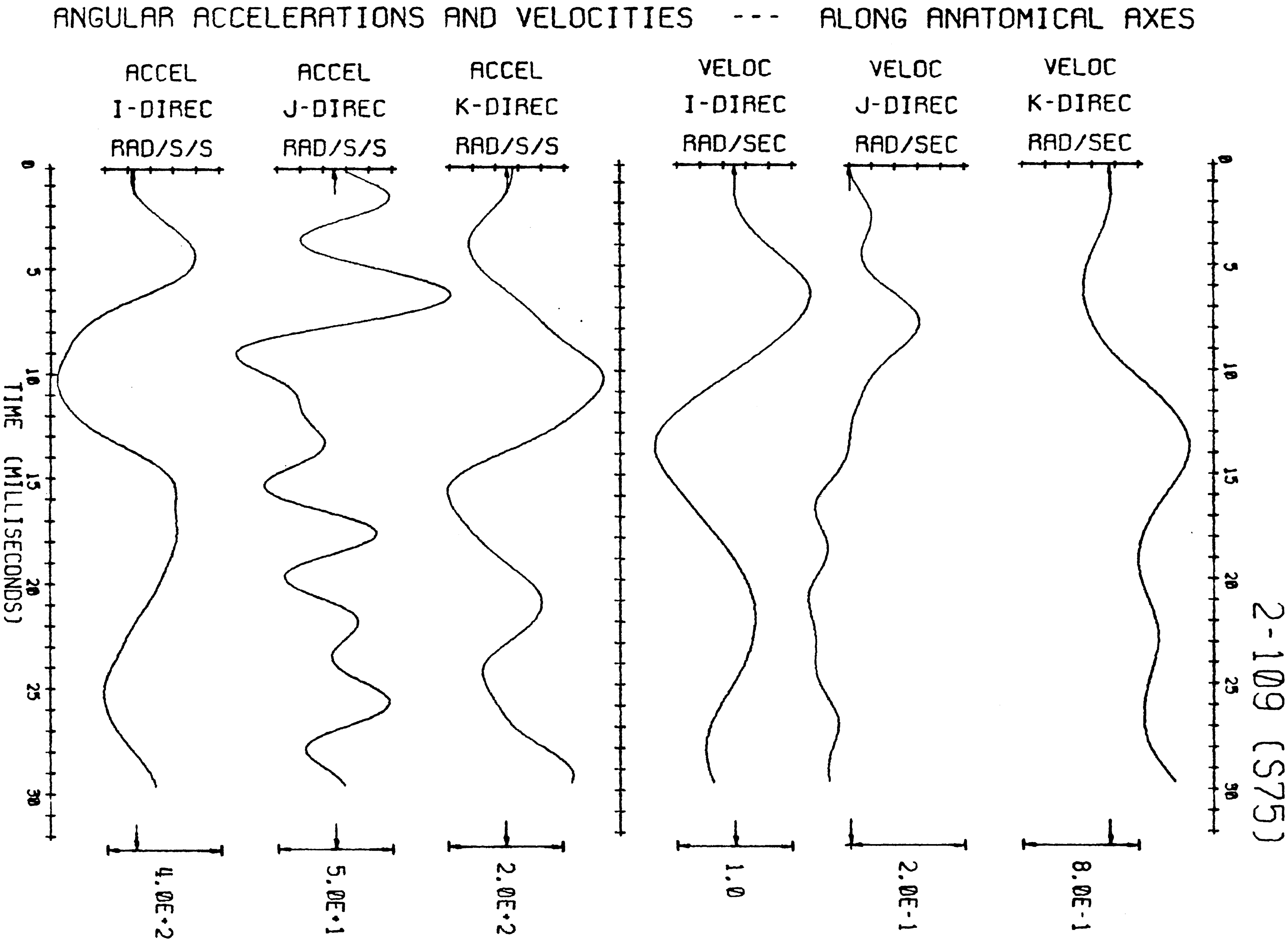

2-109 (S75)
ACCEL ALONG INERTIAL Z-AXIS
G'S
-70.00
-50.00
-30.00
-10.00
10.00
30.00
49 g's
0
4
8
12
16
20
24
28
TIME (MILLISECONDS)

Figure 15



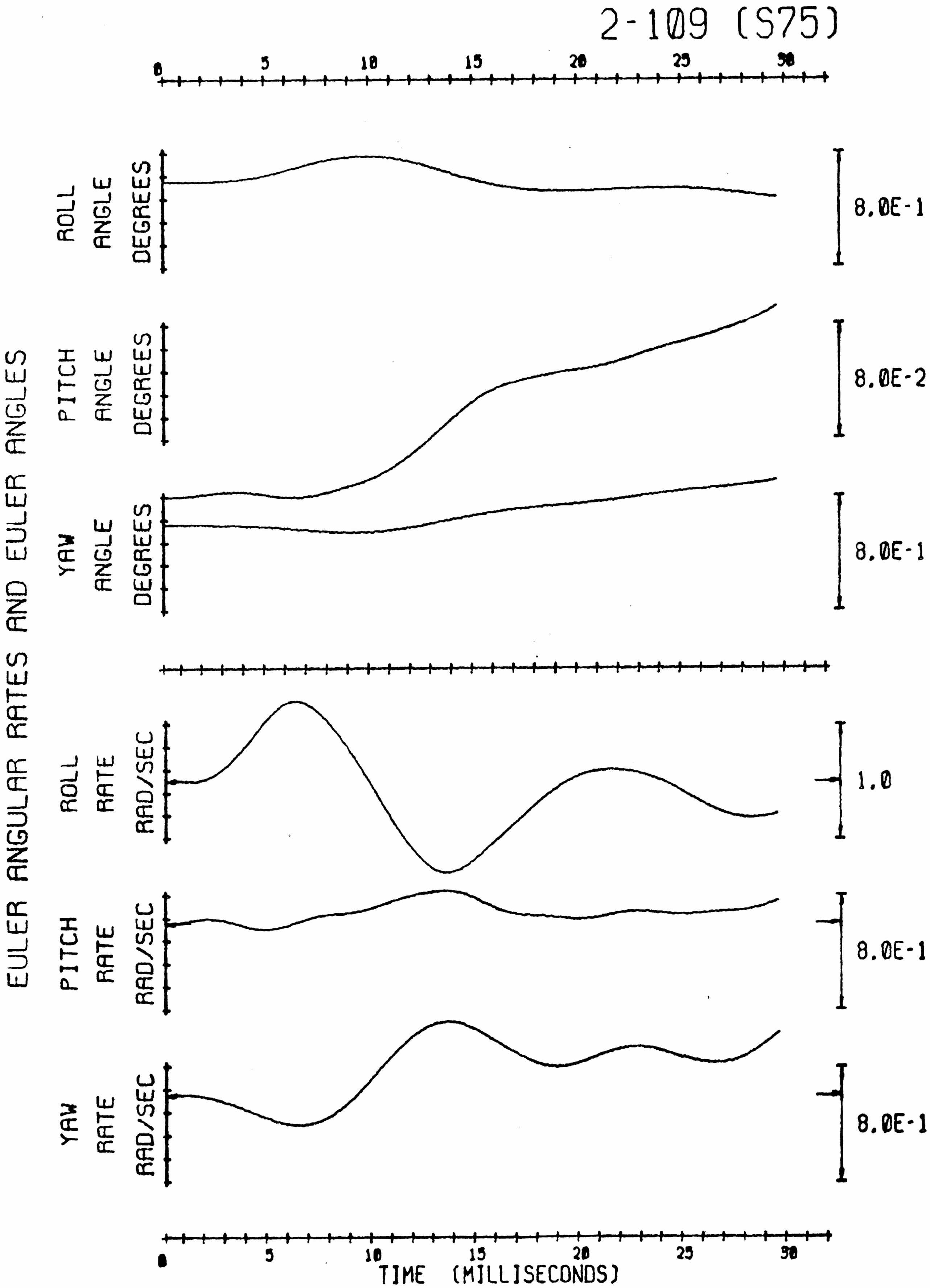
3-D RIGID BODY MOTION ANALYSIS

Figure 16



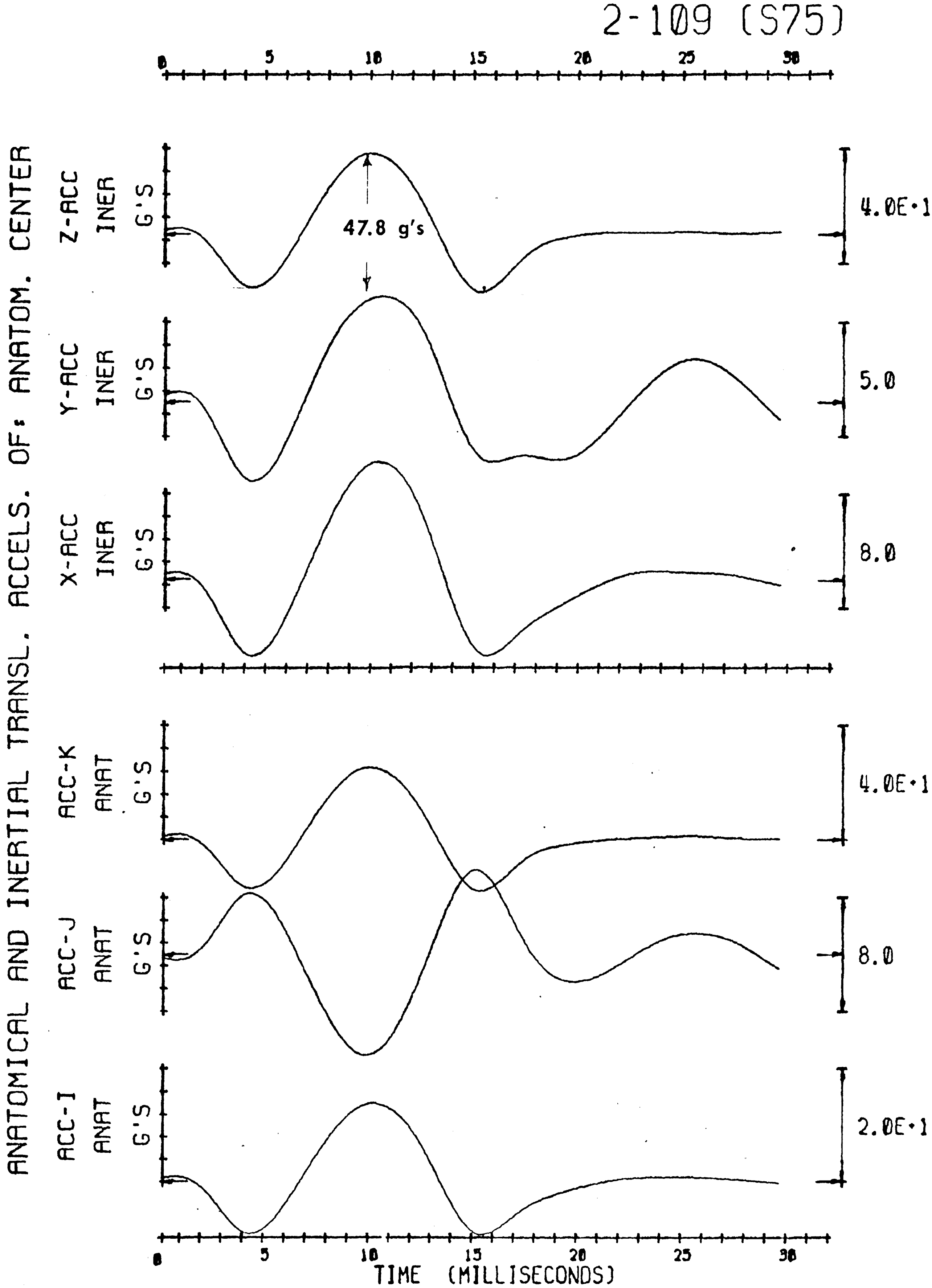
3-D RIGID BODY MOTION ANALYSIS

Figure 17



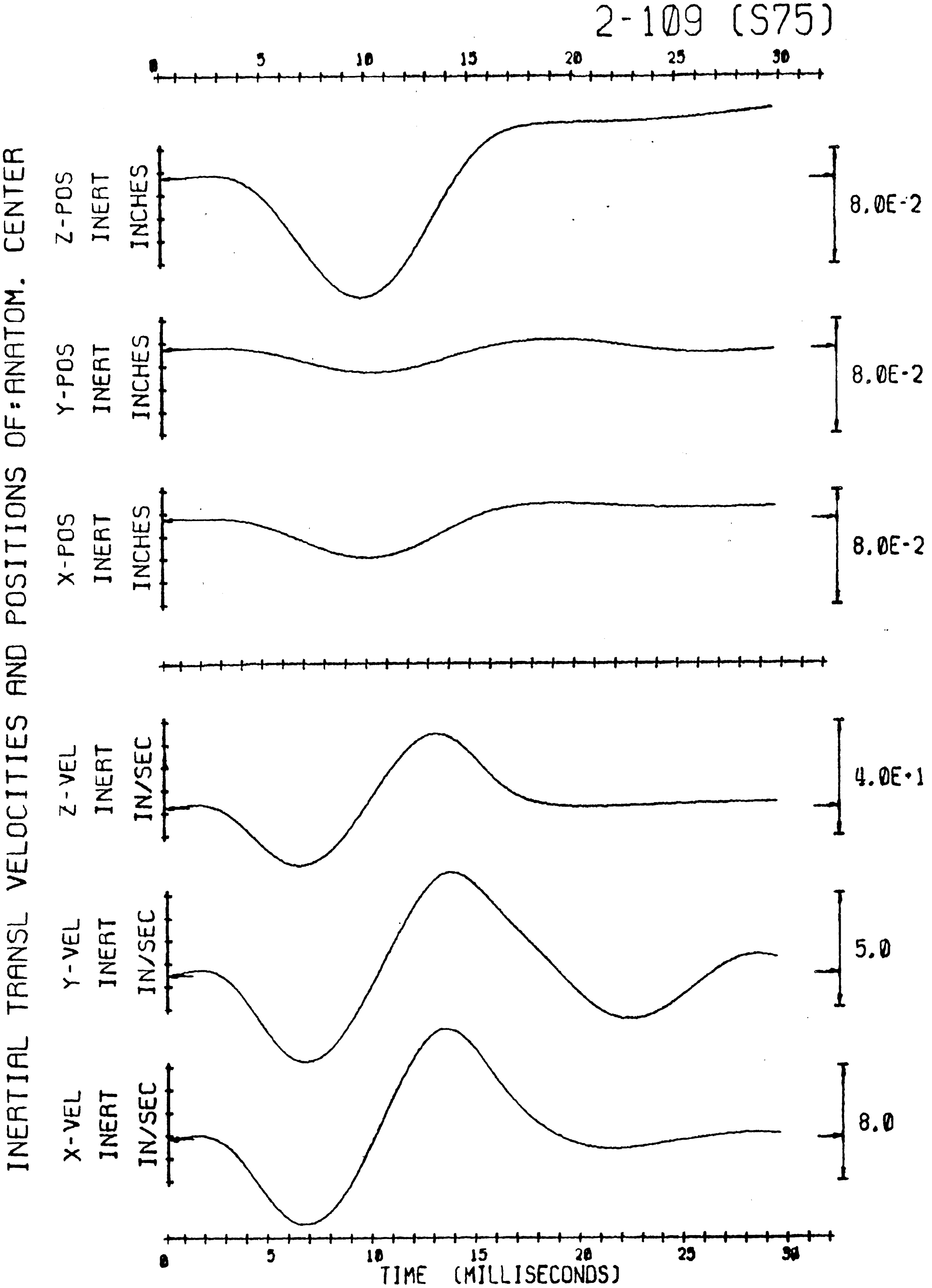
3-D RIGID BODY MOTION ANALYSIS

Figure 18



3-D RIGID BODY MOTION ANALYSIS

FIGURE 19



3-D RIGID BODY MOTION ANALYSIS

FIGURE 20

APPENDIX A-2

THREE DIMENSIONAL X-RAY TECHNIQUE

A-2 THREE DIMENSIONAL X-RAY TECHNIQUE

A.2.1 Introduction

In measuring accelerations of points on the head, it is difficult to locate and orient the accelerometers in standard anatomical locations and directions. It is therefore more convenient to resolve quantities measured in an arbitrary coordinate system into components in the standard anatomical directions. All that is needed is an accurate description of the mathematical transformations between the two coordinate systems.

Let $(\hat{e}_1, \hat{e}_2, \hat{e}_3)$ be an arbitrary coordinate system used in instrumenting the head, and let $(\hat{i}, \hat{j}, \hat{k})$ be the standard anatomical coordinate system, commonly referred to as the (A-P), (L-R) and (S-I) axes. Both systems may be termed body-axes triads, which are fixed one relative to the other, but moving with the head. An inertial frame $(\hat{I}, \hat{J}, \hat{K})$ is used as a reference to both moving frames. Then

$$\begin{Bmatrix} \hat{e}_1 \\ \hat{e}_2 \\ \hat{e}_3 \end{Bmatrix} = [E] \begin{Bmatrix} \hat{I} \\ \hat{J} \\ \hat{K} \end{Bmatrix} \qquad (1)$$

and

$$\begin{Bmatrix} \hat{i} \\ \hat{j} \\ \hat{k} \end{Bmatrix} = [A] \begin{Bmatrix} \hat{I} \\ \hat{J} \\ \hat{K} \end{Bmatrix} \qquad (2)$$

where [E] and [A] are the direction cosines matrix relative to the inertial frame of the instrumentation and the anatomical coordinate systems, respectively.

The objective is to obtain a transformation matrix, [R], between $(\hat{e}_1, \hat{e}_2, \hat{e}_3)$ and $(\hat{i}, \hat{j}, \hat{k})$.

$$\begin{Bmatrix} \hat{e}_1 \\ \hat{e}_2 \\ \hat{e}_3 \end{Bmatrix} = [R] \begin{Bmatrix} \hat{i} \\ \hat{j} \\ \hat{k} \end{Bmatrix} . \qquad (3)$$

From (2), an expression for $(\hat{I},\hat{J},\hat{K})$ is obtained:

$$\begin{Bmatrix} \hat{I} \\ \hat{J} \\ \hat{K} \end{Bmatrix} = [A]^{-1} \begin{Bmatrix} \hat{i} \\ \hat{j} \\ \hat{k} \end{Bmatrix} \tag{4}$$

Equation (4) is then substituted into equation (1)

$$\begin{Bmatrix} \hat{e}_1 \\ \hat{e}_2 \\ \hat{e}_3 \end{Bmatrix} = [E] \; [A]^{-1} \begin{Bmatrix} \hat{i} \\ \hat{j} \\ \hat{k} \end{Bmatrix} \tag{5}$$

By comparing equations (3) and (5)

$$[R] = [E]\,[A]^{-1} \tag{6}$$

A.2.2 <u>Method</u>

To obtain [R], one must obtain [E] and [A] which involve the following steps:

a. define $(\hat{e}_1,\hat{e}_2,\hat{e}_3)$.
b. define $(\hat{i},\hat{j},\hat{k})$.
c. devise a method to compute the direction cosine matrix [E] of $(\hat{e}_1,\hat{e}_2,\hat{e}_3)$ relative to an arbitrary inertial frame.
d. devise a method to compute the direction cosine matrix [A] of $(\hat{i},\hat{j},\hat{k})$ relative to the <u>same</u> arbitrary inertial frame.
e. compute the matrix product $[E]\,[A]^{-1}$ to obtain the direction cosines matrix [R] of $(\hat{e}_1,\hat{e}_2,\hat{e}_3)$ relative to $(\hat{i},\hat{j},\hat{k})$.

A.2.3 <u>Instrumentation Definitions</u>

The configuration of the 6 accelerometers necessary to measure the head motion was chosen so that they lie on the 3 axes of the instrumentation coordinate system. Each pair is located at a known distance from the origin P of this system (see Figure 1).

$$\overrightarrow{PQ_1} = \rho_1 \hat{e}_1 = \hat{e}_1 = \frac{PQ_1}{|PQ_1|} \tag{7}$$

$$\overrightarrow{PQ_2} = \rho_2 \hat{e}_2 = \hat{e}_2 = \frac{PQ_2}{|PQ_2|} \tag{8}$$

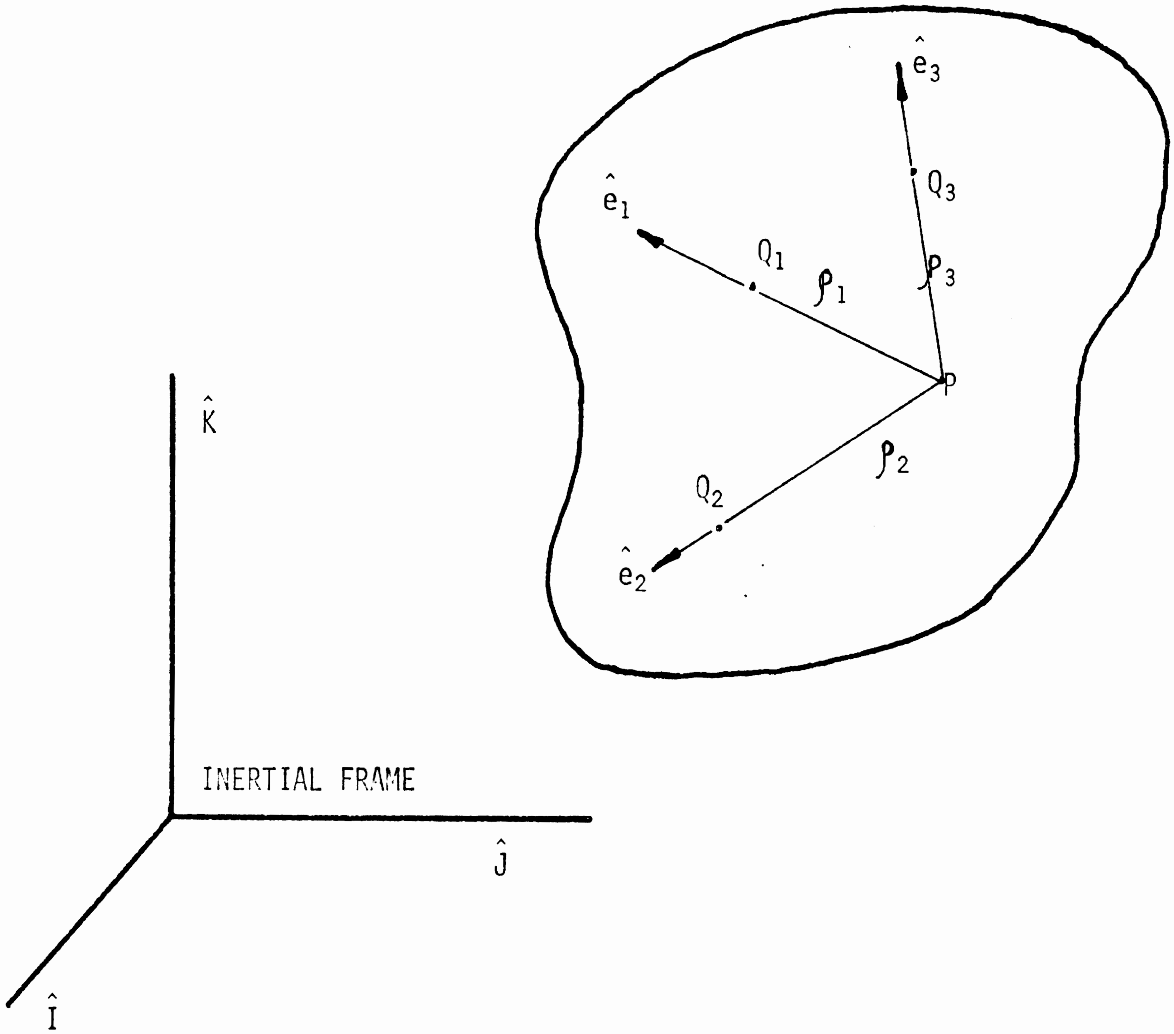


FIGURE 1. INSTRUMENTATION COORDINATE SYSTEM FOR THE HEAD

$$\overrightarrow{PQ_3} = \rho_3 \hat{e}_3 = \hat{e}_3 = \frac{PQ_3}{|PQ_3|} \qquad (9)$$

A.2.4 Anatomical Definitions

The standard definition of the (A-P), (L-R) and (S-I) axes, or alternately the $(\hat{i}, \hat{j}, \hat{k})$ system is based on the Frankfort plane. This plane is defined by the four points (Figure 2).

P_1 : superior edge of the right auditory meatus,

P_2 : superior edge of the left auditory meatus,

P_3 : right infra-orbital notch, and

P_4 : left infra-orbital notch.

Let C be the midpoint between P_1 and P_2, and M the mid-point between P_3 and P_4, then

a. the anatomical center is defined as point C.

b. the A-P axis is defined as:

$$\hat{i} = \frac{\overrightarrow{CM}}{|CM|} \qquad (10)$$

c. the L-R axis is defined as:

$$\hat{j} = \frac{\overrightarrow{CP_2}}{|CP_2|} \qquad (11)$$

d. the S-I axis is defined by the cross product

$$\hat{k} = \hat{i} \times \hat{j} \qquad (12)$$

A.2.5 Two-Dimensional Coordinates

The x-ray photograph of an object is simply the shadow of that object captured on a photo-sensitive film and generated by a near-point source of x-rays.

It is proposed to obtain the true coordinates (x,z) of an object (see Figure 3) given the x-ray photo itself, and relevant characteristics of the x-ray set-up which produced it.

A typical x-ray set-up is simplified in the diagram of Figure 3. The x-ray table is vertical in this case, and the film cassette

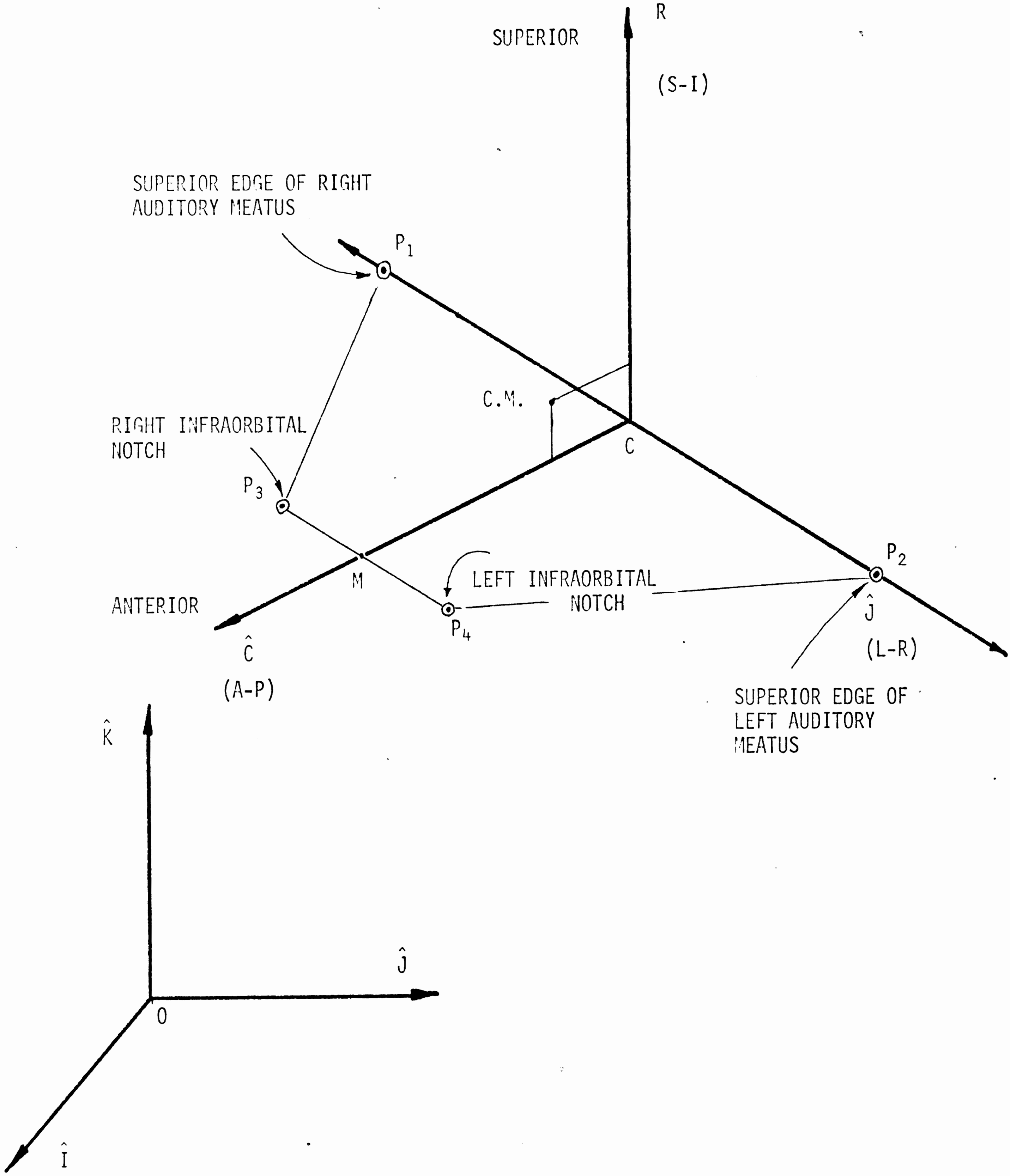


FIGURE 2. ANATOMICAL POINTS DEFINING THE FRANKFORT PLANE

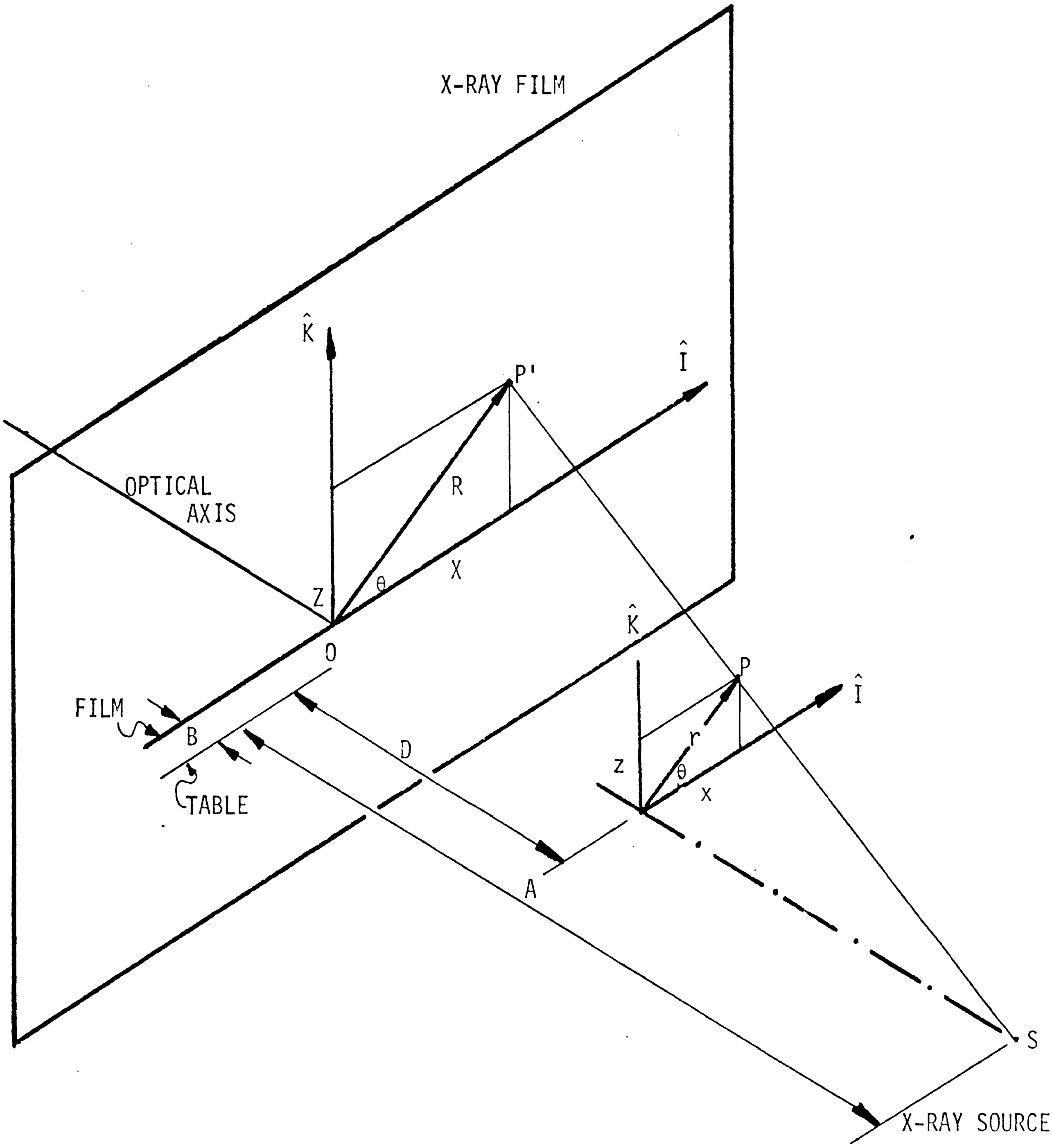


FIGURE 3. SIMPLIFIED X-RAY SET-UP FOR A SINGLE POINT

is located behind the table at a distance B. The distance between the table and the x-ray source is A, and between the table and the object is D. After the film has been developed, the trace 0 of the optical axis is physically located on the film and the distances X and Z are measured.

Given the measured X and Z, the radial distance R and the angle θ may be computed:

$$R = \sqrt{X^2 + Z^2} \tag{13}$$

$$\theta = \tan^{-1} \frac{Z}{X} \tag{14}$$

Now the true radial distance r may be obtained from the geometrical property:

$$\frac{r}{R} = \frac{A-D}{A+B} = \left[\frac{A}{A+B}\right] - \left[\frac{1}{A+B}\right] D \tag{15}$$

or

$$r = [\alpha - \beta D]R \tag{16}$$

so that the true coordinates are:

$$x = r \cos\theta \tag{17}$$

$$y = r \sin\theta \tag{18}$$

The constants α and β depend solely on the x-ray set-up and are the same for any object at any distance D from the x-ray table.

The relationship of the equation (16) was experimentally determined and is shown in Figure 4. Note that this parametric calibration curve is valid for the x-ray set-up at HSRI and will vary depending on the A and B distances.

A.2.6 Three-Dimensional Coordinates

To obtain complete 3-D coordinates of an object, the procedure followed in the previous section may be repeated for the (Y-Z) plane. This can be done simultaneously with the (X-Z) measurement which requires two separate x-ray sources and two separate, mutually perpendicular film planes. A simpler method is to x-ray the (X-Z) plane first, then rotate the object 90° and obtain a new x-ray of the

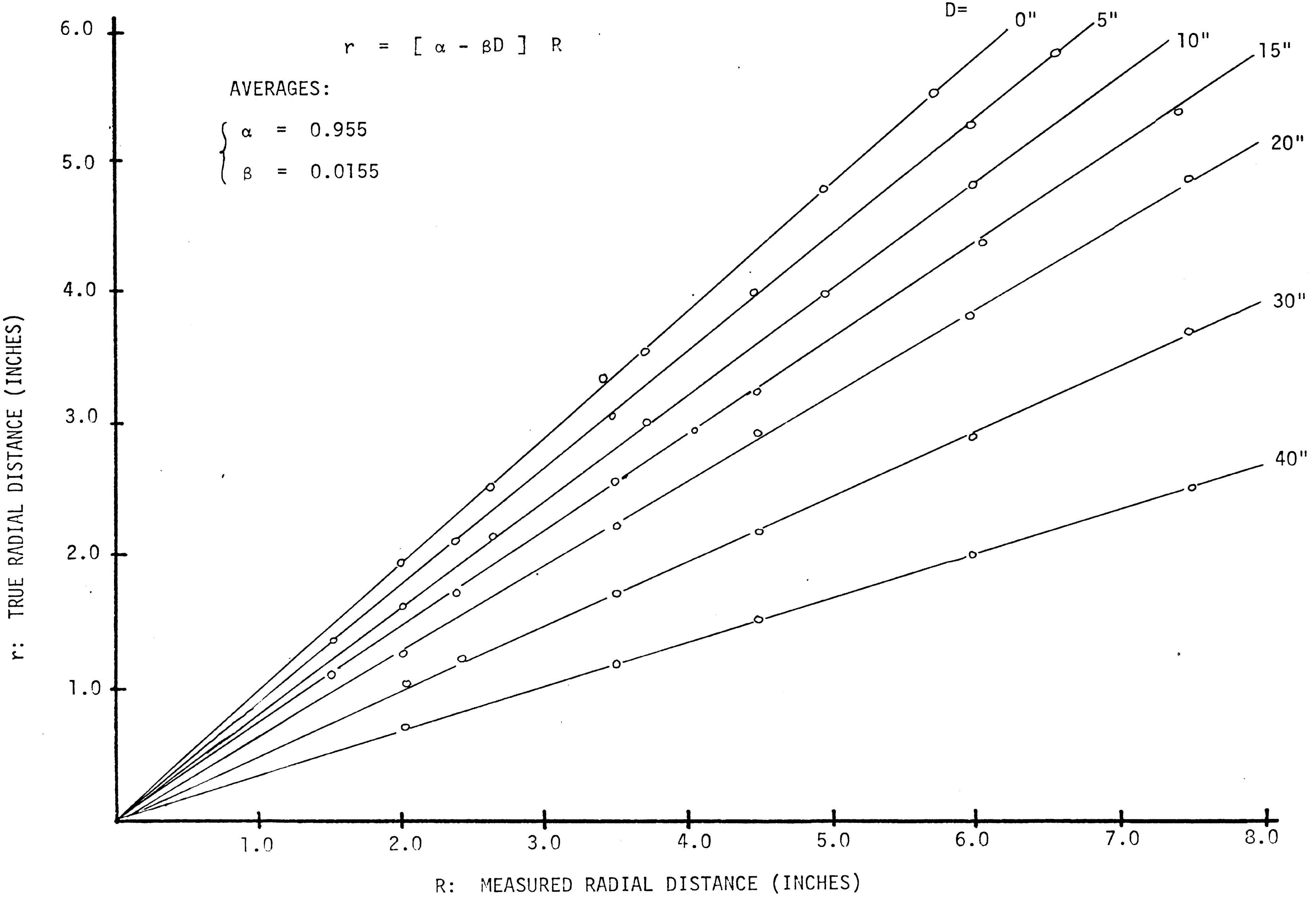


FIGURE 4. CALIBRATION OF X-RAY SET-UP

(Y-Z) plane. The analysis of the two x-rays would yield true (x,z) and (y,z) coordinates. The z-coordinate would be the average of the two values obtained, since experimental errors would normally result in slightly different values.

The inertial coordinate reference system is formed by the optical axis going once through the (x,z) plane, then going again through the (y,z) plane of the head. Therefore, care must be taken to keep the head at the same elevation with respect to the optical axis when it is being rotated. This elevation may, however, be arbitrary.

A.2.7 Experimental X-Ray Procedure

The experimental procedure in x-raying the head must be oriented toward an accurate measurement of the transformation matrix between the instrumentation and the anatomical coordinate system.

On each x-ray, the optical (inertial) reference frame must be defined. For this purpose, a special lead plate, Figure 5, was machined to fit precisely over the window of the x-ray source. This plate will allow a thin circular ring of x-rays to pass through and be recorded on the film, prior to taking the x-ray of the head. Careful machining ensures that the optical center is the same as the center of the ring. A vertical axis was obtained on the film by hanging a weight from a long lead wire and taping the top end of the wire onto the x-ray table. Thus, the optical center as well as the vertical and horizontal optical axes may be accurately drawn on the film and used to measure the (X, Y, Z) coordinates of any given point.

In order to identify the 4 anatomical points of the Frankfort plane, lead pellets with distinctive tabs are used as follows: The lowest points on the two orbital cavities are exposed by small incisions and, using Eastman-910 cement, two pellets are cemented directly on the bone at the lowest point of each orbital cavity. This is the closest approximation to the two infraorbital notches P_3 and P_4 used in defining the Frankfort plane. To approximate the other two points of this plane, P_1 and P_2, two wooden plugs (short cylinders) are used to carry lead pellets so that, when

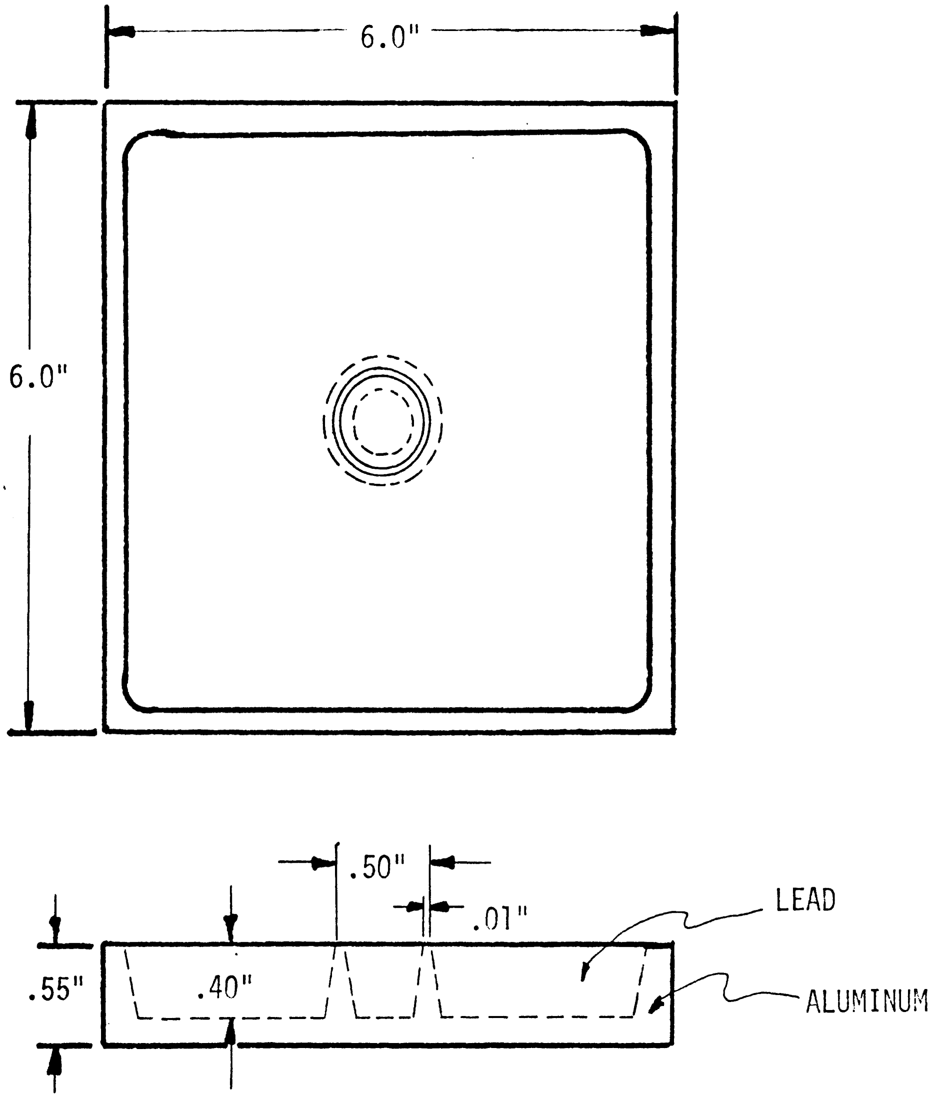


FIGURE 5. LEAD PLATE FOR PRE-RECORDING OF OPTICAL CENTER

these plugs are inserted in the auditory meati, the lead pellets would approximate the superior edges of the two meati.

Finally, to identify the 3 points Q_1, Q_2, Q_3 which represent the centers of mass of the 3 pairs of accelerometers, 3 aluminum dummy blocks are machined to replace the 3 pairs of accelerometers during the x-raying. Each dummy block contains a pellet, so located as to precisely fall on the c.m. of the accelerometer-pair which is being replaced.

Once the seven pellets are properly mounted on the head, the subject whose head is being x-rayed is then placed (or seated) on a rolling chair or platform and the following steps are taken:

Step 1. With the subject outside the x-ray field, expose the film with the circular ring.

Step 2. Place the subject in the x-ray field, expose the film with the circular ring.

Step 3. Expose the film to obtain the x-ray of the head structure and vertical lead wire. This gives the x-ray of the $(\hat{J}\text{-}\hat{K})$ plane.

Step 4. Remove the subject from the x-ray field, and change the film cassette.

Step 5. Expose the film to obtain the circular ring.

Step 6. Replace the subject to exactly the same previous elevation and in the x-ray field.

Step 7. Rotate the platform carrying the subject through +90° about the $\hat{K}$-axis.

Step 8. Obtain and record the seven distances between the x-ray table and the individual pellets.

Step 9. Expose the head and the vertical lead wire to obtain an x-ray of the $(\hat{X},\hat{K})$ plane.

Once the two orthogonal x-rays have been developed, the optical center and axes are drawn and the seven pellets labeled on each x-ray, then for each pellet, (X,Z) and (Y,Z) pairs are measured directly on the x-ray films. These readings are supplemented with the corresponding distances from the x-ray table obtained earlier during steps 2 and 8 of the x-raying procedure. Each pellet will then have (X, Z, D_{XZ})

and (Y,Z,D_{yz}) which can be used to obtain true (x,y,z) coordinates with respect to an arbitrary reference frame, given the calibration constants α and β of the x-ray set-up.

A.2.8 Computation of the Instrumentation Frame

Given

x_1, y_1, z_1 of Q_1 and $PQ_1 = \rho_1$

x_2, y_2, z_2 of Q_2 and $PQ_2 = \rho_2$

x_3, y_3, z_3 of Q_3 and $PQ_3 = \rho_3$

and assuming that Q_1, Q_2, and Q_3 are located on the respective axes of an instrumentation right-handed triad, it is required to find x_p, y_p, z_p of the origin P of $(\hat{e}_1,\hat{e}_2,\hat{e}_3)$, then to compute the direction cosines of $\hat{e}_1$, $\hat{e}_2$, $\hat{e}_3$.

Consider spheres (Q_1,ρ_1) and (Q_2,ρ_2). In order for P to exist, they must intersect along a circle with center at H_1 which must be located on line Q_1Q_2 connecting the centers. Furthermore, this circle is the locus of origin P, thus it has a radius H_1P. The third sphere (Q_3,ρ_3) which is orthogonal to each of the first two, must intersect the circle (H_1,H_1P) at right angles, i.e., Q_3P must be in the plane of that circle tangent to it. Therefore, the plane Q_3PH_1 is normal to line Q_1Q_2, or line Q_1Q_2 must be normal to all lines contained in plane Q_3PH_1; in particular Q_1Q_2 is perpendicular to line Q_3H_1. Thus Q_3H_1 is the height of triangle $Q_1Q_2Q_3$ at the base of Q_1Q_2. Similar reasoning may be followed for each of the other two heights Q_2H_3 and Q_1H_2. Since all three heights in any triangle intersect at a common point, this intersection is called point G.

Next, consider plane Q_3H_1P which is perpendicular to Q_1Q_2. Since point G is in this plane, line GP must be perpendicular to Q_1Q_2. Similarly, GP must be perpendicular to Q_2Q_3 and to Q_3Q_1. It may be concluded that line GP is perpendicular to the plane of the triangle $Q_1Q_2Q_3$, or that G is the orthogonal projection of a single point P on the plane $Q_1Q_2Q_3$.

Armed with these properties, the solution of the problem may be

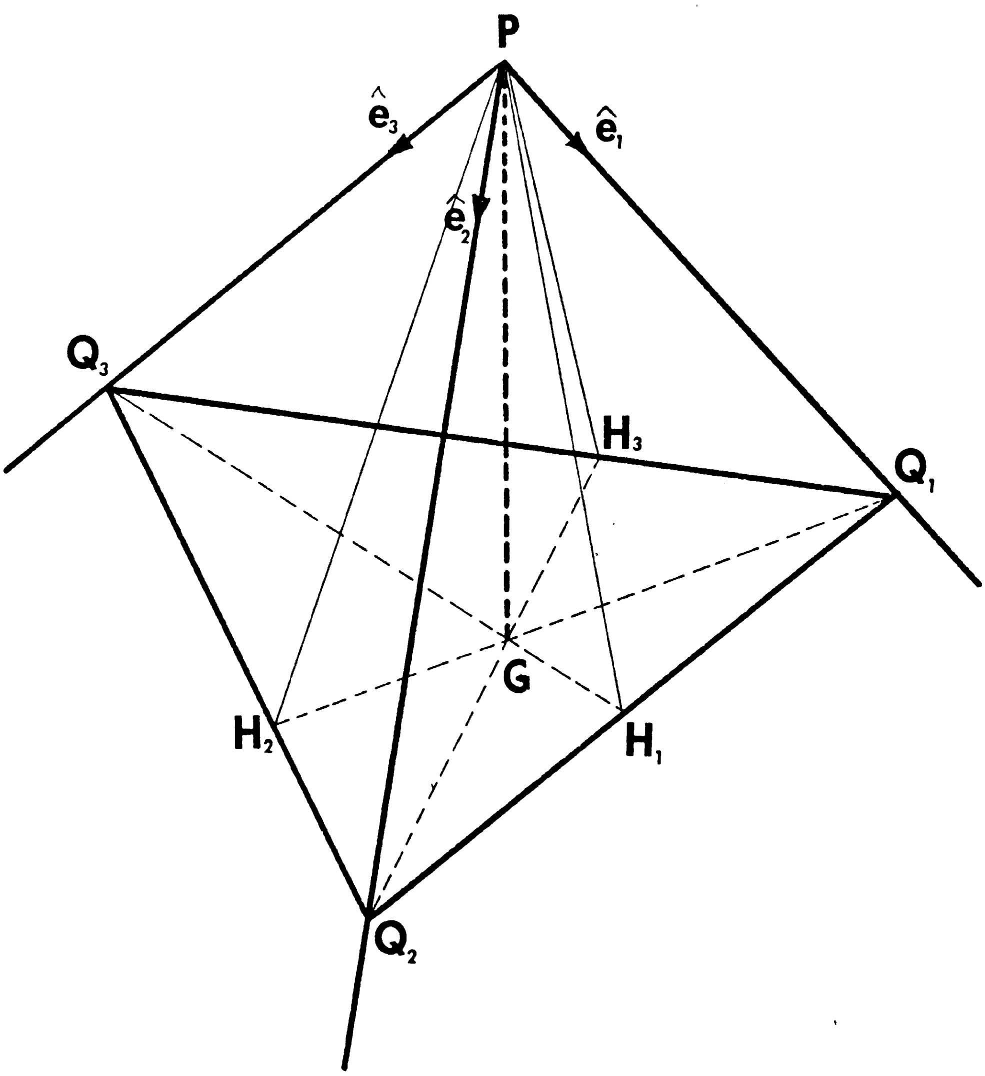


Figure 6.

broken into smaller problems of line-plane intersections.

Given a plane defined by a point (x_1, y_1, z_1) and the direction cosines of a normal vector (a_1, b_1, c_1), and given a line defined by a point (x_2, y_2, z_2) and its direction cosines (a_2, b_2, c_2), solve for the trace (x,y,z) of the line of the plane.

The normal form of the equation of the plane is:

$$a_1(x - x_1) + b_1(y - y_1) + c_1(z - z_1) = 0 \tag{19}$$

and the parametric form of the equation of the line:

$$\begin{aligned} x &= x_2 + a_2 t \\ y &= y_2 + b_2 t \\ z &= z_2 + c_2 t \end{aligned} \tag{20}$$

At the intersection, (x,y,z) must satisfy both equation (19) and (20):

$$a_1[(x_2 + a_2 t) - x_1] + b_1[(y_2 + b_2 t) - y_1] + c_1[(z_2 + c_2 t) - z_1] = 0 \tag{21}$$

which yields:

$$t = \frac{a_1(x_1 - x_2) + b_1(y_1 - y_2) + c_1(z_1 - z_2)}{a_1 a_2 + b_1 b_2 + c_1 c_2} \tag{22}$$

The parameter t is precisely the distance along (a_2, b_2, c_2) of the line between the piercing point and the line's particular point. Once it is computed from equation (22), it is substituted in equation (20) to yield the coordinate (x,y,z) of the intersection.

The first step towards a solution is to compute the location of H_1 as the intersection of Q_1Q_2 whose direction cosines and particular points are known, and the plane Q_3H_1P which has the same direction cosines as Q_1Q_2 and a particular point Q_3. This is repeated for H_2 and H_3.

The second step is to locate G as the intersection of line Q_3H_1 and plane Q_1H_2P whose direction cosines and particular points are known. The location of G may be obtained with two other methods:

intersection of line Q_1H_2 with plane Q_2H_3P, or intersection of line Q_2H_3 with plane Q_3H_1P. One method is sufficient, but the average of the three methods reduces the experimental reading errors.

The direction cosines of line GP are obtained as the normal vector to any two vectors connecting 3 points (Q_1,Q_2,Q_3). The proper order is important so that point P would be on the correct side of the plane (Q_1,Q_2,Q_3). The direction cosines (u_1,u_2,u_3) of this vector $\hat{u}$ are:

$$\hat{u} = \left(\overrightarrow{Q_2Q_1} \times \overrightarrow{Q_1Q_3}\right) \cdot \frac{1}{\left|Q_2Q_1 \times Q_1Q_3\right|} \tag{23}$$

To complete the required information, the magnitude of line GP must be computed. Again there are three methods which would yield that length. The average is taken to minimize experimental error. The length GP is obtained by solving the right-angle triangle Q_3GP, given Q_3, G and ρ_3. The procedure is repeated using triangle Q_1GP (Q_1,G,ρ_1) and triangle Q_2GP (Q_2,G,ρ_2), and the average GP is retained.

Finally, the parametric equations of line GP are used to compute the location of P:

$$\begin{aligned} x_p &= x_c + |GP|\, u_1 \\ y_p &= y_c + |GP|\, u_2 \\ z_p &= z_c + |GP|\, u_3 \end{aligned} \tag{24}$$

Once P is located, the components of $\hat{e}_1$, $\hat{e}_2$, and $\hat{e}_3$ may be determined via equations (7), (8), and (9).

A.2.9 Computations of Anatomical Frame

Using the same notation for the anatomical pellets, the inertial position vectors of the four anatomical pellets are:

$$\begin{aligned} OP_1 &= x_1\hat{I} + y_1\hat{J} + z_1\hat{K} \\ OP_2 &= x_2\hat{I} + y_2\hat{J} + z_2\hat{K} \\ OP_3 &= x_3\hat{I} + y_3\hat{J} + z_3\hat{K} \\ OP_4 &= x_4\hat{I} + y_4\hat{J} + z_4\hat{K} \end{aligned} \tag{25}$$

First define the direction cosines of $\hat{j}$-axis or the L-R axis. This may be done by one of two methods:

$$\hat{j} = \frac{\overrightarrow{P_1P_2}}{|P_1P_2|} = \ell_1\hat{I} + m_1\hat{J} + n_1\hat{K}$$

or

$$\hat{j} = \frac{\overrightarrow{P_3P_4}}{|P_3P_4|} = \ell_2\hat{I} + m_2\hat{J} + n_2\hat{K}$$

The two methods are equivalent within some experimental error. To minimize this error, the average is taken as the final direction cosines of unit vector $\hat{j}$, i.e.:

$$\hat{j} = \frac{\ell_1+\ell_2}{2}\hat{I} + \frac{m_1+m_2}{2}\hat{J} + \frac{n_1+n_2}{2}\hat{K} \tag{26}$$

Next, define the S-I or $\hat{k}$ axis. This axis is perpendicular to the Frankfort plane defined by the 4 anatomical pellets. The unit vector $\hat{k}$ must be along the cross product of the vector $\hat{j}$ and any vector P lying in the Frankfort plane. Thus:

$$\hat{k} = \frac{\hat{j} \times \overrightarrow{P_3P_1}}{|\hat{j} \times P_3P_1|} = \ell_1\hat{I} + m_1\hat{J} + n_1\hat{K}$$

or $$\hat{k} = \frac{\hat{j} \times \overrightarrow{P_4P_1}}{|\hat{j} \times P_4P_1|} = \ell_2\hat{I} + m_2\hat{J} + n_2\hat{K}$$

or $$\hat{k} = \frac{\hat{j} \times \overrightarrow{P_3P_2}}{|\hat{j} \times P_3P_2|} = \ell_3\hat{I} + m_3\hat{J} + n_3\hat{K}$$

or $$\hat{k} = \frac{\hat{j} \times \overrightarrow{P_4P_2}}{|\hat{j} \times P_4P_2|} = \ell_4\hat{I} + m_4\hat{J} + n_4\hat{K}$$

The average is then:

$$\hat{k} = \frac{\ell_1+\ell_2+\ell_3+\ell_4}{4}\hat{I} + \frac{m_1+m_2+m_3+m_4}{4}\hat{J} + \frac{n_1+n_2+n_3+n_4}{4}\hat{K} \tag{27}$$

Finally, the direction cosines of the A-P or $\hat{i}$ axis are obtained by the cross product:

$$\hat{i} = \hat{k} \times \hat{j} \qquad (28)$$

Equations (26), (27), and (28) may be written compactly as:

$$\begin{Bmatrix} \hat{i} \\ \hat{j} \\ \hat{k} \end{Bmatrix} = [A] \begin{Bmatrix} \hat{I} \\ \hat{J} \\ \hat{K} \end{Bmatrix}$$

A.2.10 <u>Transformation Matrix [R]</u>

Since the transformation matrix [R], defined by

$$\begin{Bmatrix} \hat{e}_1 \\ \hat{e}_2 \\ \hat{e}_3 \end{Bmatrix} = [R] \begin{Bmatrix} \hat{i} \\ \hat{j} \\ \hat{k} \end{Bmatrix} ,$$

is the desired result, it is simply obtained by:

$$[R] = [E] \; [A]^{-1}$$

The matrix [A] is an orthogonal transformation, therefore, its inverse is equal to its transpose.

$$[A]^{-1} = [A]^T$$

Thus,

$$[R] = [E] \; [A]^T \qquad (29)$$

However, the transformation matrix [R] is computed using experimental readings, its elements will carry some error. Fortunately, this matrix must be orthogonal, a property which can be used to determine the amount of error and to perturbate its elements so that it becomes as close to being orthogonal as desired.

Given the uncorrected matrix:

$$\begin{Bmatrix} \hat{e}_1 \\ \hat{e}_2 \\ \hat{e}_3 \end{Bmatrix} = [R] \begin{Bmatrix} \hat{I} \\ \hat{J} \\ \hat{K} \end{Bmatrix} \qquad (30)$$

the magnitudes of $\hat{e}_1$, $\hat{e}_2$ and $\hat{e}_3$ must be unity; however, the computed values (e_1, e_2, e_3) are assumed to deviate slightly from $(\hat{e}_1, \hat{e}_2, \hat{e}_3)$. If the deviations are not acceptable, a new unit vector is computed using normalized versions of the other two:

$$e_1^* = [e_2/|e_2|] \times [e_3/ |e_3|]$$
$$e_2^* = [e_3/|e_3|] \times [e_1/ |e_1|] \qquad (31)$$
$$e_3^* = [e_1/|e_1|] \times [e_2/ |e_2|]$$

then the old components are replaced by:

$$e_1 = [e_1^* + e_1]/2$$
$$e_2 = [e_2^* + e_2]/2 \qquad (32)$$
$$e_3 = [e_3^* + e_3]/2$$

If the new values of e_1, e_2, e_3 are not acceptable, another iteration is performed. A check on the orthogonality of the matrix is:

$$[R]\,[R]^T = [I] \qquad (33)$$

This equation will be true only if:

$$[R]^T = [R]^I \qquad (34)$$

i.e., when [R] is orthogonal. It was found that 5 iterations were required for the worst case, a case in which the off-diagonal terms of equation (33) started with as high as 0.18 and ended with 0.00001. In all the cases computed, none of the 3 unit vectors were perturbed more than four degrees in space, an amount which can conceivably be produced by measurement errors. It should be noted finally that the exact orthogonality of [R] does not imply that it is the true transformation matrix, instead, this matrix is only a measured one and will carry some experimental error, be it orthogonal or not.

A.2.11 Translation of the Two Origins

In addition to the transformation matrix between the instrumentation and tne anatomical coordinate systems, the location of the instrumentation origin P must be known relative to the anatomical coordinate system, i.e.,

$$\overrightarrow{CP} = d_1\hat{i} + d_2\hat{j} + d_3\hat{k} \qquad (35)$$

This vector can be computed from

$$\overrightarrow{CP} = \overrightarrow{OP} - \overrightarrow{OC}$$

then expressed in the anatomical system. First, the vector OC is by definition

$$\vec{OC} = \frac{1}{2}[\vec{OP}_1 + \vec{OP}_2]$$

$$\vec{OC} = \frac{x_1+x_2}{2}\hat{I} + \frac{y_1+y_2}{2}\hat{J} + \frac{z_1+z_2}{2}\hat{K} \qquad (36)$$

or $\vec{OC} = x_c\,\hat{I} + y_c\,\hat{J} + z_c\,\hat{K}$

and $\vec{OP} = x_p\,\hat{I} + y_p\,\hat{J} + z_p\,\hat{K}$

therefore

$$\vec{CP} = (x_p-x_c)\,\hat{I} + (y_p-y_c)\,\hat{J} + (z_p-z_c)\,\hat{K} \qquad (37)$$

To obtain (d_1,d_2,d_3), the anatomical components of CP, we express CP in the anatomical system:

$$\vec{CP} = \left[(x_p-x_c) \quad (y_p-y_c) \quad (z_p-z_c)\right] \begin{Bmatrix} \hat{I} \\ \hat{J} \\ \hat{K} \end{Bmatrix}$$

Using equation (2), (I,J,K) is substituted to obtain:

$$\left[d_1\ d_2\ d_3\right] = \left[(x_p-x_c) \quad (y_p-y_c) \quad (z_p-z_c)\right] \quad [A]^T \qquad (38)$$

A.2.12 Summary

The x-ray technique described above results in a complete description of an arbitrary instrumentation frame in a standard anatomical frame. The procedure was described for the head, but could easily be extended to any body segment.

APPENDIX A-3

DIGITAL SIGNAL PROCESSING

A.3.1 SIGNAL PROCESSING AND DATA ANALYSIS

The complexity of experimental measurements of head impact situations has become so great, that an equally sophisticated system is required to handle and process the resulting data.

With the availability of digital computers, this task is greatly simplified. First, analog signals are converted to digital signals which are then cleaned up and prepared for subsequent analyses and presentation. The cleaning process consists of truncating undesired portions of the signals, and filtering out frequencies, irrelevant to the anticipated analysis, using high-performance digital filters. The mathematical analyses are more complicated but, with digital computers, can be done with little effort. Finally, results are usually presented in graphical and/or tabular forms for easier interpretation and evaluation of the experiment.

The HSRI signal processing package, developed in the past year is only one phase of the total data handling system, which is diagrammed in figure 1.

A.3.2 Analog-to-Digital Conversion

A general-purpose PDP-11/45 computer, with a 16-channel A/D unit is currently used at HSRI to convert all analog signals into digital form. Since this computer is not dedicated to A/D conversion, its real-time sampling rate is about 130 Hz, which is much lower than the requirements of biomechanical measurements, where events can be as brief as a few milliseconds.

Sampling rate may be increased by playing back the analog tape at a speed lower than the one at which it was recorded. Thus, if a tape was recorded at 120 ips during the experiment, and played back at 1 7/8 ips during digitizing, the sampling rate is multiplied 64 times, resulting in a sampling rate of about 8.3 kHz.

However, in most applications, this sampling rate may not be sufficient. In this case, either a faster digitizing hardware is required, or a further expansion of time is necessary. The latter can simply be accomplished by re-recording the analog signal at

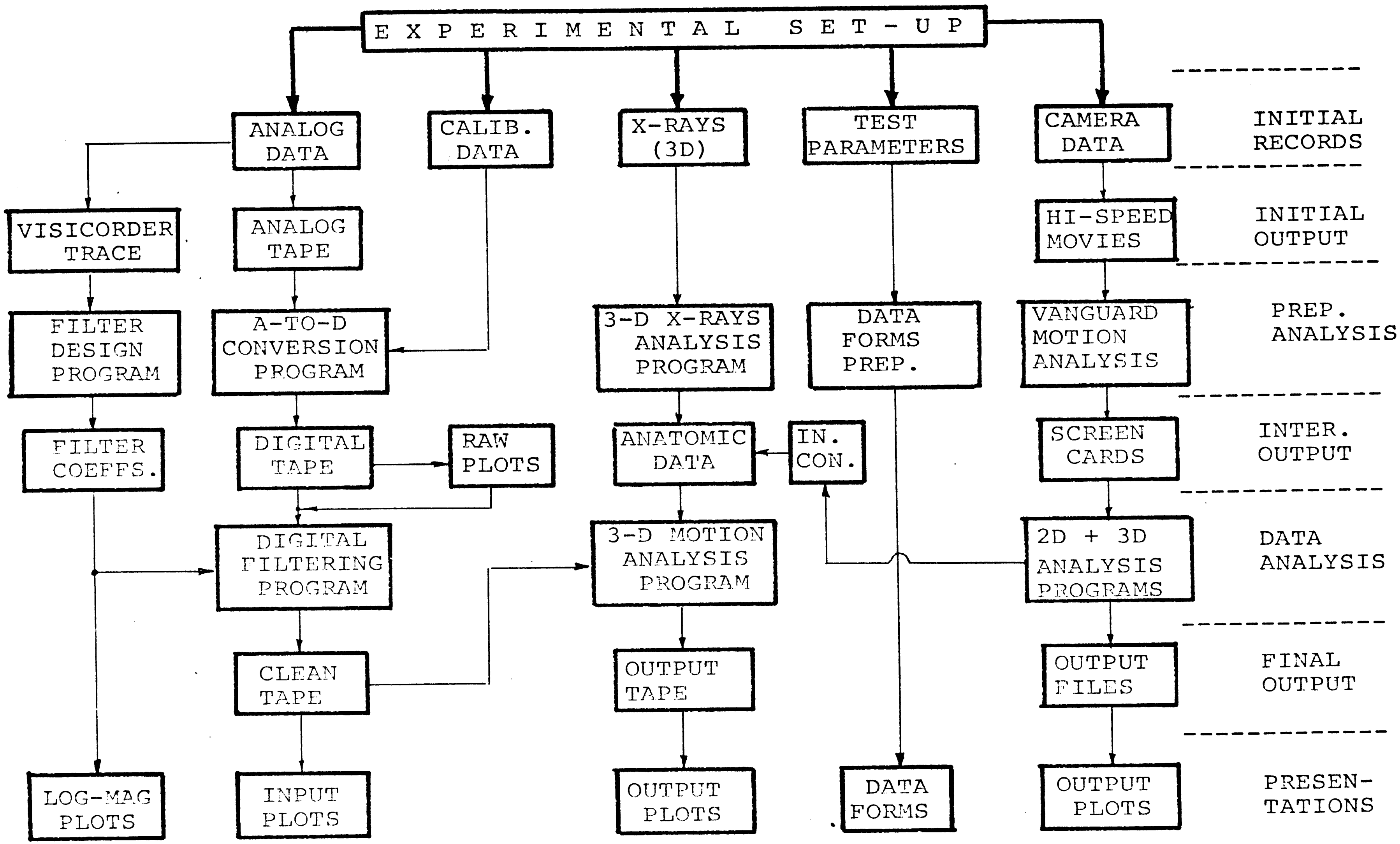


FIGURE 1. HSRI DATA HANDLING SYSTEM

a higher speed than the speed intended for playback. Thus, an analog tape, originally recorded at 120 ips, can be played back at 1 7/8 ips into another recorder, which will re-record the expanded signal at 30 ips. This last recording is played back at 1 7/8 ips during digitizing, resulting in a sampling rate of 133 kHz, which is 16 times higher than previously obtained.

The user has the option of reducing the sampling rate by as much as he desires. This is done by selecting, say every 5th point, to be saved, thus reducing the maximum rate of 133 kHz by a factor of 5 resulting in a final sampling rate of about 2.7 kHz.

The selected samples of data are converted into physical units, and saved on a digital magnetic tape, each channel in a separate file, along with a unique run identification, a description of the contents and the units, the sampling rate and the number of resulting points.

A.3.2.1 The Sampling Process - The operation of sampling can be viewed as a form of impulse modulation. Accordingly, if an analog signal is sampled at the rate of f_s(Hz), i.e., at intervals of $T = 1/f_s$ seconds, then the sampled signal $x^*(t)$ may be represented as a train of impulses given by:

$$x^*(t) = T \sum_{n=0}^{\infty} x(nt)\delta(t-nT) \qquad (1)$$

where

$x(t) = 0$ for $t < 0$

$\delta(t) = 1$ for $t = nT$

$\delta(t) = 0$ for $t \neq nT$

The digital signal $x^*(t)$ is not a continuous function of time, but a sequence of numbers, taken as the values of $x(t)$ at $t = nT$. The z-transform of equation (1) is

$$X^*(z) = T \sum_{n=0}^{\infty} x(nT)z^{-n} \qquad (2)$$

The original signal $x(t)$ can be recovered by passing $x^*(t)$ through an ideal low-pass filter of bandwidth $\pm f_s/2$. The recovery is exact only if the Fourier transform of $x(t)$ is identically zero outside the central strip $\pm f_s/2$. This band is called the Nyquist band, and $f_s/2$ is called the Nyquist rate, which is half the sampling rate.

A.3.2.2 The Sampling Theorem

"If a signal $x(t)$ has a Fourier transform that is identically zero for $|f| \geq B$, it can be completely reconstructed from samples taken at the rate of $f_s \geq 2B$."

The implications of this theorem is that if we sample at a rate $f_s = 1/T$, with f_s sufficiently faster than the Nyquist rate, then we can retrieve the original $x(t)$ by the use of the ideal interpolation operator, which has an impulse response:

$$p(t,n) = \frac{\sin\left[\frac{\pi}{T}(t-nT)\right]}{\frac{\pi}{T}(t-nT)}, \qquad (3)$$

then the recovered signal $x_0(t)$ is given by

$$x_0(t) = \sum_{n=0}^{\infty} x(nT)p(t,n). \qquad (4)$$

Again, $x_0(t)$ will be identical to $x(t)$ only if the analog $x(t)$ is band-limited to the Nyquist band, i.e., if $x(t)$ contained no frequencies higher than half the sampling rate.

To guarantee this, the analog signals may be electronically filtered prior to the A/D conversion process, thus eliminating all frequencies above the Nyquist frequency. If analog filters are to be avoided altogether, then the sampling rate must be sufficiently faster than any suspected frequency component in the analog signal. In measurements of head impacts, frequencies above 10 kHz are not present, therefore the sampling of 27 kHz is adequate for use without analog pre-filters.

A.3.3 Signal Filtering

The presence of high-frequency components in the digital signals is undesirable. These components are usually noises or mechanical resonances of transducers which are not relevant to the physical quantity being measured. To eliminate these components, analog filtering may be employed. However, the cut-off frequencies must change depending on the signal being measured. Sophisticated analog filters are expensive and usually have a fixed cut-off frequency. Variable filters of equal sophistication are large and bulky, so that the only alternative is digital filtering.

A.3.3.1 Digital Filters - Just like analog filters, digital filters have input-output response, but they can be "constructed" at a much lower cost, and are just as easy to use.

The output/input transfer function of a general linear system may be transformed to a digital transfer function of the form:

$$H^*(z) = \frac{\sum_{j=0}^{N-1} a_j z^{-j}}{1 + \sum_{j=1}^{N} b_j z^{-j}} \tag{5}$$

Equation (5) is used to compute the current value of the output y(nT), given current value of the input x(nT) and previous values of the input and output:

$$y(kT) = \sum_{j=0}^{N-1} a_j x(kT-jT) - \sum_{j=1}^{N} b_j y(kT-jT) \tag{6}$$

The order N of the filter must be finite in order to reconstruct the signal. Furthermore, the data is reconstructed using a finite number of impulse responses, hence the term finite duration impulse response (FIR) filter.

The case where all the b-coefficients in equation (5) are zero reduce the transfer function to:

$$H^*(z) = \sum_{j=0}^{N-1} a_j z^{-j} \tag{7}$$

The filter is then classified as a non-recursive digital filter, since it does not use previous values of the output, as can be seen from equation (6) with only the a-coefficient.

A.3.3.2 FIR Filter Design - Any finite-duration sequence is completely specified by N samples of its Fourier transform, so that the design of an FIR filter may be accomplished by finding N coefficients of its impulse response. The truncation of the infinite duration impulse response of the first N terms means that discontinuities at the corner-frequencies are replaced by smoother transitions. Accompanying this transition is some under- and over-shoots which are generally described as the Gibbs phenomenon.

The frequency response of an FIR filter is no longer flat in its pass- and stop-bands, but contains some ripples which vary in magnitudes depending on the design characteristics of the filter. These ripples may be spread uniformly over the frequency spectrum, resulting in an equiripple design. For a given filter length N, and a given set of corner (edge) frequencies and band gains, an optimum filter becomes one which has the minimum peak-to-peak ripple.

The Alternation theorem (Parks & McClellan, 1970) is the basis for finding such optimum filters. Essentially, this theorem implies that there is a precise number of frequencies corresponding to peaks in the error function describing the ripples in the magnitude frequency response. Armed with this theorem, an optimum filter may be found by searching (on the frequency axis) for the "best" extremal frequencies, i.e., those for which the ripples satisfy a specified tolerance.

Subsequently, McClellan & Parks (1973) published a paper in which they present a general purpose computer program which is capable of designing a large class of optimum non-recursive linear-phase FIR digital filters. The search algorithm is based on the Remez exchange method, which is a fast method to approximate an ideal frequency response using the minimum weighted Chebychev error. The program replaces the specified design by an equivalent problem, then solves the approximation of the equivalent problem using the Remez exchange method, then produces, among others, the filter impulse response.

The program now used at HSRI to design digital filters is based on the McClellan design program. However, it is an interactive program, where a user can use a terminal to design, test, check frequency response and save, if he so desires, the impulse response of an acceptable filter on a master file containing all the filters designed up to date. This master file is effectively a "storage shelf" for all the digital filters, and when a filter is needed, it is either pulled out of the "shelf," or a new filter is designed and saved if none of the available filters fits the requirements.

A.3.3.3 <u>The Filtering Operation</u> - An FIR digital filter of Length L, is specified by M terms of its impulse response:

$$h(m); \quad m = 1, 2, \ldots M.$$

The impulse response is symmetric, i.e.,

$$h(1+k) = h(M-k); \quad k = 1, L. \tag{8}$$

Given then a finite number M terms of its impulse response, and given a digital signal specified as a sequence of N values:

$$x(n); \quad n = 1,2, \ldots N,$$

the filtered signal is given by:

$$y(n) = \sum_{k=1}^{M} x(n-k)\, h(k) \tag{9}$$

Note that the furthest point of the unfiltered signal which can be used is x(n-M) which cannot be smaller than x(1); therefore, the first filtered point is y(M+1). This also implies that the digital signal must have at least M points to produce at least 1 filtered point. Furthermore, the last filtered point which may be produced is y(n+1), by using the last M points of the unfiltered signal. This results in an output signal which is shorter than the input signal, and which is phase shifted with respect to the input signal.

The first problem may be solved by extending the input signal below the first point. This is done by rotating ths signal 180 degrees about the first point. Thus:

$$x(1-k) - x(k) = -[x(1+k) - x(1)]$$

or

$$x(1-k) = 2x(1) = x(1+k) \qquad (10)$$

The extension is carried out until enough points are generated to produce y(1), i.e., k = 1,2, ... (M-1).

The time delay problem is inherent in non-recursive filters. However, this problem can be solved either by making a correction in the phase when the phase frequency-response is known, or by using the filter itself to shift back the signal by the same amount.

The latter method of filtering forward, then filtering backwards is an outstanding method, since in general, each component is shifted by an amount depending on its frequency. Because the frequency content of a given signal is not known a priori, each component which the filter passes is phase-shifted during the forward operation, but it is shifted back by exactly the same amount during the backward operation.

However, for the backward filtering operation, the first point generated is the (N-M)th point, leaving the last M points unprocessed. In order to be able to obtain the Nth point of the signal in a filtered form, the input signal must be extended (M-1) points beyond the last point, much the same way the extension was done for the beginning of the signal. Thus:

$$x(N+k) - x(N) = -[x(N-k) - x(N)]$$

or

$$x(N+k) = 2x(N) - x(N-k) \qquad (11)$$

with k = 1,2, ... (M-1).

In this forward/backward operation, the gains of the various bands are doubled. For example, a low-pass filter with a pass-band ripple of ±0.1 dB and a stop-band gain of -65 dB and a considerable phase-shift, effectively becomes a filter with a pass-band ripple of ±0.2 dB which is still excellent, a stop-band gain of -130 dB, which surpasses any stringent design specification, and best of all, it becomes phase transparent.

Therefore, the method of applying a given filter should be taken into consideration during its design. Thus, if a low-pass filter must have a gain of -60 dB in the stop-band and ±0.1 dB ripple in the pass-band, and is to be applied twice to a signal, it is sufficient to loosen the stop gain to -30 dB, and to tighten the pass ripple to ±0.05 dB. This should decrease the length of the filter, and possibly shorten the transition band.

A.3.4 Filter Specifications

During a head impact test, forces, accelerations, strains and/or pressures are recorded. For each of these quantities, low-pass filter characteristics are nominally specified by their corner frequencies:

a. impact force (lbs) $f_c = 500$ Hz
b. accelerations (g's) $f_c = 1000$ Hz
c. strains (μ in/in) $f_c = 1500$ Hz
d. pressures (psi) $f_c = 1500$ Hz.

For a given low-pass filter, the corner frequency is specified in normalized form,

$$f_c = f_c^* \cdot f_s$$

where: f_c is the corner frequency in Hz,
f_s is the sampling rate in Hz,
f_c^* is the normalized corner frequency of filter.

Most of the data was digitized at the rate of $f_s = 27000$ Hz, and the later data at the rate of 16000 Hz. It was therefore necessary to employ two different filters for each sampling rate, to achieve a filtering at the given corner freauency.

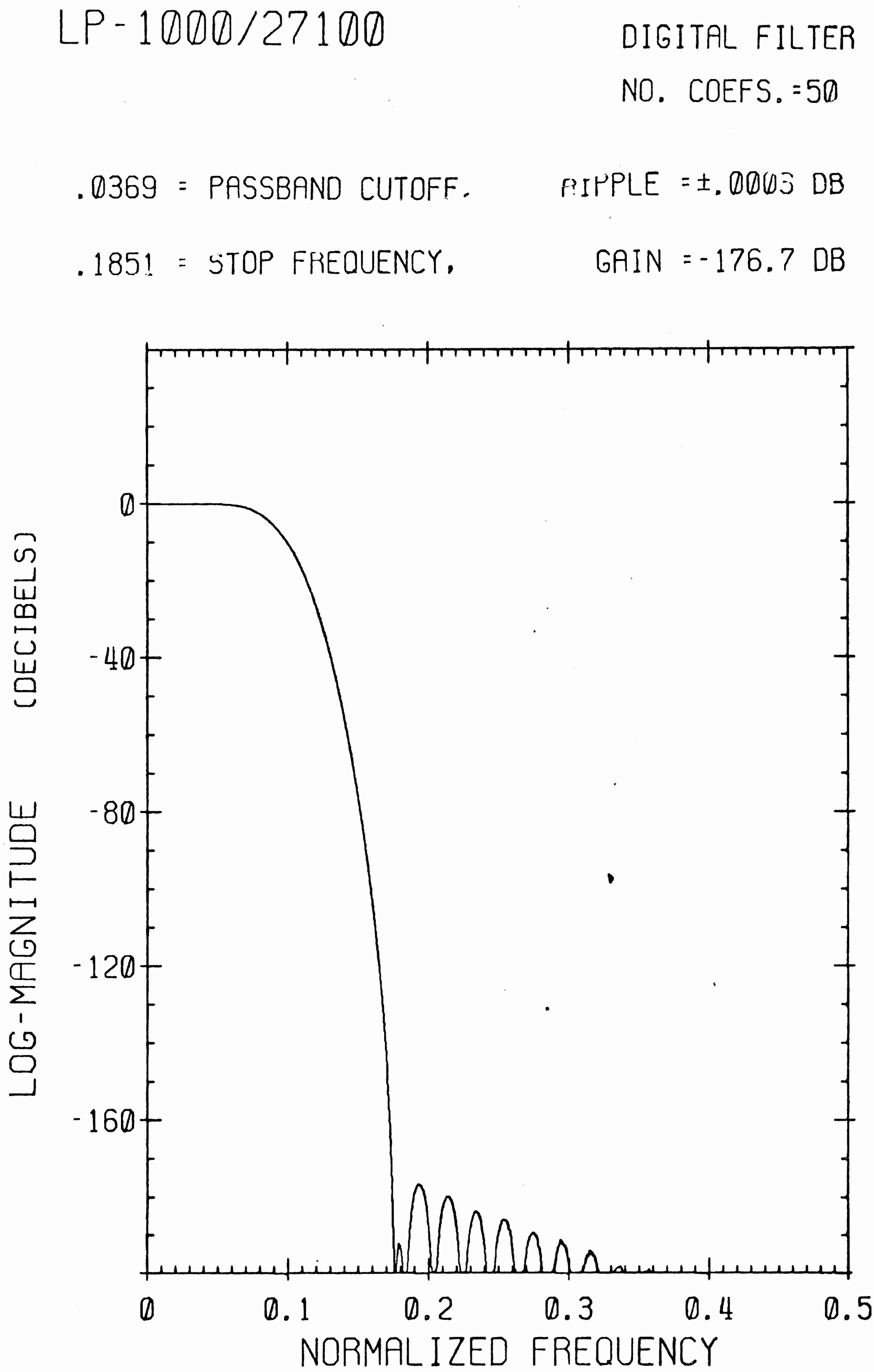
Finally, it should be realized that the digital filters used are linear phase, with the knee at the corner frequency round and not as sharp as the Butterworth filters more commonly used. Typically therefore, a corner frequency of 1000 Hz means that the filter would have -3 dB gain at approximately 1500 Hz and -7.5 dB at approximately 2000 Hz. Consequently, the filters used were tolerated if the -3 dB point was between 1000 and 1500 Hz.

The following filters were used in processing the head impact data; the selection of the appropriate filter depended on the sampling rate and the availability of the filter at the time the data was processed:

FORCE	ACCELERATIONS	STRAINS/PRESSURES
LP -100/27100	LP-1000/27100	LP-2000/27100
LP.04*WS	LP.05*WS	LP.09*WS

The frequency response of these filters are shown in Figures 2, 3, 4, 5 and 6.

Figure 2.



LP-1000/27100
DIGITAL FILTER
NO. COEFS.=50
.0369 = PASSBAND CUTOFF.
RIPPLE =±.0003 DB
.1851 = STOP FREQUENCY,
GAIN =-176.7 DB
0
-40
-80
-120
-160
LOG-MAGNITUDE (DECIBELS)
0
0.1
0.2
0.3
0.4
0.5
NORMALIZED FREQUENCY

Figure 3

LP.040*WS

DIGITAL FILTER
NO. COEFS.=50

.0400 = PASSBAND CUTOFF, RIPPLE =±.0736 DB

.1200 = STOP FREQUENCY, GAIN =-174.0 DB

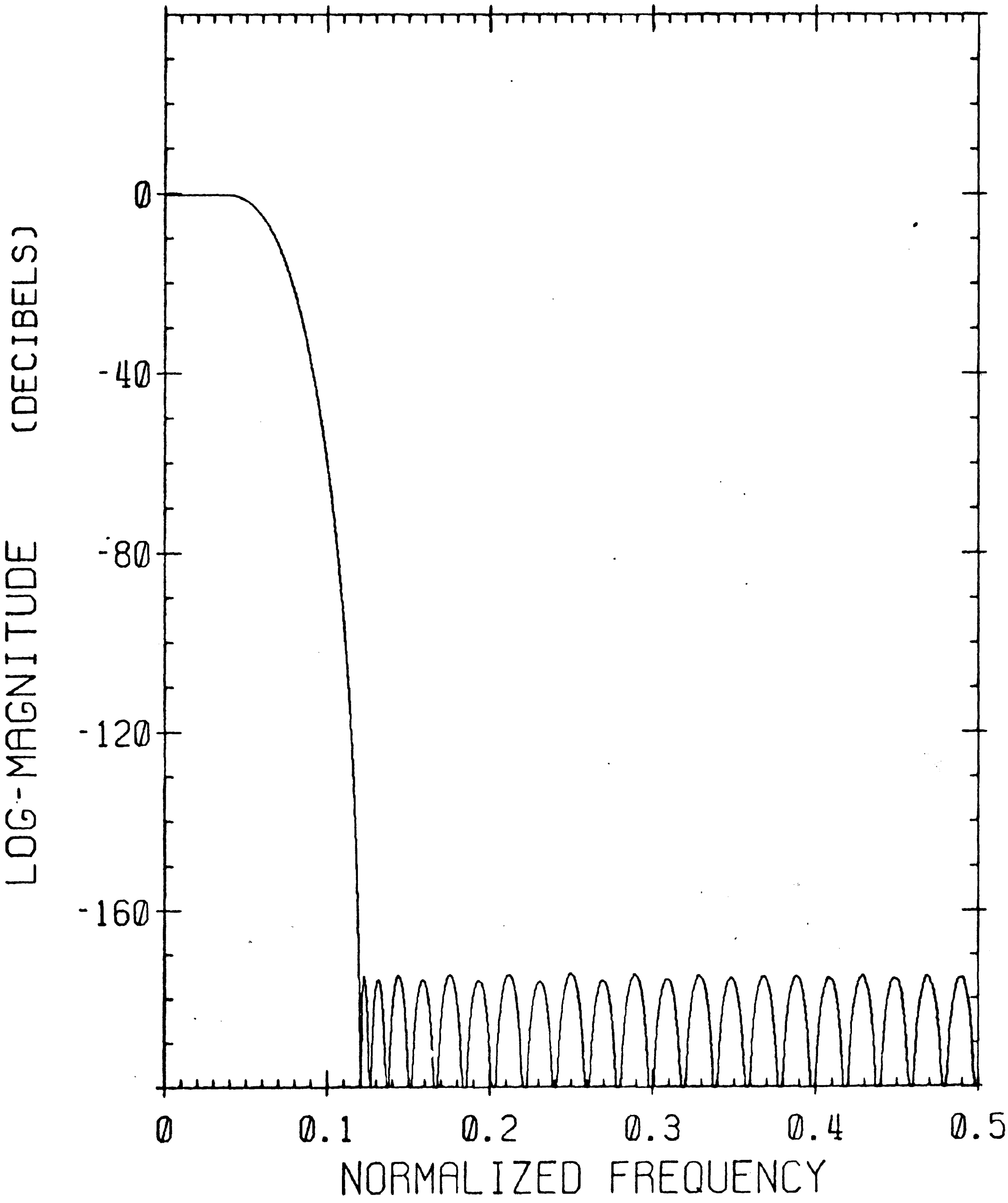
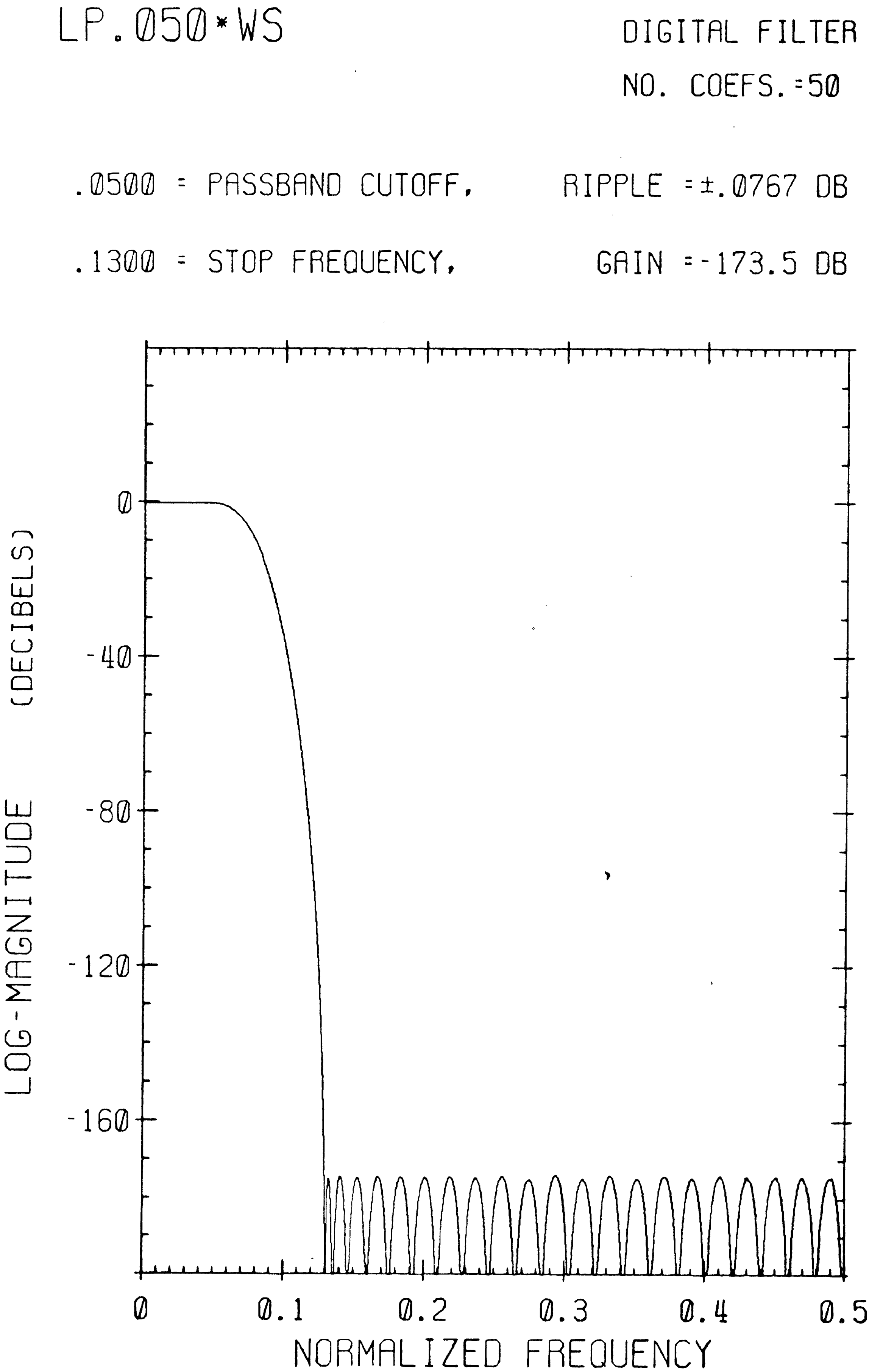


Figure 4.



LP.050*WS
DIGITAL FILTER
NO. COEFS.=50
.0500 = PASSBAND CUTOFF,
RIPPLE =±.0767 DB
.1300 = STOP FREQUENCY,
GAIN =-173.5 DB
0
-40
-80
-120
-160
LOG-MAGNITUDE (DECIBELS)
0
0.1
0.2
0.3
0.4
0.5
NORMALIZED FREQUENCY

Figure 5.

LP-2000/27100 DIGITAL FILTER

NO. COEFS.=50

.0738 = PASSBAND CUTOFF, RIPPLE =±.0006 DB

.2220 = STOP FREQUENCY, GAIN =-183.0 DB

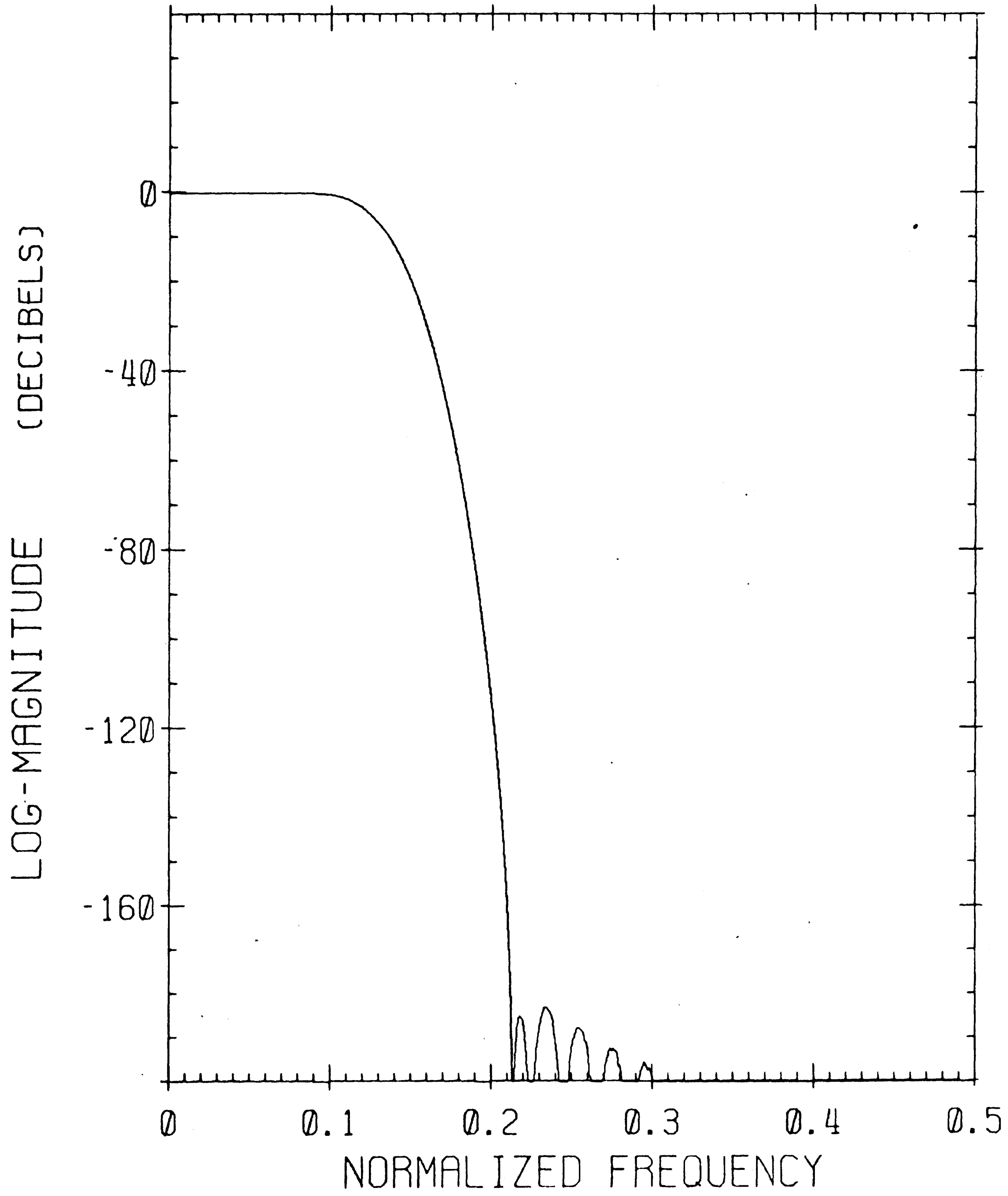
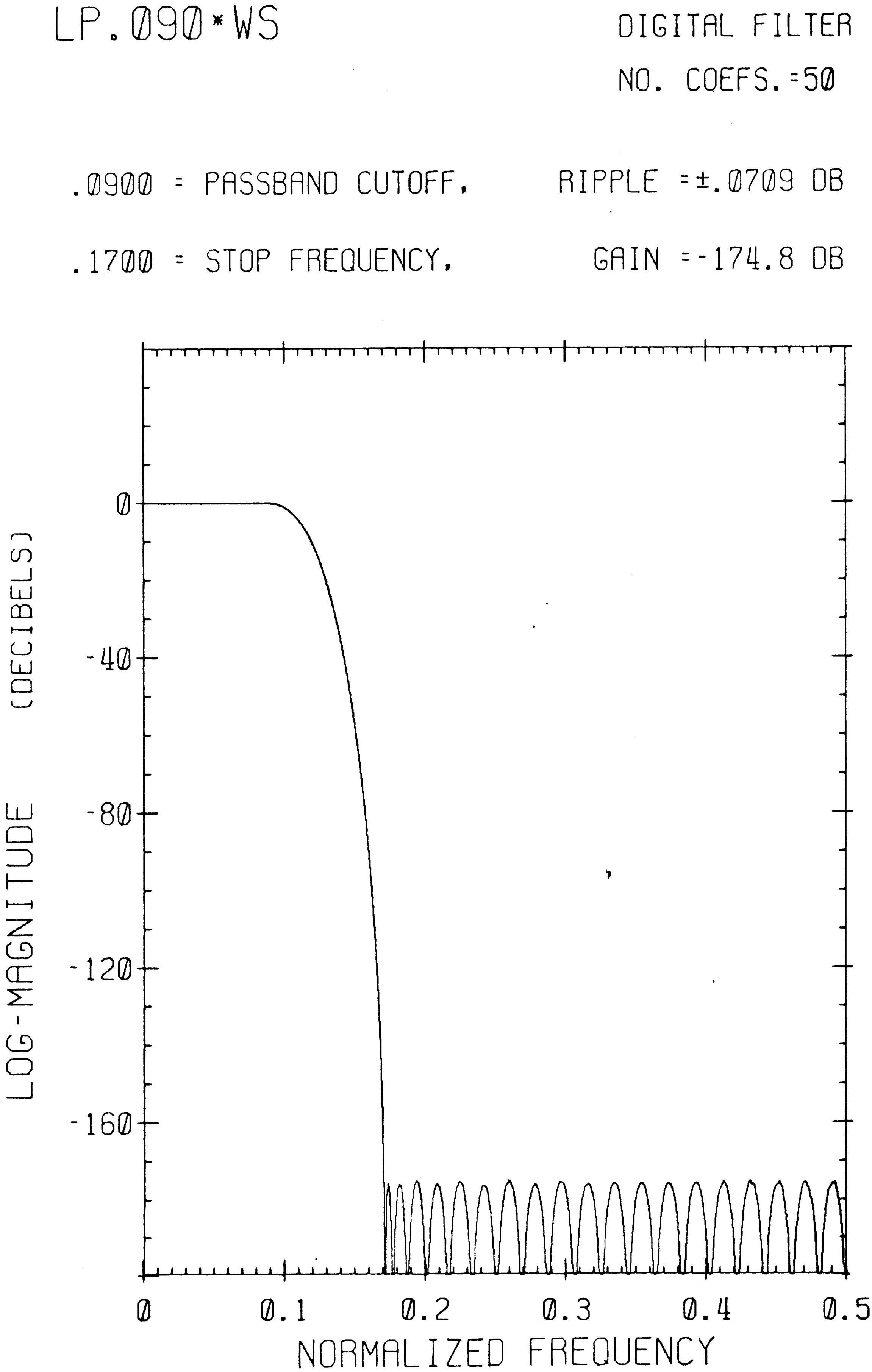


Figure 6.



LP.090*WS
DIGITAL FILTER
NO. COEFS.=50
.0900 = PASSBAND CUTOFF,
RIPPLE =±.0709 DB
.1700 = STOP FREQUENCY,
GAIN =-174.8 DB
0
-40
-80
-120
-160
LOG-MAGNITUDE (DECIBELS)
0
0.1
0.2
0.3
0.4
0.5
NORMALIZED FREQUENCY

APPENDIX B

TEST RESULTS

APPENDIX B-1

STATIC SKULL

APPENDIX B-1a

MONKEY SKULL I

METHODOLOGY FOR RHESUS MONKEY STATIC SKULL COMPRESSION TESTS

Four rosette strain gages were mounted on the skull as shown in Figures 1, 3. The skull was loaded along the L-R, A-P, and S-I directions, and LVDT's measured the resulting displacements (e.g., see Figure 2). The speed of the Instron crosshead was set at 0.1 inches per second, and a Visicorder recorded the output of the strain rosettes, load cell and LVDT's.

Principal strains and principal stresses for delta rosettes were calculated from the following equations:

$$\varepsilon_{1,2} \quad \frac{\varepsilon_A+\varepsilon_B+\varepsilon_C}{3} \pm \sqrt{\left(\varepsilon_A - \frac{\varepsilon_A+\varepsilon_B+\varepsilon_C}{3}\right)^2 + \frac{(\varepsilon_C-\varepsilon_B)^2}{3}}$$

$$\sigma_{1,2} = E\left(\frac{\varepsilon_A+\varepsilon_B+\varepsilon_C}{3\,(1-\mu)} \pm \frac{1}{1+\mu}\sqrt{\left(\varepsilon_A - \frac{\varepsilon_A+\varepsilon_B+\varepsilon_C}{3}\right)^2 + \frac{(\varepsilon_C-\varepsilon_B)^2}{3}}\right)$$

$$\tan 2\phi_{1,2} = \frac{\left[-\sqrt{3}\,(\varepsilon_C-\varepsilon_B)\right]}{\left[-2\varepsilon_A - (\varepsilon_B-\varepsilon_C)\right]} = \frac{\sqrt{3}\,(\varepsilon_B-\varepsilon_C)}{\varepsilon_B+\varepsilon_C-2\varepsilon_A}$$

where

$\varepsilon_{1,2}$ are the maximum and minimum principal strains, respectively

$\varepsilon_A, \varepsilon_B, \varepsilon_C$ are the strains at gages A, B, and C

$\sigma_{1,2}$ are the maximum and minimum principal stresses, respectively

ϕ_1 is the angle between the axis of gage A and the direction of maximum principal strain, ε_1

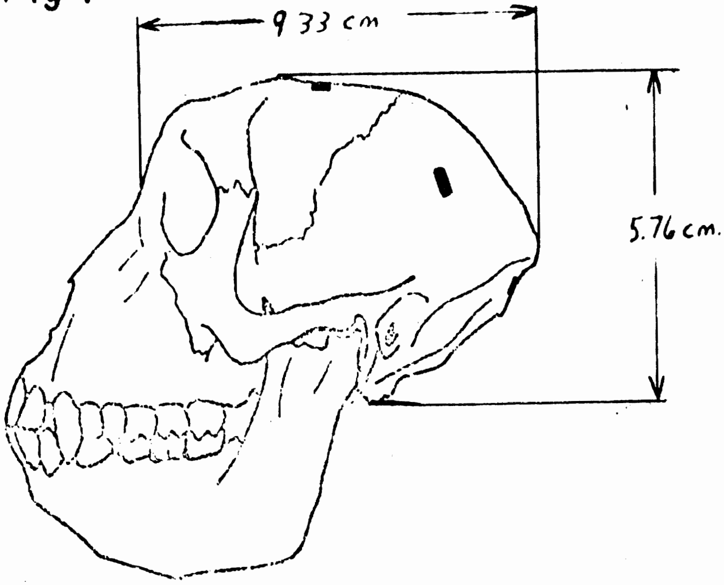
ϕ_2 is the angle between the axis of gage A and the direction of minimum principal strain ε_2. All angles are measured counterclockwise from gage A.

$E = 1.78 \times 10^5$ psi for compact table in tension

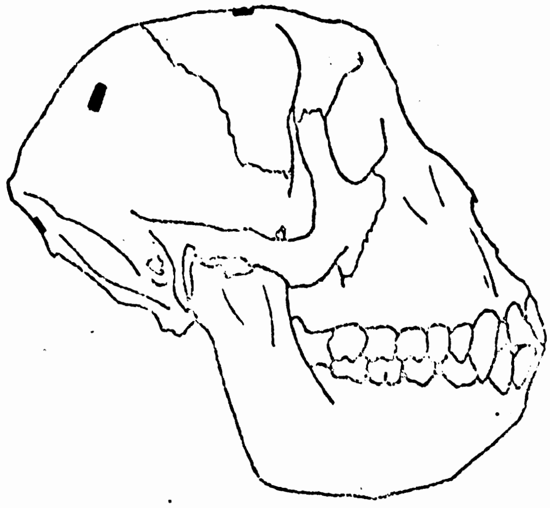
$\mu = 0.19$ in radial compression

Fig. 1: Skull Dimensions and Rosette Positions

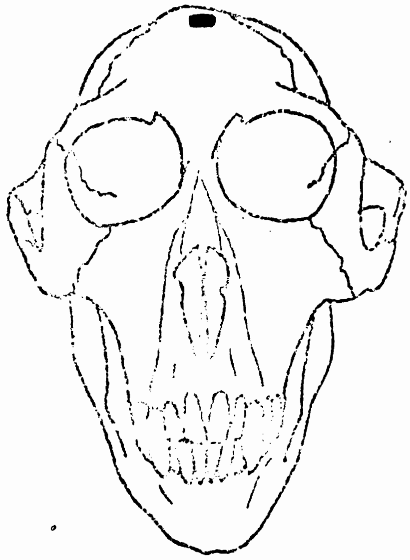
Skull 1



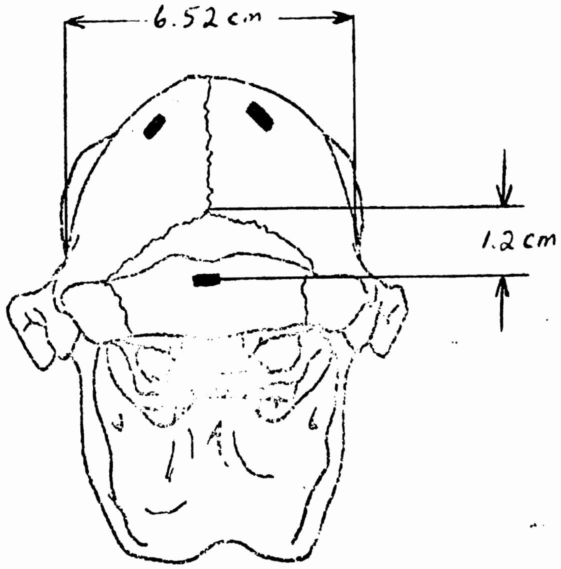
Left Lateral View



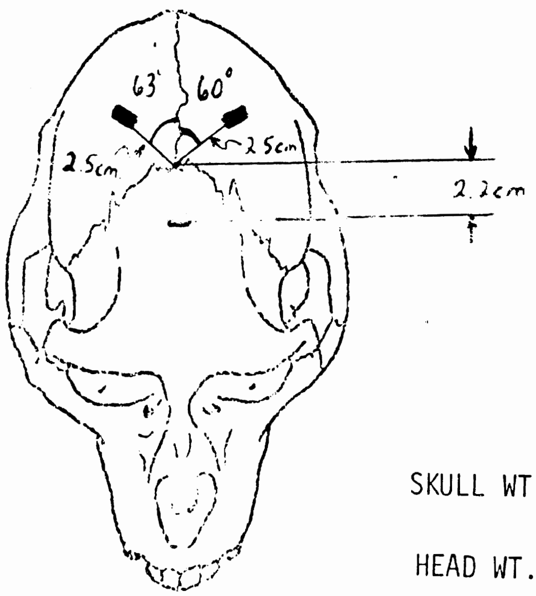
Right Lateral View



Anterior View



Posterior View

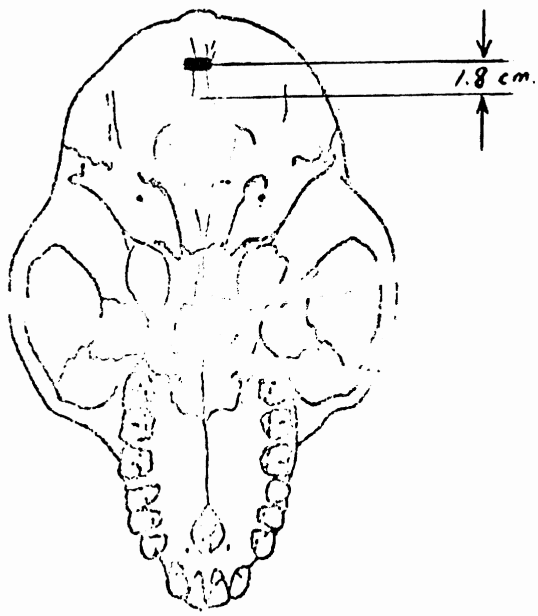


Superior View

SKULL WT. .57 kg.

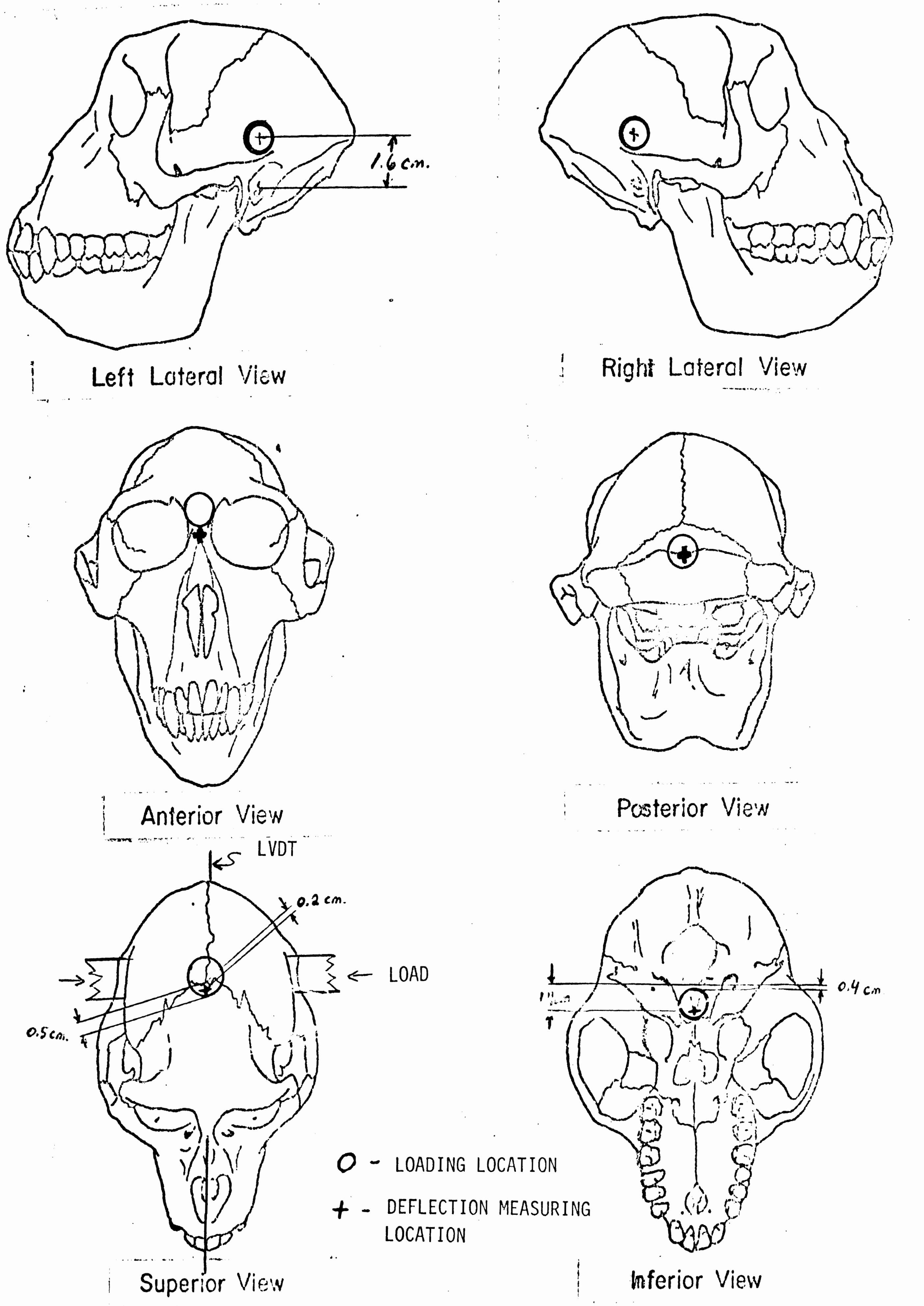
HEAD WT. .69 kg.

MONKEY WT. 7.6 kg



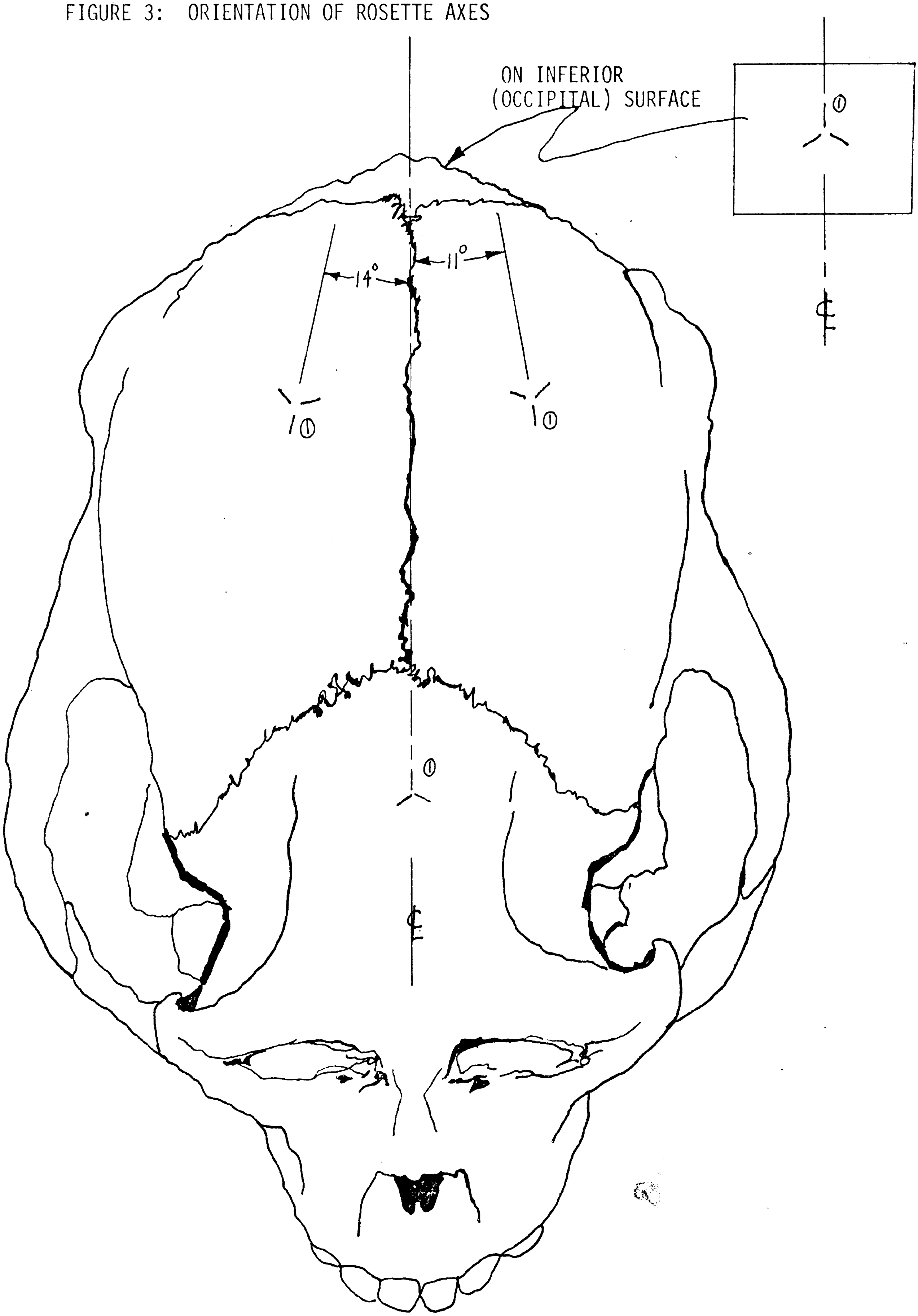
Inferior View

Fig 2: Loading and Deflection Measuring Locations Skull 1



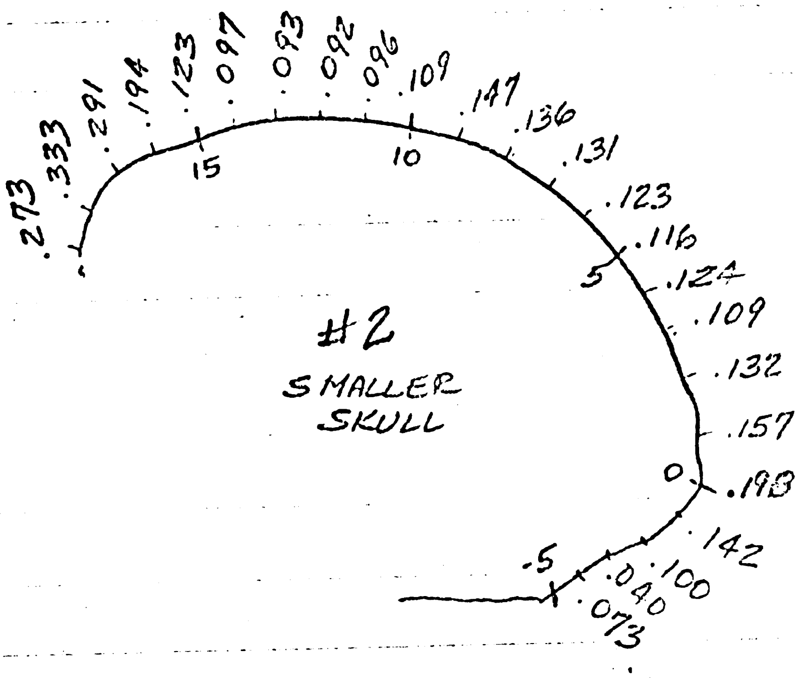
SKULL 1

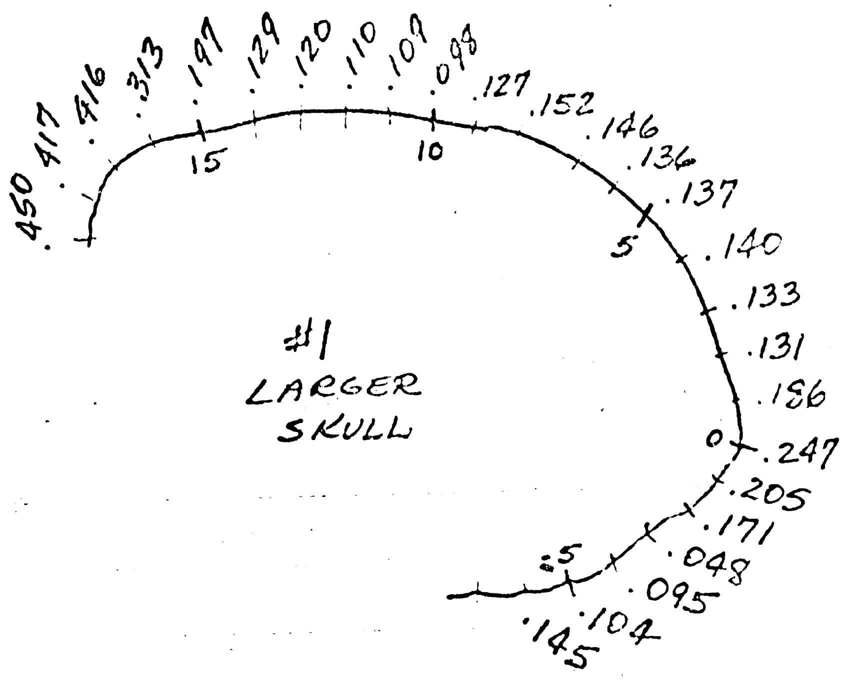
FIGURE 3: ORIENTATION OF ROSETTE AXES



SUPERIOR VIEW

THE DIMENSIONS WERE TAKEN ALONG THE CIRCUMFERENCE EVERY .250 INCHES. THE THICKNESS IS MEASURED IN INCHES AS SHOWEN ON THE SKULL AND BELOW.





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RHESUS MONKEY SKULL COMPRESSION TEST

SKULL NO. 1 RUN NO. 4

LOADING L-R HORIZONTAL LVDT A-P

TIME BETWEEN READINGS 4 sec.

NO.	VERT LOAD (LBS)	HORIZ. DISPL. (IN) x 10^{-3}	VERTICAL COMP. (IN) x 10^{-3}
1	0	LOD	0
2	17	LOD	-6.25
3	38	LOD	-13.50
4	65	LOD	-19.75
5	96	LOD	-26.25
6	128	LOD	-32.25
7	163	LOD	-37.75
8	198	LOD	-43.75

LOD - Loss of Data

ALL STRAINS IN MICRO-INCHES/INCH

RIGHT ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	1.4	-18.0	14.4
3	5.4	-45.8	25.9
4	19.3	-97.3	19.7
5	35.1	-150.6	17.2
6	54.2	-215.4	16.2
7	78.2	-281.6	16.0
8	115.7	-357.7	16.0

LEFT ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	4.9	-33.0	38.9
3	0.4	-59.1	-34.5
4	0.0	-99.2	-29.6
5	0.3	-145.5	-27.2
6	2.4	-203.5	-23.8
7	5.1	-256.6	-22.0
8	3.0	-307.8	-24.3

FRONT ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	0.1	-19.8	-34.3
3	-4.9	-28.3	-13.7
4	-6.1	-42.4	-22.4
5	-4.4	-55.2	-17.6
6	3.6	-74.5	-12.6
7	13.6	-95.9	-6.8
8	10.7	-119.6	-6.5

REAR ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	18.5	-4.2	-25.5
3	38.7	-4.0	-17.7
4	61.2	4.4	-11.0
5	87.3	19.8	-21.5
6	111.0	27.1	-24.7
7	143.7	46.0	-20.3
8	182.1	50.5	-13.6

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RHESUS MONKEY SKULL COMPRESSION TEST

SKULL NO. 1 RUN NO. 6

LOADING S-I HORIZONTAL LVDT A-P

TIME BETWEEN READINGS 2 sec.

*preload

NO.	VERT LOAD (LBS)	HORIZ. DISPL. (IN) x 10^{-3}	VERTICAL COMP. (IN) x 10^{-3}
1	2*	DNA	-10.75
2	3	DNA	-11.00
3	11	DNA	-14.50
4	21	DNA	-17.25
5	31	DNA	-19.50
6	41	DNA	-23.25
7	54	DNA	-26.75
8	64	DNA	-29.75
9	75	DNA	-32.75

DNA = Data Not Available

ALL STRAINS IN MICRO-INCHES/INCH

FRONT ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	2.2	-6.7	--
2	3.7	-8.1	-10.1
3	15.6	-15.6	-15.0
4	27.8	-12.2	-8.3
5	32.5	-10.4	-13.1
6	37.2	-1.9	-17.4
7	34.6	3.0	-9.9
8	33.7	19.4	2.6
9	30.7	26.8	-12.6

SKULL 1, RUN 6 (Continued)

REAR ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	6.1	-2.0	--
2	6.4	-4.4	39.6
3	6.6	-18.9	-38.3
4	10.3	-39.3	-43.1
5	6.8	-62.6	-37.8
6	-5.5	-77.1	-34.9
7	-10.9	-98.5	-34.1
8	43.8	-141.7	41.3
9	57.3	-167.7	41.1

RIGHT ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	6.0	-17.2	-20.4
3	13.2	-55.3	-19.1
4	13.9	-117.6	-26.6
5	13.7	-185.5	-28.0
6	0.1	-244.5	-30.9
7	-5.4	-305.8	-30.6
8	-10.8	-353.7	-30.3
9	-16.2	-388.6	-30.5

LEFT ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	3.3	-10.0	0.0
2	3.0	-15.2	6.2
3	-3.0	-42.7	26.1
4	-9.5	-80.7	28.0
5	-16.0	-134.3	29.9
6	-38.1	-176.4	33.2
7	-47.3	-235.6	33.8
8	-62.7	-274.0	34.9
9	-78.8	-295.5	34.8

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RHESUS MONKEY SKULL COMPRESSION TEST

SKULL NO. 1 RUN NO. 7

LOADING S-I HORIZONTAL LVDT L-R

TIME BETWEEN READINGS 2 sec

*preload

NO.	VERT LOAD (LBS)	HORIZ. DISPL. (IN) x 10^{-3}	VERTICAL COMP. (IN) x 10^{-3}
1	1*	0	-1.50
2	11	0	-4.00
3	19	.368	-6.50
4	26	.789	-9.25
5	35	1.316	-12.50
6	44	1.737	-15.50
7	52	2.316	-18.00
8	62	3.158	-21.00
9	71	3.684	-23.75

ALL STRAINS IN MICRO-INCHES/INCH

REAR ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	0.3	-15.0	22.0
3	-6.1	-31.4	28.5
4	-6.1	-44.0	28.6
5	-9.2	-68.1	28.6
6	-21.4	-76.6	28.2
7	-32.8	-96.5	23.1
8	-48.7	-107.4	25.8
9	-51.4	-136.4	17.8

SKULL 1, Run 7 (Continued)

RIGHT ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	2.7	-45.8	-30.1
3	0.0	-98.0	-29.4
4	-2.6	-137.2	-31.3
5	-9.7	-179.1	-34.5
6	-13.0	-229.1	-32.8
7	-15.6	-264.9	-32.7
8	-13.1	-305.4	-32.0
9	-16.1	-350.6	-31.0

LEFT ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	-2.6	-34.8	38.1
3	-14.4	-70.7	39.9
4	-6.5	-113.9	39.8
5	-13.1	-154.1	38.3
6	-18.7	-191.9	38.4
7	-33.7	-226.8	39.1
8	-41.8	-266.4	39.6
9	-56.1	-304.3	40.4

FRONT ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	16.8	-3.6	-23.7
3	20.1	-0.3	-23.4
4	23.0	3.3	-34.0
5	16.7	9.8	-42.8
6	27.4	10.1	-2.1
7	32.7	9.2	-11.3
8	34.9	11.5	-16.8
9	37.1	7.3	-27.2

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RHESUS MONKEY SKULL COMPRESSION TEST

SKULL NO. 1 RUN NO. 11

LOADING L-R HORIZONTAL LVDT S-I

TIME BETWEEN READINGS 4 sec.

*preload

NO.	VERT LOAD (LBS)	HORIZ. DISPL. (IN) x 10^{-3}	VERTICAL COMP. (IN) x 10^{-3}
1	4*	.526	-1.25
2	23	1.737	-7.75
3	47	2.579	-13.75
4	70	3.631	-20.00
5	100	4.263	-26.25
6	130	5.105	-33.50
7	161	5.972	-39.75
8	190	6.731	-46.00

ALL STRAINS IN MICRO-INCHES/INCH

RIGHT ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	10.9	-45.9	24.7
3	15.1	-103.1	18.5
4	45.0	-137.9	14.0
5	60.8	-176.9	17.3
6	70.1	-225.4	15.6
7	73.1	-300.2	16.2
8	92.5	-359.3	13.1

LEFT ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	-9.5	-26.8	-18.8
3	-16.6	-57.9	-25.9
4	-22.0	-67.5	-19.3
5	-24.2	-109.7	-19.6
6	-19.7	-163.7	-14.3
7	-23.8	-219.2	-17.0
8	-20.4	-282.4	-17.0

FRONT ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	15.9	-18.5	12.8
3	15.5	-38.4	17.2
4	5.8	-53.0	11.7
5	6.3	-64.5	4.9
6	17.5	-91.6	4.2
7	25.0	-114.6	0.1
8	28.5	-135.5	-3.9

REAR ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	9.2	-3.1	--
2	35.0	-4.4	-19.5
3	67.6	4.2	-17.0
4	95.6	30.1	-16.4
5	127.1	46.2	-22.2
6	162.6	66.7	-27.1
7	200.2	74.4	-24.7
8	238.3	94.1	-22.7

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RHESUS MONKEY SKULL COMPRESSION TEST

SKULL NO. 1 RUN NO. 15

LOADING A-P HORIZONTAL LVDT S-I

TIME BETWEEN READINGS 2 sec.

*preload

NO.	VERT LOAD (LBS)	HORIZ. DISPL. (IN) x 10^{-3}	VERTICAL COMP. (IN) x 10^{-3}
1	1*	0	-.50
2	21	.105	-3.00
3	46	.474	-6.00
4	76	.789	-8.75
5	113	1.368	-12.00
6	151	1.895	-15.25
7	183	2.631	-18.00
8	236	3.105	-20.50

ALL STRAINS IN MICRO-INCHES/INCH

RIGHT ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	31.9	-18.0	6.9
3	59.7	-29.8	8.8
4	88.2	-40.5	10.4
5	140.6	-64.0	11.8
6	180.5	-106.2	10.8
7	217.9	-140.2	11.4
8	261.5	-177.5	11.3

SKULL 1, RUN 15 (Continued)

LEFT ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	26.4	-18.7	-10.1
2	52.2	-34.6	-9.1
3	88.3	-52.0	-8.8
4	128.2	-74.1	-7.2
5	160.4	-99.7	-8.3
6	209.9	-113.5	-8.7
7	260.8	-148.6	-9.4
8	183.5	-96.7	-10.0

FRONT ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	21.1	-23.1	-7.9
3	37.2	-45.4	-1.8
4	57.4	-78.3	1.9
5	77.5	-113.5	0.6
6	104.6	-153.2	1.1
7	135.5	-198.7	2.7
8	169.2	-247.1	2.3

REAR ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
[illegible]	0.0	-0.0	--
2	160.6	60.5	14.8
3	333.7	154.0	15.4
4	565.5	239.5	14.3
5	871.8	322.2	12.2
6	1072.0	486.9	16.1
7	1334.7	616.0	15.4
8	1611.9	751.0	16.7

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RHESUS MONKEY SKULL COMPRESSION TEST

SKULL NO. 1 RUN NO. 16

LOADING A-P HORIZONTAL LVDT L-R

TIME BETWEEN READINGS 2 sec.

*preload

NO.	VERT LOAD (LBS)	HORIZ. DISPL. (IN) $\times 10^{-3}$	VERTICAL COMP. (IN) $\times 10^{-3}$
1	22*	0	5.00
2	45	.263	7.50
3	80	1.053	11.00
4	119	1.842	13.75
5	158	2.631	16.25
6	200	3.526	19.00
7	234	4.210	21.50

ALL STRAINS IN MICRO-INCHES/INCH

RIGHT ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	24.1	-21.8	13.6
3	67.7	-46.5	15.1
4	108.3	-80.5	13.2
5	128.5	-115.6	13.5
6	196.3	-162.7	12.3
7	238.6	-207.2	12.3

LEFT ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	31.2	-20.2	-8.8
3	62.3	-44.7	-8.5
4	103.8	-70.0	-8.5
5	141.0	-93.7	-9.2
6	187.6	-119.6	-7.4
7	216.0	-154.3	-5.6

FRONT ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	13.5	-26.4	-0.7
3	37.3	-71.6	2.3
4	64.1	-109.0	0.6
5	94.7	-154.3	2.0
6	131.9	-201.7	2.0
7	162.5	-244.9	2.4

REAR ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	176.5	61.4	16.8
3	417.2	162.6	15.9
4	673.6	285.4	16.6
5	953.3	401.7	17.2
6	1225.7	545.7	17.8
7	1461.3	655.9	17.7

APPENDIX B-1b

MONKEY SKULL II

METHODOLOGY FOR RHESUS MONKEY STATIC SKULL COMPRESSION TESTS

Four rosette strain gages were mounted on the skull as shown in Figures 1, 3. The skull was loaded along the L-R, A-P, and S-I directions, and LVDT's measured the resulting displacements (e.g., see Figure 2). The speed of the Instron crosshead was set at 0.1 inches per second, and a Visicorder recorded the output of the strain rosettes, load cell and LVDT's.

Principal strains and principal stresses for delta rosettes were calculated from the following equations:

$$\varepsilon_{1,2} \quad \frac{\varepsilon_A+\varepsilon_B+\varepsilon_C}{3} \pm \sqrt{\varepsilon_A - \left(\frac{\varepsilon_A+\varepsilon_B+\varepsilon_C}{3}\right)^2 + \frac{(\varepsilon_C-\varepsilon_B)^2}{3}}$$

$$\sigma_{1,2} = E\left(\frac{\varepsilon_A+\varepsilon_B+\varepsilon_C}{3\,(1-\mu)} \pm \frac{1}{1+\mu}\sqrt{\left(\varepsilon_A - \frac{\varepsilon_A+\varepsilon_B+\varepsilon_C}{3}\right)^2 + \frac{(\varepsilon_C-\varepsilon_B)2}{3}}\right)$$

$$\tan 2\phi_{1,2} = \frac{\left[-3\,(\varepsilon_C-\varepsilon_B)\right]}{\left[-2\varepsilon_A - (\varepsilon_B-\varepsilon_C)\right]} = \frac{3\,(\varepsilon_B-\varepsilon_C)}{\varepsilon_B+\varepsilon_C-2\varepsilon_A}$$

where

$\varepsilon_{1,2}$ are the maximum and minimum principal strains, respectively

$\varepsilon_A, \varepsilon_B, \varepsilon_C$ are the strains at gages A, B, and C

$\sigma_{1,2}$ are the maximum and minimum principal stresses, respectively

ϕ_1 is the angle between the axis of gage A and the direction of maximum principal strain, ε_1

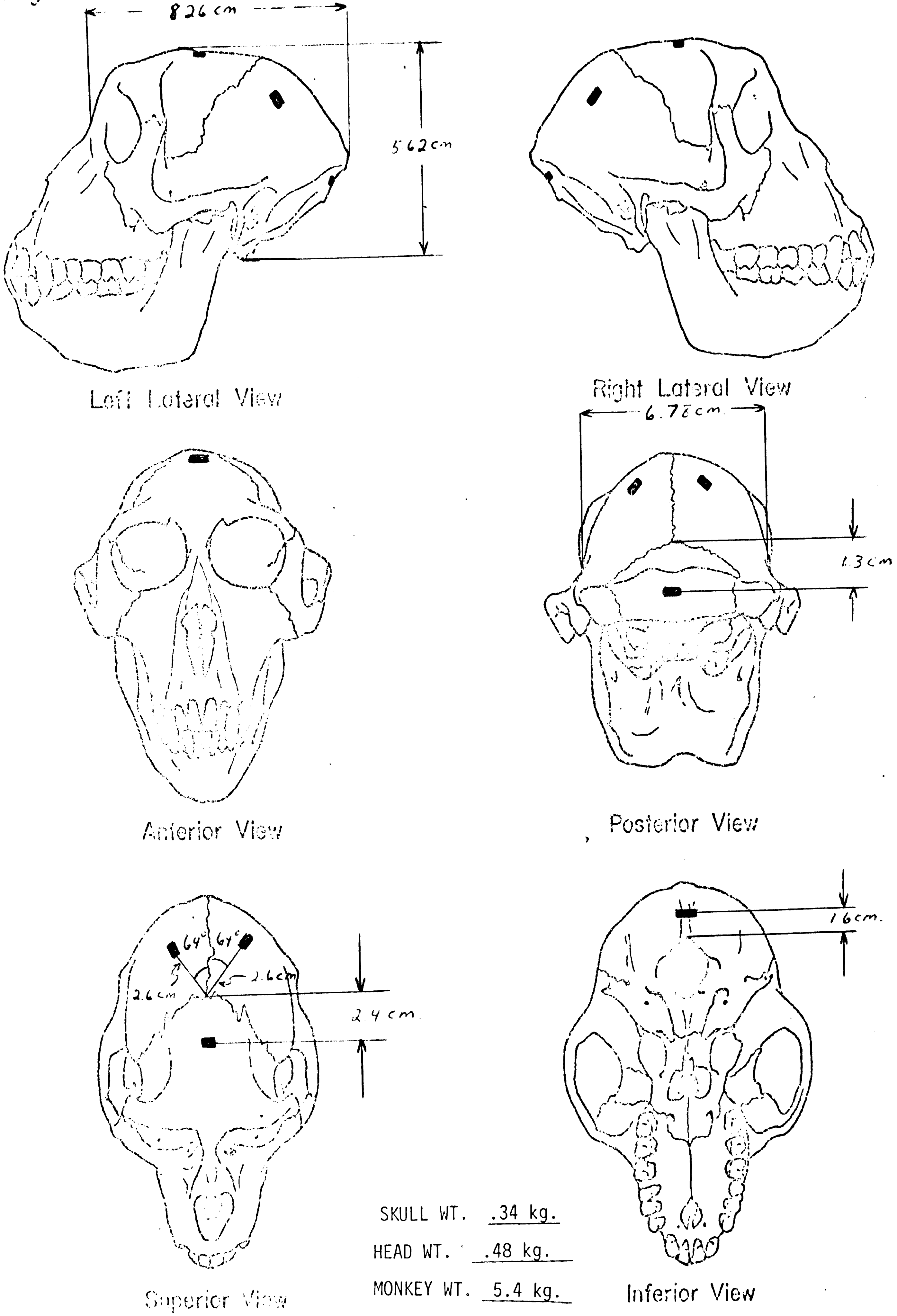
ϕ_2 is the angle between the axis of gage A and the direction of minimum principal strain ε_2. All angles are measured counterclockwise from gage A.

$E = 1.78 \times 10^5$ psi for compact table in tension

$\mu = 0.19$ in radial compression

Fig. I: Skull Dimensions and Rosette Positions

Skull 2

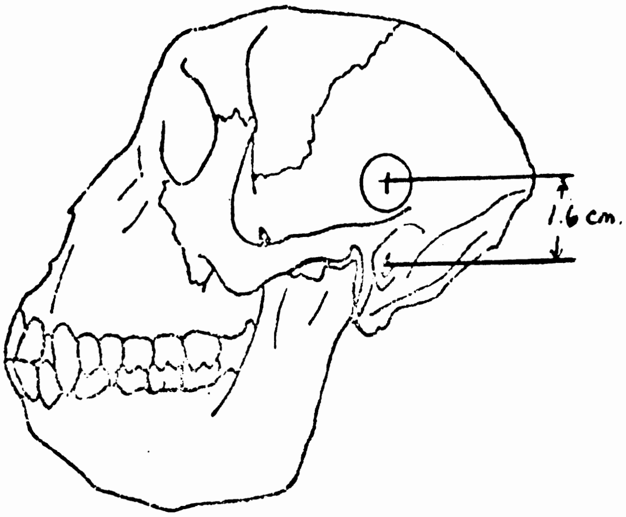


SKULL WT. .34 kg.

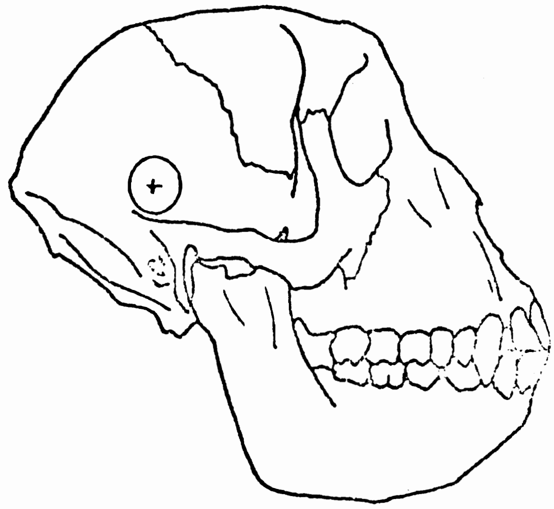
HEAD WT. .48 kg.

MONKEY WT. 5.4 kg.

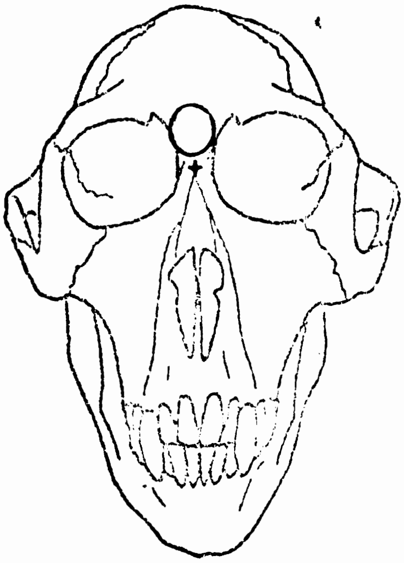
Fig. 2: Loading and Deflection Measuring Locations   Skull 2



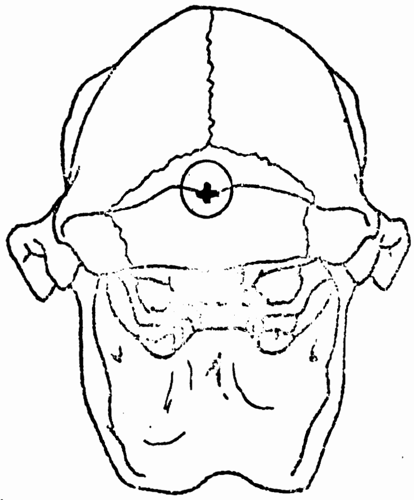
Left Lateral View



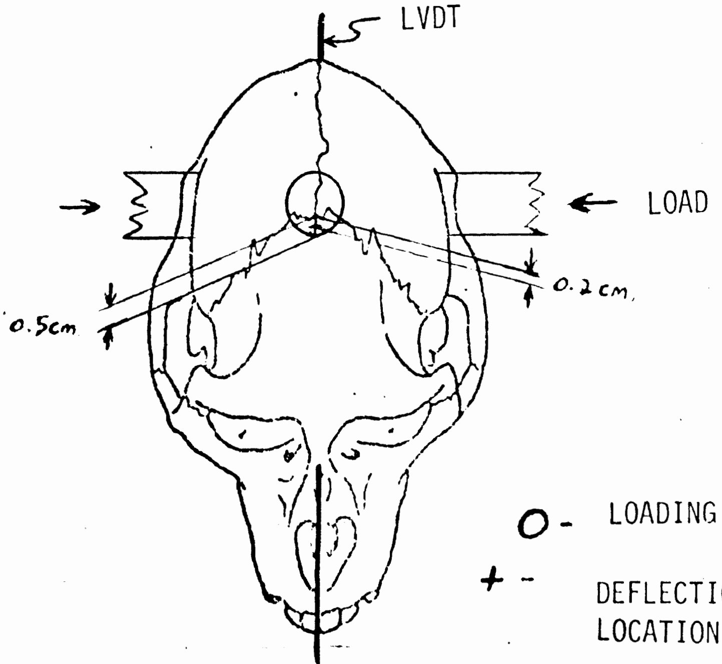
Right Lateral View



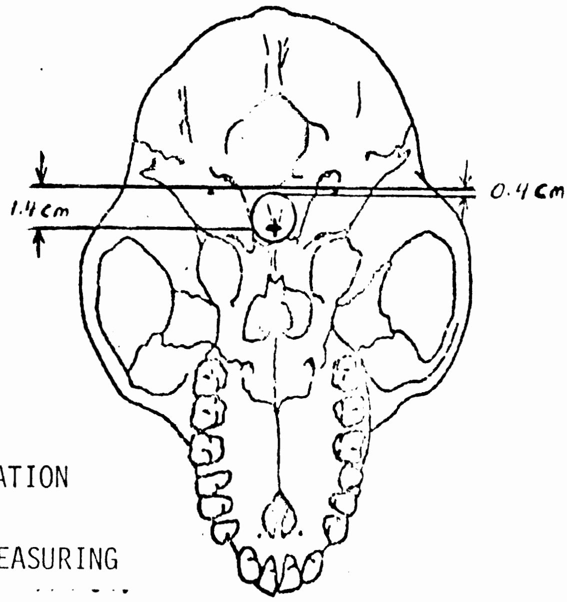
Anterior View



Posterior View



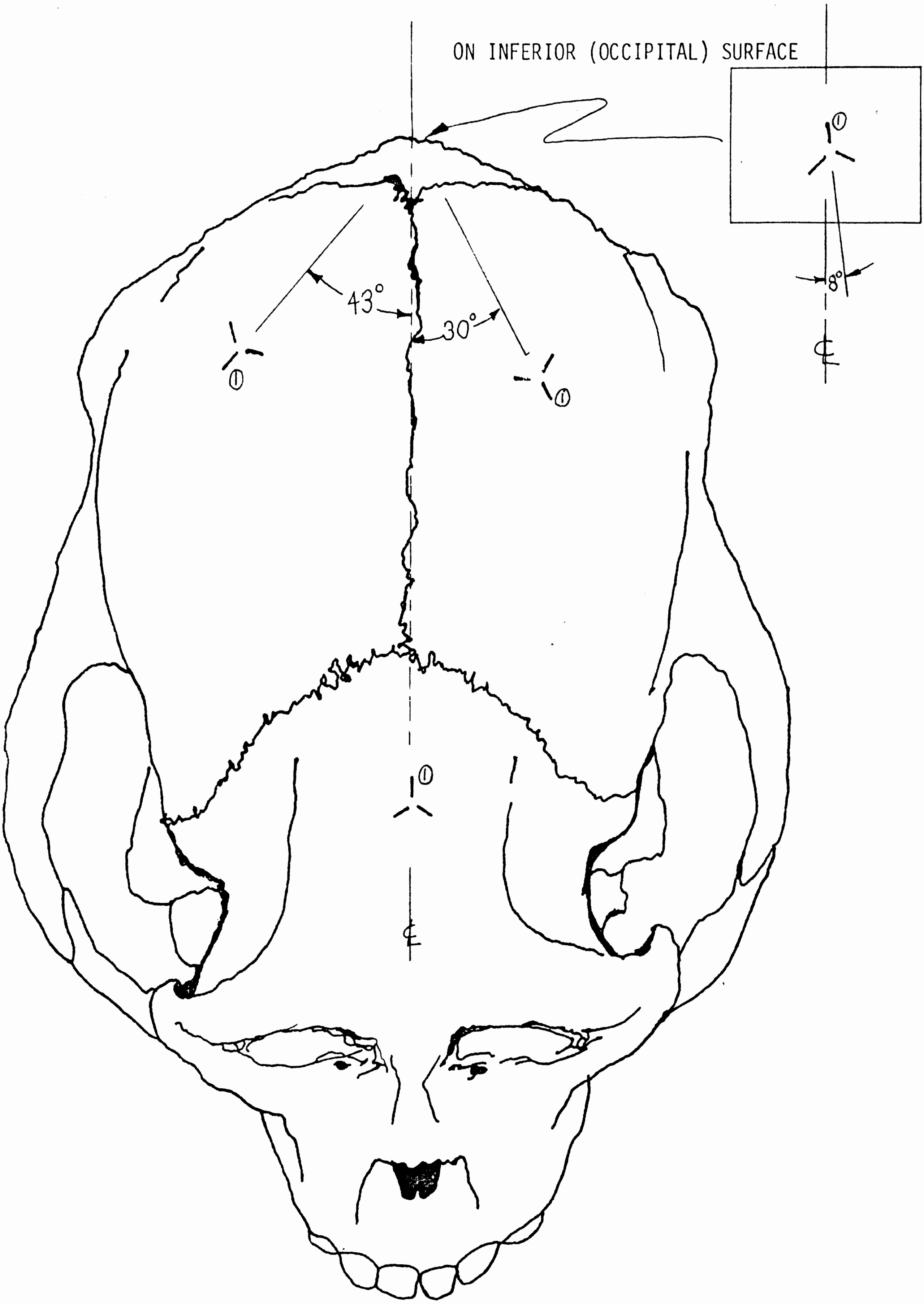
Superior View



Inferior View

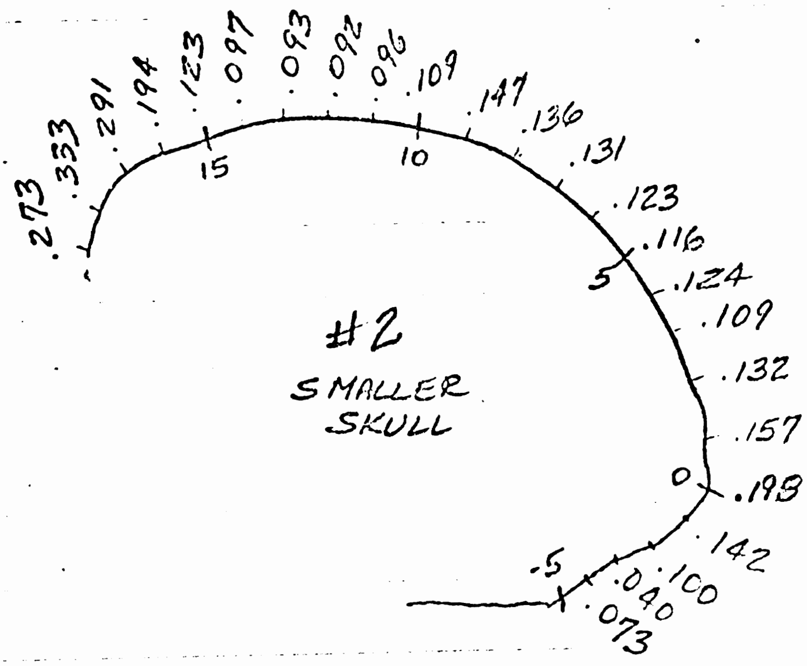
FIGURE 3: ORIENTATION OF ROSETTE AXES

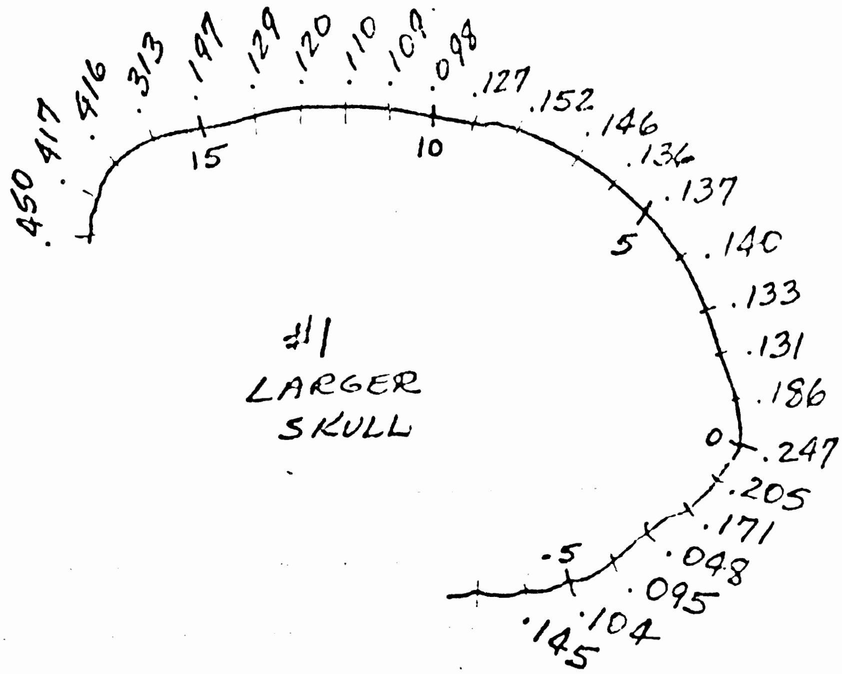
SKULL 2



SUPERIOR VIEW

THE DIMENSIONS WERE TAKEN ALONG THE CIRCUMFERENCE EVERY .250 INCHES. THE THICKNESS IS MEASURED IN INCHES AS SHOWEN ON THE SKULL AND BELOW.





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RHESUS MONKEY SKULL COMPRESSION TEST

SKULL NO. 2 RUN NO. 2

LOADING L-R HORIZONTAL LVDT A-P

TIME BETWEEN READINGS 4 sec

* = Preload

NO.	VERT LOAD (LBS)	HORIZ. DISPL. (IN) x 10^{-3}	VERTICAL COMP. (IN) x 10^{-3}
1	10*	.25	-7.5
2	20	.25	-11.25
3	40	.25	-17.8
4	60	.75	-25.0
5	82	1.95	-32.0
6	109	2.95	-38.75
7	130	2.8	-46.0

ALL STRAINS IN MICRO-INCHES/INCH

RIGHT ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	-
2	28.9	-39.1	23.7
3	42.2	-111.8	31.3
4	56.5	-194.6	32.1
5	84.7	-301.7	31.9
6	113.1	-389.3	32.1
7	141.6	-491.1	32.4

SKULL NO. 2, RUN 2 (continued)

LEFT ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	9.8	-17.3	36.9
3	17.9	-102.2	43.7
4	34.0	-197.0	42.9
5	43.3	-294.3	-44.4
6	61.3	-359.1	-42.3
7	74.6	-477.3	-40.5

FRONT ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	12.8	-24.0	-83.9
3	20.8	-53.3	-73.4
4	39.9	-77.0	-76.6
5	44.1	-105.8	-79.8
6	55.4	-128.5	-81.7
7	53.7	-144.5	-82.9

REAR ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	32.8	4.5	-16.2
3	98.1	20.5	-2.8
4	171.5	24.1	1.5
5	244.8	47.8	0.3
6	312.2	74.3	1.1
7	367.4	90.2	1.4

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RHESUS MONKEY SKULL COMPRESSION TEST

SKULL NO. 2 RUN NO. 4

LOADING L-R HORIZONTAL LVDT S-I

TIME BETWEEN READINGS 4 sec

NO.	VERT LOAD (LBS)	HORIZ. DISPL. (IN) x 10^{-3}	VERTICAL COMP. (IN) x 10^{-3}
1	0	1.25	0
2	15	1.25	-3.75
3	29	1.3	-9.5
4	46	1.65	-15.75
5	65	3.95	-21.25
6	85	4.85	-27.5
7	108	5.6	-33.25
8	132	6.8	-38.75
9	155	8.7	-43.75

ALL STRAINS IN MICRO-INCHES/INCH

FRONT ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	12.8	-24.0	6.1
3	30.4	-44.3	4.8
4	51.8	-68.3	5.0
5	66.2	-92.0	4.6
6	81.6	-116.3	5.4
7	90.7	-136.6	5.2
8	93.7	-166.4	4.0
9	104.0	-194.3	5.0

Skull 2, Run 4

REAR ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	30.9	12.5	-7.2
3	76.6	22.5	-2.9
4	125.5	37.4	1.3
5	180.9	49.9	3.0
6	238.7	69.7	0.5
7	293.9	82.3	1.7
8	352.0	113.1	1.3
9	404.4	128.6	2.5

LEFT ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	7.8	-37.8	-42.6
3	14.7	-99.0	43.6
4	23.7	-168.0	43.6
5	45.0	-260.4	40.6
6	53.6	-344.0	42.3
7	66.0	-450.1	44.3
8	79.2	-570.0	-44.3
9	91.6	-664.9	-43.9

RIGHT ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	53.4	-34.0	28.5
3	84.6	-97.4	32.4
4	99.4	-173.4	33.6
5	95.7	-246.8	31.3
6	123.6	-334.8	29.7
7	126.5	-440.3	30.7
8	146.4	-537.3	31.2
9	168.6	-642.9	30.4

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RHESUS MONKEY SKULL COMPRESSION TEST

SKULL NO. 2 RUN NO. 10

LOADING S-I HORIZONTAL LVDT L-R

TIME BETWEEN READINGS 4 sec

NO.	VERT LOAD (LBS)	HORIZ. DISPL. (IN) x 10^{-3}	VERTICAL COMP. (IN) x 10^{-3}
1	0	0.0	0.0
2	1	0.0	-4.25
3	9	0.3	-8.75
4	21	0.35	-15.5
5	36	0.15	-20.75
6	50	-0.05	-26.75
7	62	-0.35	-32.0

ALL STRAINS IN MICRO-INCHES/INCH

REAR ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	6.8	-5.9	13.0
3	-2.0	-9.3	-21.9
4	21.1	-28.4	-13.6
5	50.2	-42.0	-12.5
6	68.6	-55.2	-14.1
7	69.3	-57.9	-14.6

FRONT ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	15.8	-14.4	39.9
3	27.5	-23.2	16.0
4	44.7	-41.6	5.7
5	68.7	-58.6	5.7
6	91.3	-58.8	2.6
7	104.5	-54.3	1.0

LEFT ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	0.0	-0.0	--
3	6.2	-34.3	-83.1
4	14.4	-109.9	-87.0
5	31.9	-174.3	-83.2
6	39.8	-253.4	-83.9
7	32.3	-300.2	-85.2

RIGHT ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	-2.5	-42.1	-15.3
3	-9.7	-114.0	-7.2
4	-20.6	-178.3	-5.2
5	-44.0	-230.0	-6.4
6	-83.6	-277.2	-5.5
7	-104.1	-133.9	-30.0

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RHESUS MONKEY SKULL COMPRESSION TEST

SKULL NO. 2 RUN NO. 11

LOADING S-I HORIZONTAL LVDT A-P

TIME BETWEEN READINGS 4 Sec

*preload

NO.	VERT LOAD (LBS)	HORIZ. DISPL. (IN) x 10^{-3}	VERTICAL COMP. (IN) x 10^{-3}
1	5*	2.0	0.
2	18	2.15	-2.5
3	26	4.5	-9.25
4	40	6.35	-15.0
5	55	9.6	-21.25
6	68	14.0	-27.5
7	80	15.7	-33.75

ALL STRAINS IN MICRO-INCHES/INCH

RIGHT ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	0.0	-0.0	--
3	3.2	-29.4	-11.7
4	-8.6	-96.6	-6.2
5	-9.8	-156.5	-6.6
6	-9.4	-184.6	-6.1
7	-6.6	-245.1	-6.9

SKULL 2, RUN 11 (Continued)

LEFT ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	2.2	-30.3	-15.0
3	-2.3	-93.2	-4.1
4	-6.8	-154.4	-7.6
5	-10.6	-208.6	-3.3
6	6.6	-261.3	-0.3
7	11.2	-309.1	0.3

FRONT ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	17.4	-10.7	8.1
3	37.1	-29.5	0.6
4	57.7	-26.2	4.0
5	85.7	-58.1	5.7
6	107.8	-57.4	0.3
7	121.7	-62.7	2.6

REAR ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	16.0	-19.5	7.9
3	24.5	-53.0	0.0
4	19.9	-79.3	-7.1
5	-2.0	-97.4	-16.0
6	-32.7	-125.6	-19.3
7	-69.8	-153.4	-25.8

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RHESUS MONKEY SKULL COMPRESSION TEST

SKULL NO. 2 RUN NO. 15

LOADING A-P HORIZONTAL LVDT S-I

TIME BETWEEN READINGS 4 sec

NO.	VERT LOAD (LBS)	HORIZ. DISPL. (IN) x 10^{-3}	VERTICAL COMP. (IN) x 10^{-3}
1	0	2.5	0
2	13	2.7	-3.75
3	36	3.0	-10.25
4	65	2.85	-17.0
5	105	3.7	-23.5
6	151	5.15	-30.0
7	201	6.2	-36.75
8	250	6.3	-43.25
9	293	6.5	-47.5

ALL STRAINS IN MICRO-INCHES/INCH

REAR ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	28.5	3.6	-11.3
3	76.2	14.2	-22.2
4	131.3	25.5	-22.1
5	202.1	34.9	-24.0
6	268.9	55.2	-23.2
7	344.2	71.2	-22.0
8	416.9	89.9	-23.0
9	487.7	98.2	-23.0

SKULL 2, RUN 15 (Continued)

FRONT ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	21.5	-0.0	27.6
3	41.7	-18.2	21.4
4	61.7	-35.7	16.4
5	89.5	-54.6	14.1
6	116.2	-86.6	9.0
7	145.5	-142.8	6.7
8	178.3	-179.7	7.7
9	205.8	-226.0	7.3

LEFT ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	62.6	-2.7	-18.3
3	114.1	-14.8	-20.4
4	164.7	-33.6	-20.4
5	215.1	-55.8	-22.0
6	278.7	-85.8	-22.0
7	349.6	-122.9	-21.4
8	399.1	-157.5	-19.9
9	453.1	-187.0	-20.2

RIGHT ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	39.7	19.6	33.0
3	80.1	27.8	25.7
4	127.0	10.8	26.4
5	177.6	-20.8	25.6
6	246.8	-68.4	26.8
7	315.6	-130.6	24.5
8	377.3	-188.1	24.4
9	447.7	-233.7	23.4

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RHESUS MONKEY SKULL COMPRESSION TEST

SKULL NO. 2 RUN NO. 17

LOADING A-P HORIZONTAL LVDT L-R

TIME BETWEEN READINGS 4 sec

*preload

NO.	VERT LOAD (LBS)	HORIZ. DISPL. (IN) x 10^{-3}	VERTICAL COMP. (IN) x 10^{-3}
1	5*	0.25	0.0
2	10	0.45	-1.75
3	35	1.2	-7.5
4	65	2.0	-13.75
5	109	4.9	-19.75
6	142	3.85	-25.75
7	190	4.6	-31.75
8	240	5.6	-37.75
9	285	6.95	-44.5

ALL STRAINS IN MICRO-INCHES/INCH

RIGHT ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	0.0	-0.0	--
3	60.3	11.0	33.9
4	110.9	14.0	31.6
5	176.5	-11.3	29.1
6	243.3	-39.6	28.3
7	319.7	-71.7	26.5
8	382.8	-125.4	26.6
9	458.1	-165.8	26.1

SKULL 2, RUN 17 (Continued)

LEFT ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	8.4	-2.8	0.0
3	71.7	-19.2	-16.2
4	135.9	-36.6	-17.2
5	193.9	-60.0	-18.4
6	254.1	-89.3	-18.6
7	344.4	-127.1	-18.9
8	412.6	-156.0	-20.5
9	493.2	-185.9	-20.8

FRONT ROSETTE

PRINCIPAL STRAINS (E1, E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	6.7	-0.4	43.3
3	30.4	-17.8	22.1
4	49.5	-32.2	15.4
5	80.1	-75.6	14.2
6	110.4	-103.7	14.1
7	147.2	-140.7	15.0
8	181.9	-183.9	14.7
9	213.2	-219.1	13.8

REAR ROSETTE

PRINCIPAL STRAINS (E1,E2)

RDG	E1	E2	PHI
1	0.0	-0.0	--
2	7.4	-0.1	-24.1
3	60.7	6.1	-31.3
4	118.0	12.2	-29.9
5	181.8	21.4	-29.1
6	252.8	30.5	-28.6
7	322.0	51.6	-27.8
8	395.3	69.9	-27.8
9	454.9	85.2	-28.0

APPENDIX B-1c

HUMAN SKULL

Methodology for Human Skull Static Test

A load was applied to the skull in the A-P, S-I and L-R direction with deflection measured in the ortnogonal direction. Four delta rosettes were used to record strain.

The strain gages were positioned as shown in Figure 1 and produced 12 strain gage readings. Gage A was positioned in all cases to lie parallel to the mid-sagittal plane. Load was applied through two loading devices each measuring 1.125 inches in diameter. The horizontal DVDT was positioned ortnogonal to the loading direction and measured outward deflection (outward deflection of the skull produced positive displacement). The vertical DVDT registered the deflection of the skull in the loading direction. Test set-ups in the L-R and A-P direction required a twenty five pound preload to hold the skull in the desired position. All zeros were then set.

The setups for each of the loading directions are shown in Figure 2-6.

Principal strains for delta rosettes were calculated from the following equations:

$$\varepsilon_{1,2} = \frac{\varepsilon_A + \varepsilon_B + \varepsilon_C}{3} \pm \frac{\sqrt{2}}{3}\sqrt{(\varepsilon_A - \varepsilon_B)^2 + (\varepsilon_B - \varepsilon_C)^2 + (\varepsilon_C - \varepsilon_A)^2}$$

$$\tan 2\phi = \frac{\sqrt{3}(\varepsilon_B - \varepsilon_C)}{\varepsilon_B + \varepsilon_C - 2\varepsilon_A}$$

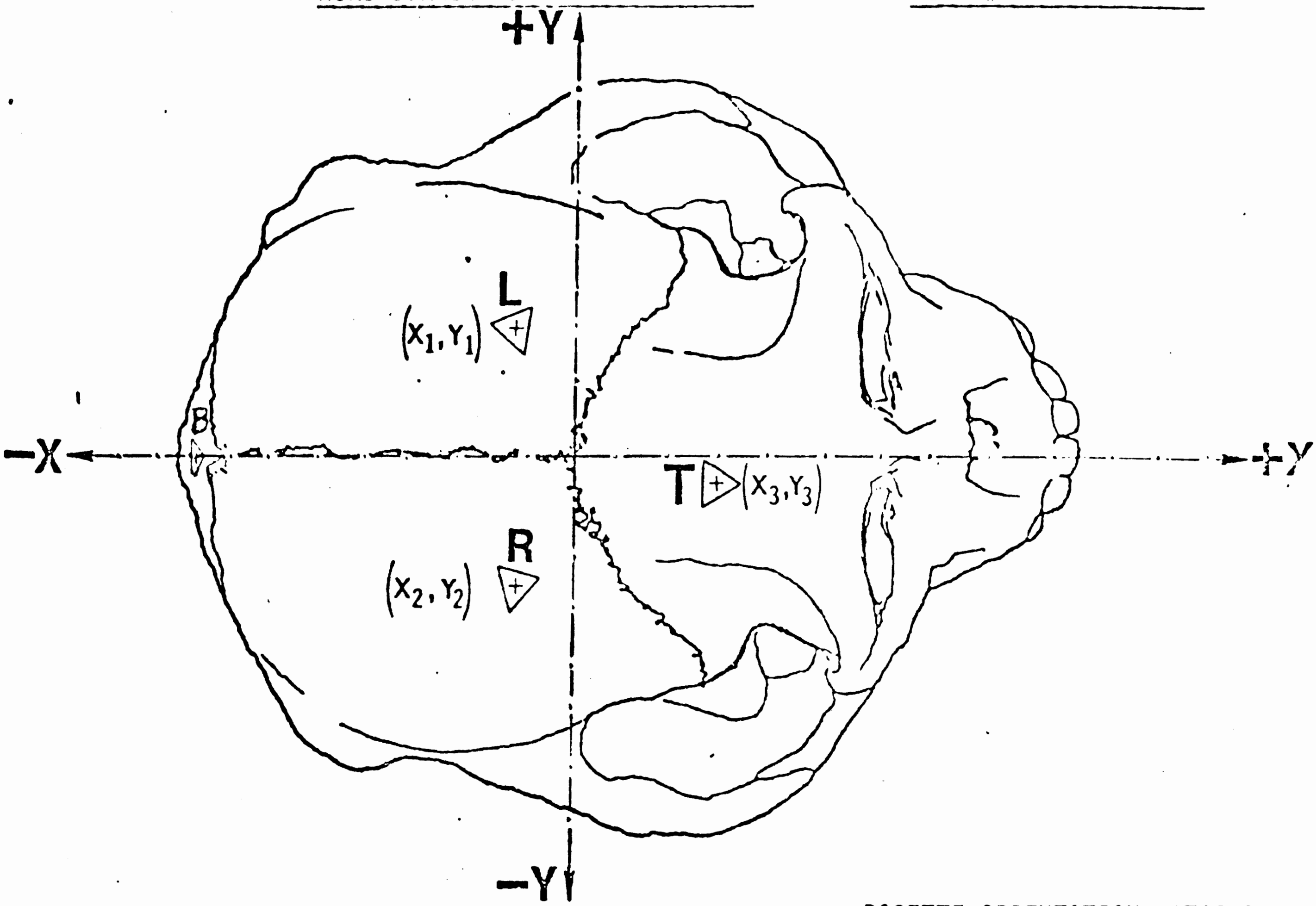
$\varepsilon_{1,2}$ are the maximum and minimum principal strains, respectively.

ϕ is the angle between the axis of gage A and the direction of maximum principal strain ε_1 measured counterclockwise from gage A.

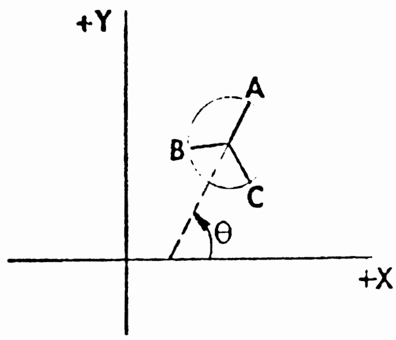
Time between readings on the data sheets is one second.

Loading and deflection measuring location for each test set-up are shown in Figures 7-12. Measurements are referenced to the intersection of the frontal and two parietal lobes. Figure 13 is a mid-sagittal view indicating the thickness of the skull.

HSRI STRAIN ROSETTE DATA SHEET TEST #



ROSETTE ORIENTATION DETAILS



a. △ -- Location of strain rosettes.

b. R -- Right L -- Left. T -- Top B -- Bottom

c. θ is the angle (measured anti-clockwise) arm 'A' of the rosette makes with the positive direction of the X-axis.
Note: Arm 'A' corresponds to arm '1' as printed on rosette.

d. All distances are measured along the surface of the skull.

LEFT ROSETTE (in)	RIGHT ROSETTE (in)	TOP ROSETTE (in)	BOTTOM ROSETTE in
x_1 = -1.4	x_2 = -1.4	x_3 = 2.1	x_4 = -5.85
y_1 = 2.3	y_2 = -2.8	y_3 = 0.	y_4 = 0.
θ_1 = 174°	θ_2 = 176°	θ_3 = 175°	θ_4 = 4.°

ORIENTATION OF ROSETTE AXES

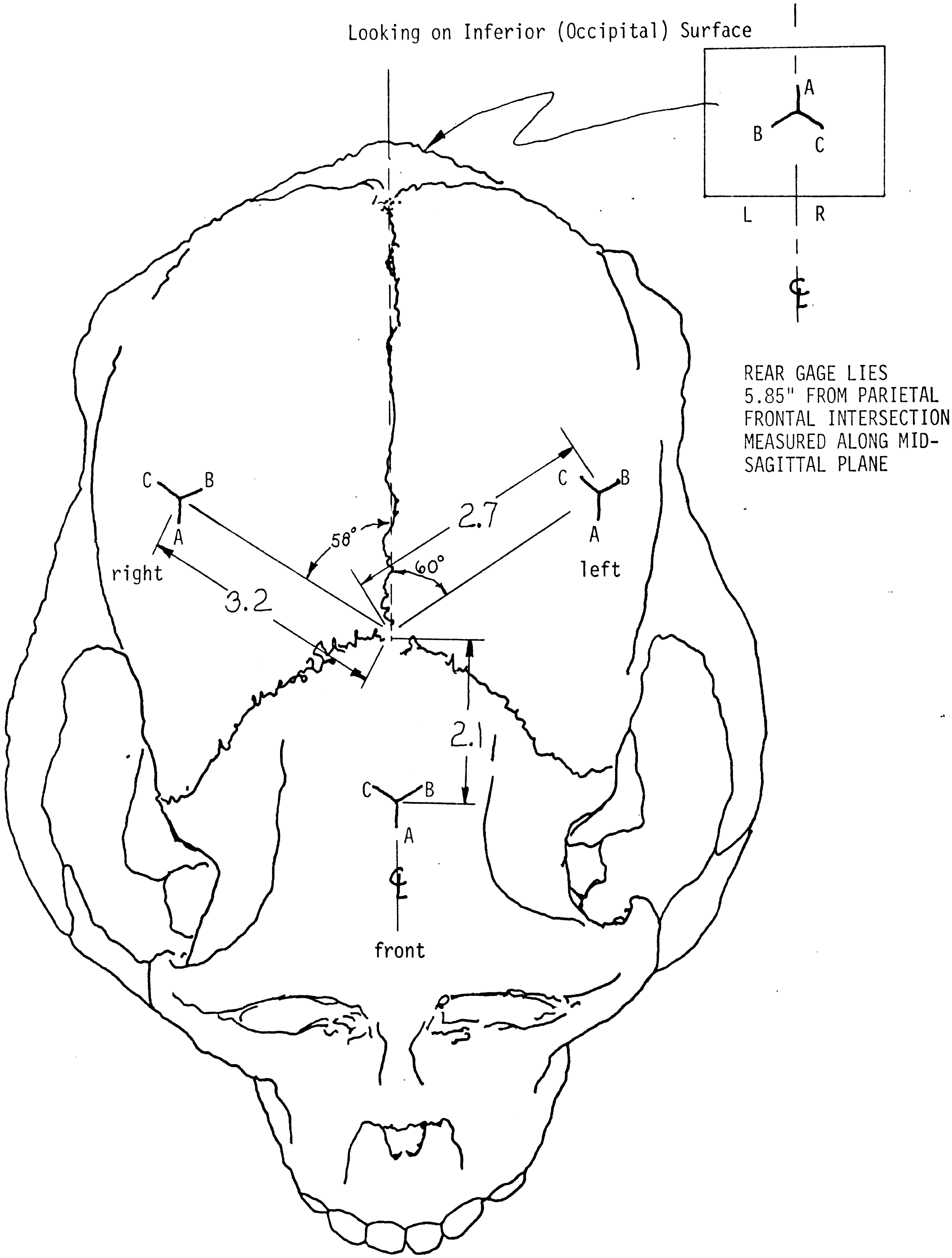


FIGURE 1

FIG 2: 1A

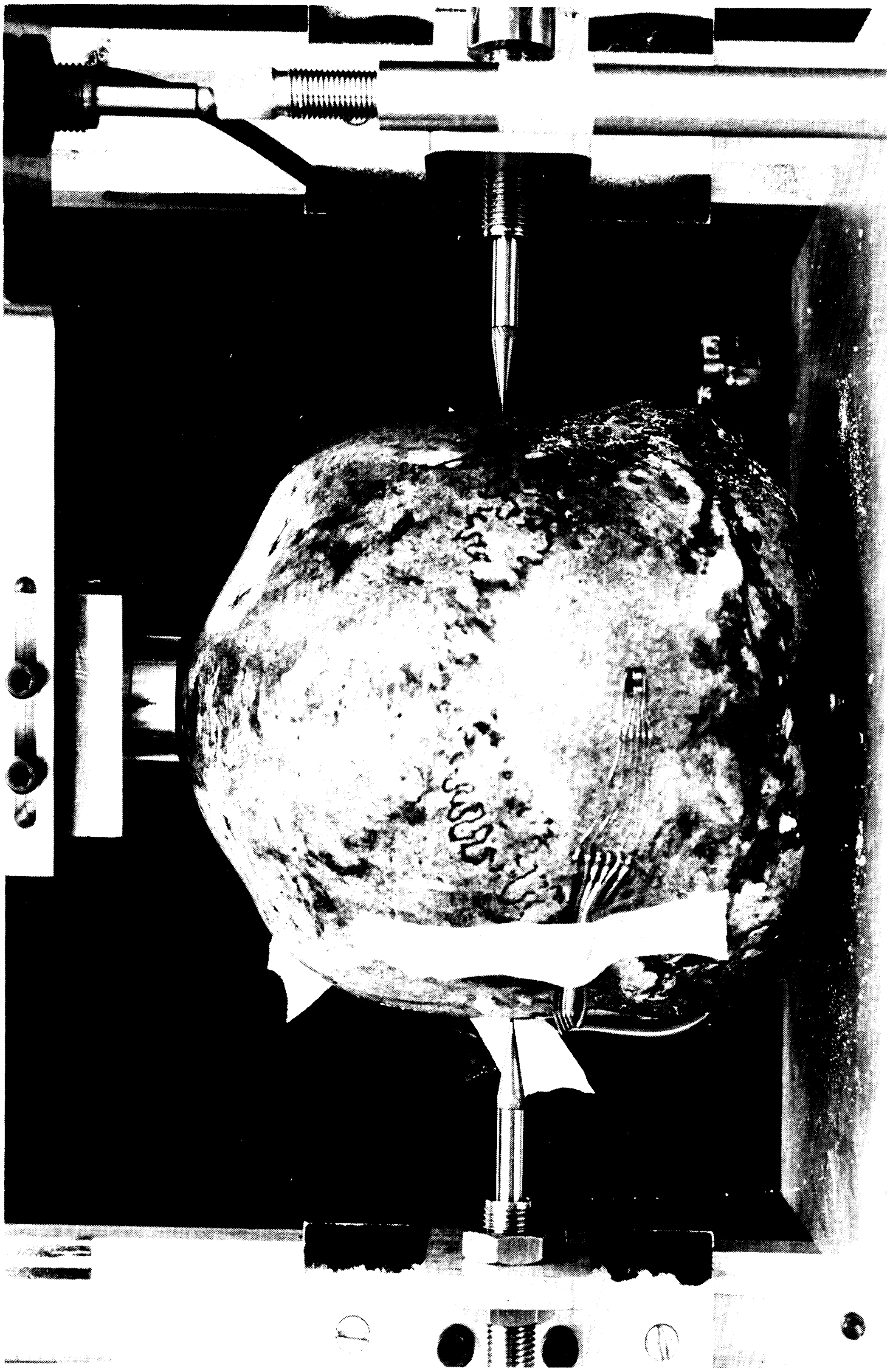


FIG 3: 1B

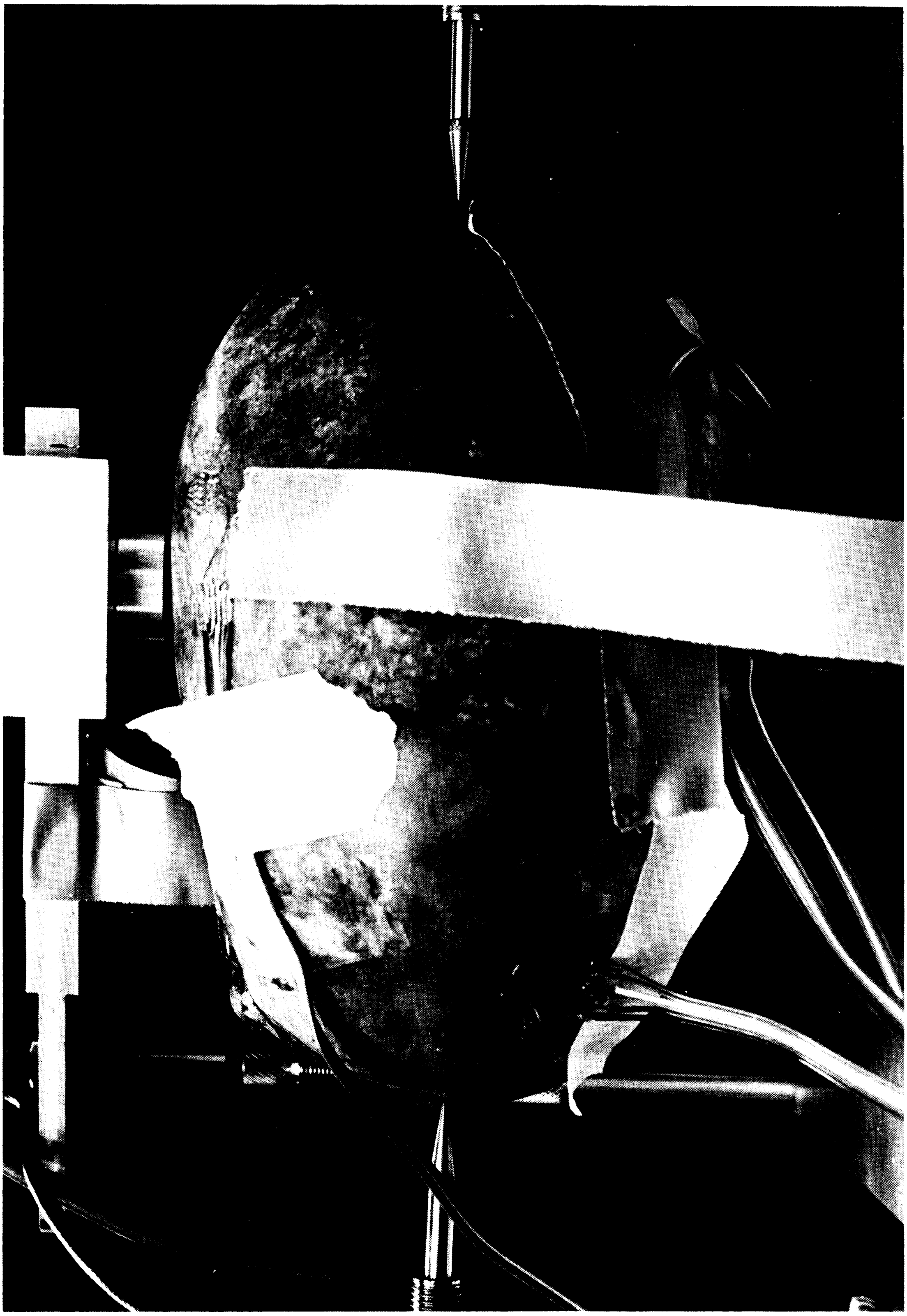


FIG 4: 2A

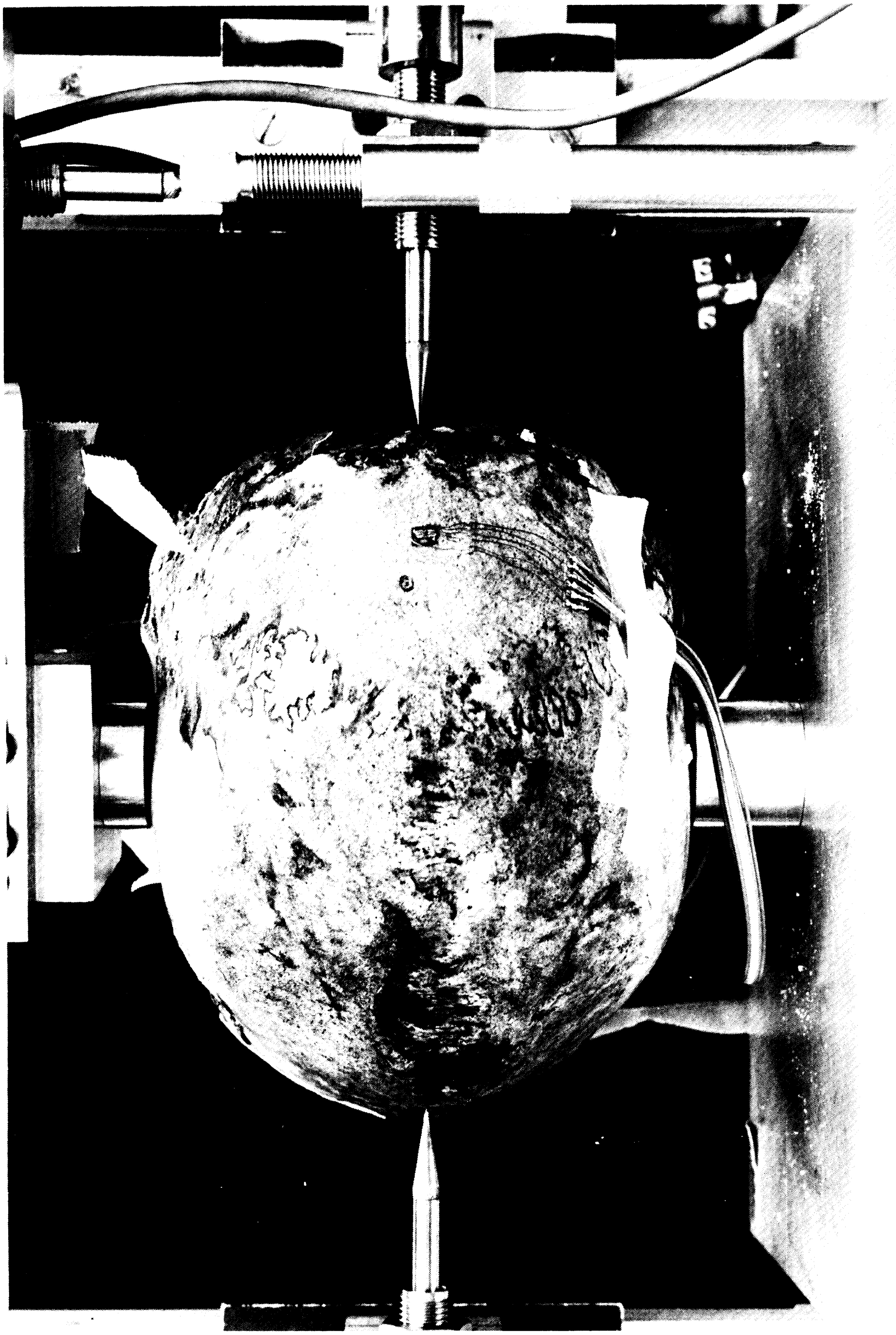


FIG 5: 2B

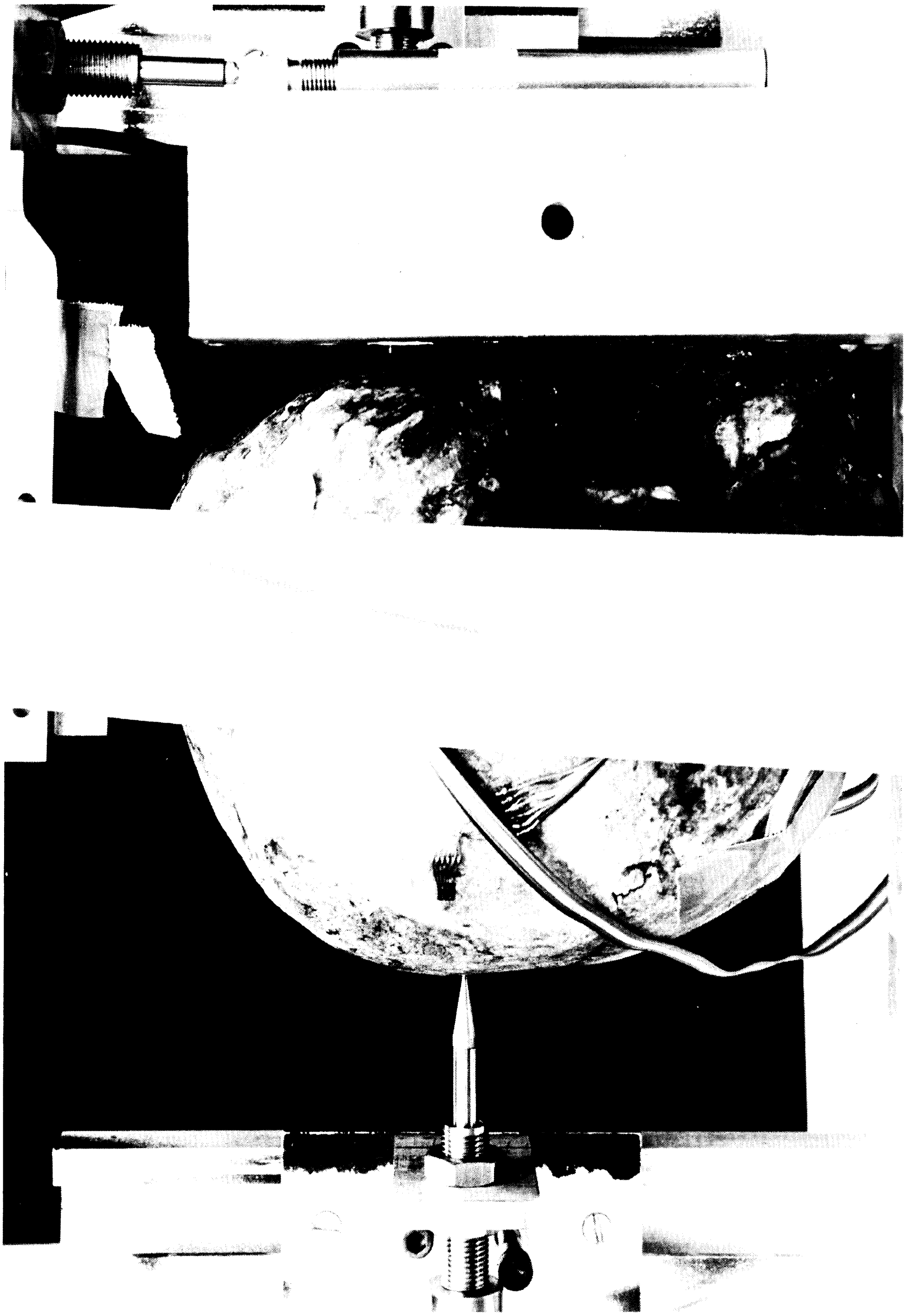


FIG 6: 3B

LOADING AND DVDT POSITIONS

1A:	LOADING	=	SUPERIOR - INFERIOR
	DVDT	=	ANTERIOR - POSTERIOR
1B	LOADING	=	S-I
	DVDT	=	LEFT - RIGHT
2A:	LOADING	=	L-R
	DVDT	=	A-P
2B	LOADING	=	L-R
	DVDT	=	S-I
3A:	LOADING	=	A-P
	DVDT	=	L-R
3B:	LOADING	=	A-P
	DVDT	=	S-I

EACH TEST WAS REPEATED ONCE, THEREFORE TEST NO.'s 1-A1 and 1-A2 etc.

Loading--Deflection Measuring Location; 1A

LOADING: S-I

DVDT: A-P

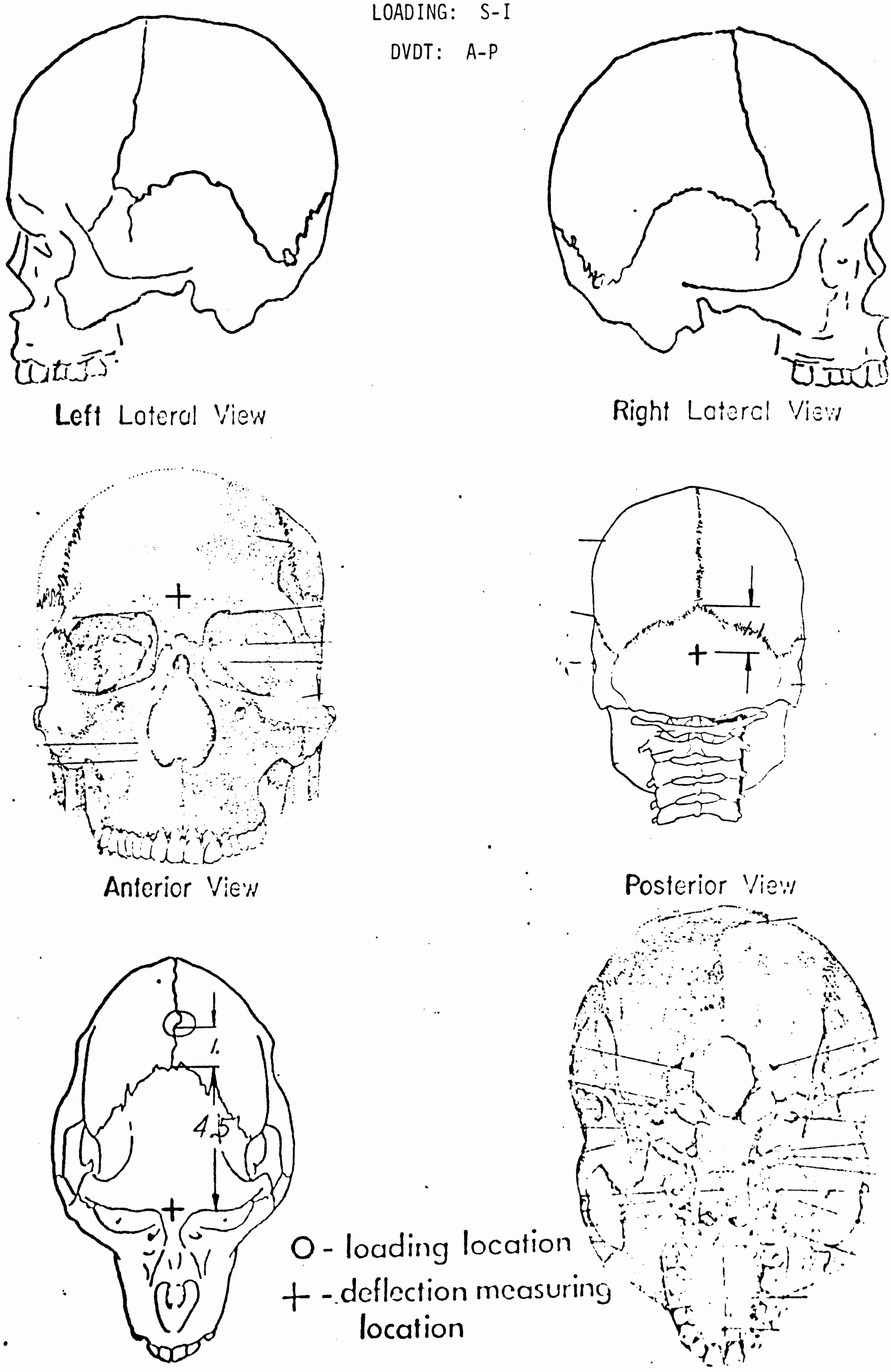


FIG 7

Loading -- Deflection Measuring Location;

LOADING: S-I

DVDT: L-R

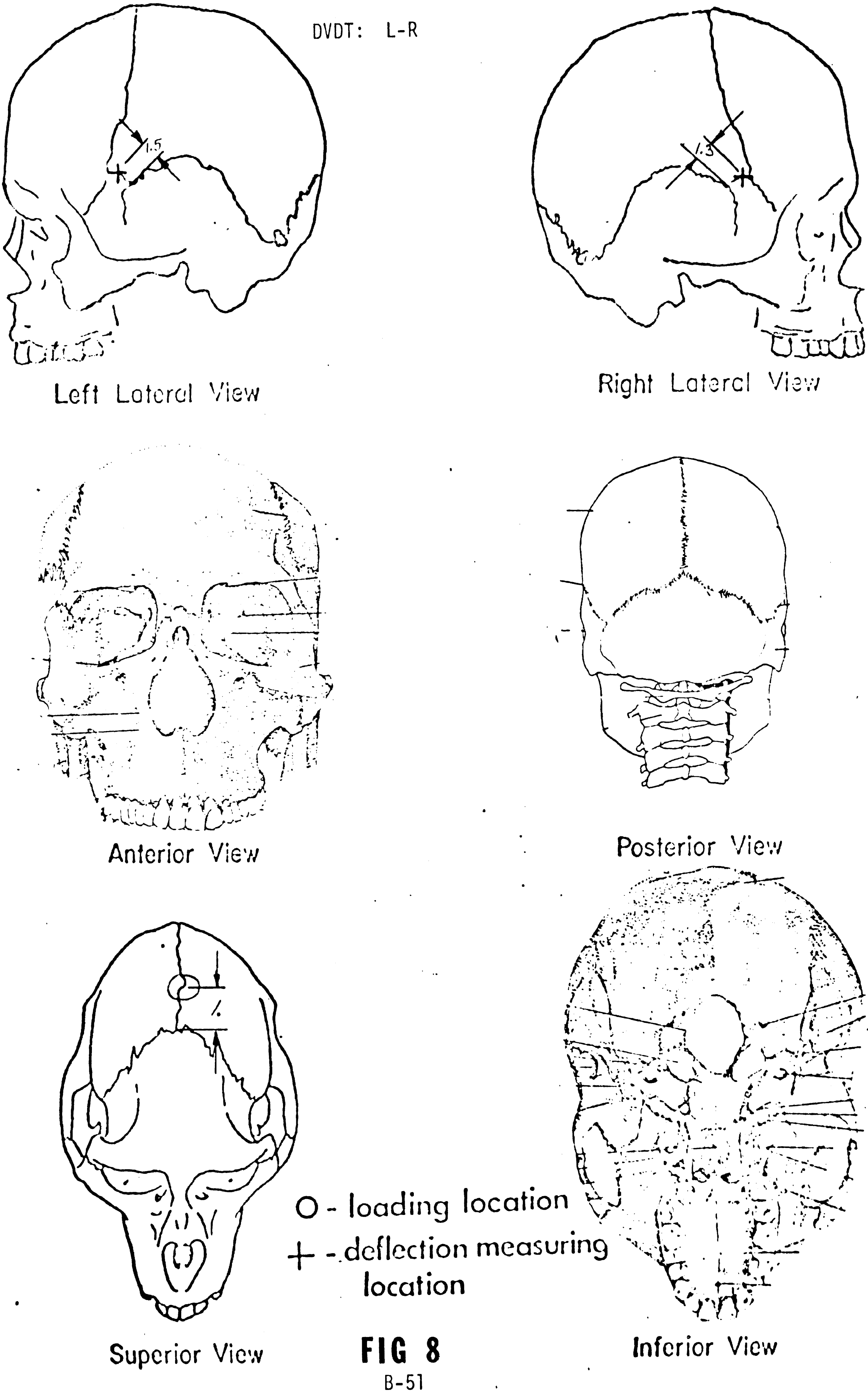


FIG 8

Loading - Deflection Measuring Location; 2A

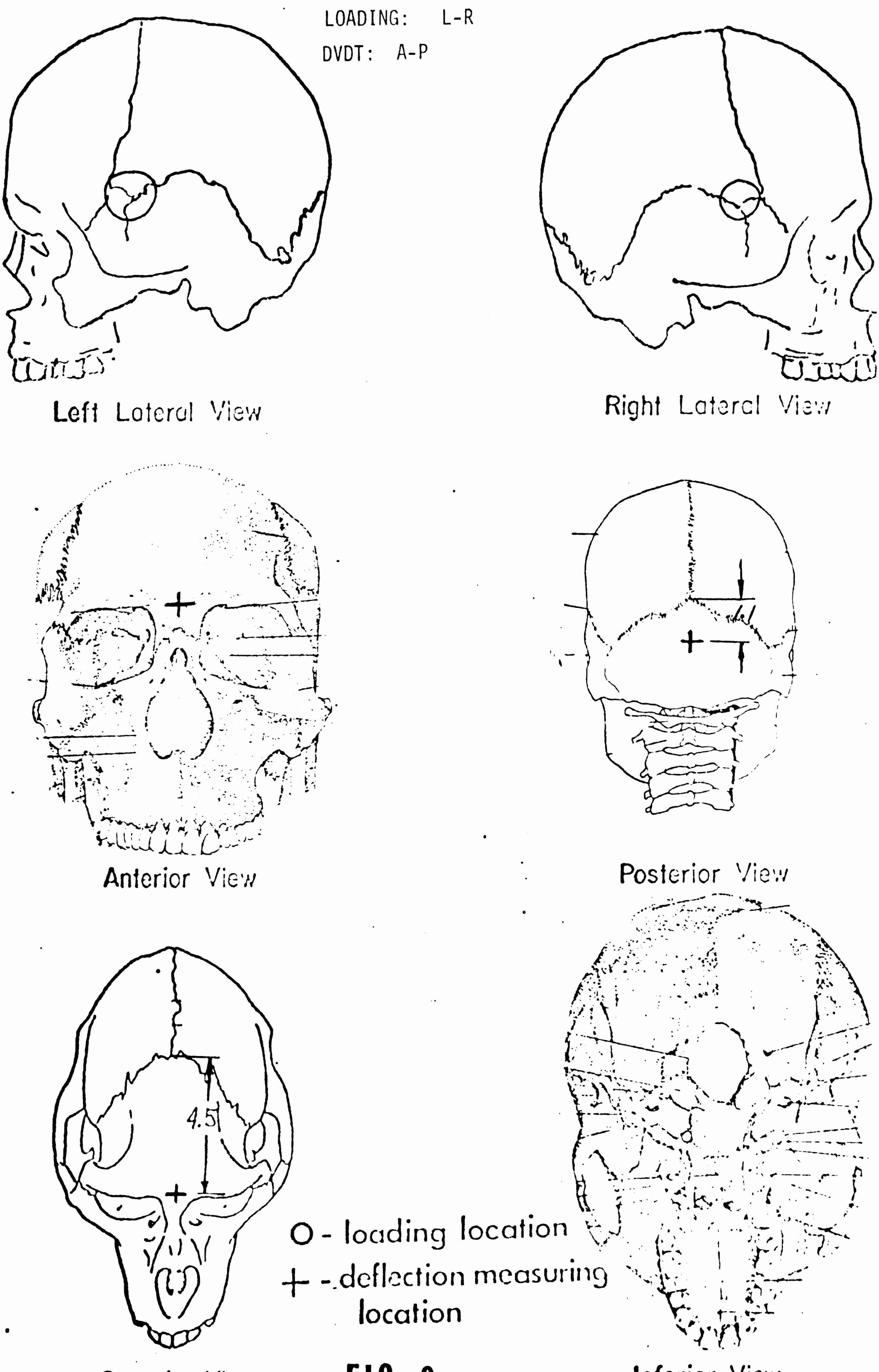


FIG 9

Loading -- Deflection Measuring Location;

LOADING: L-R

DVDT: S-I

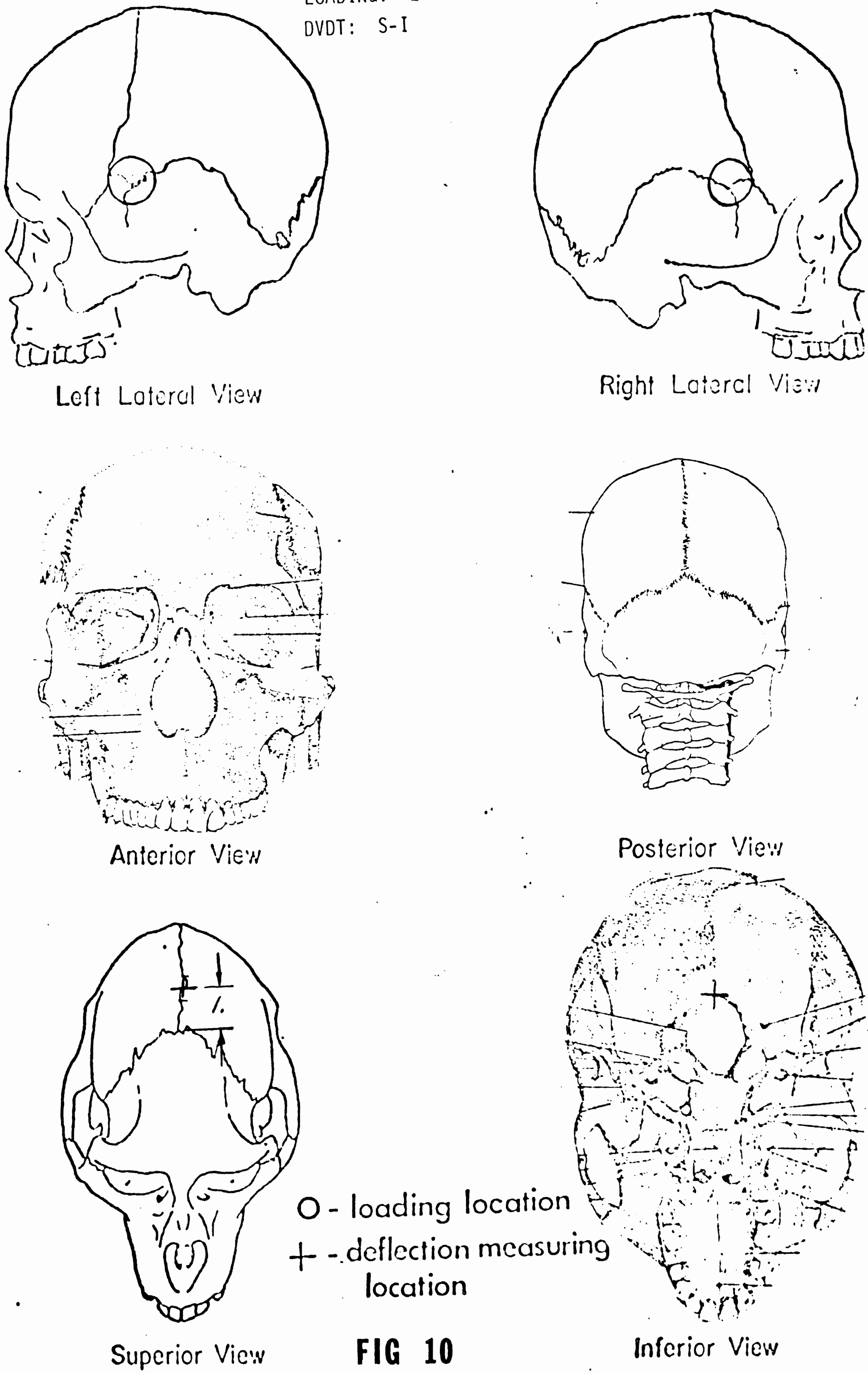


FIG 10

Loading--Deflection Measuring Location;

LOADING: A-P

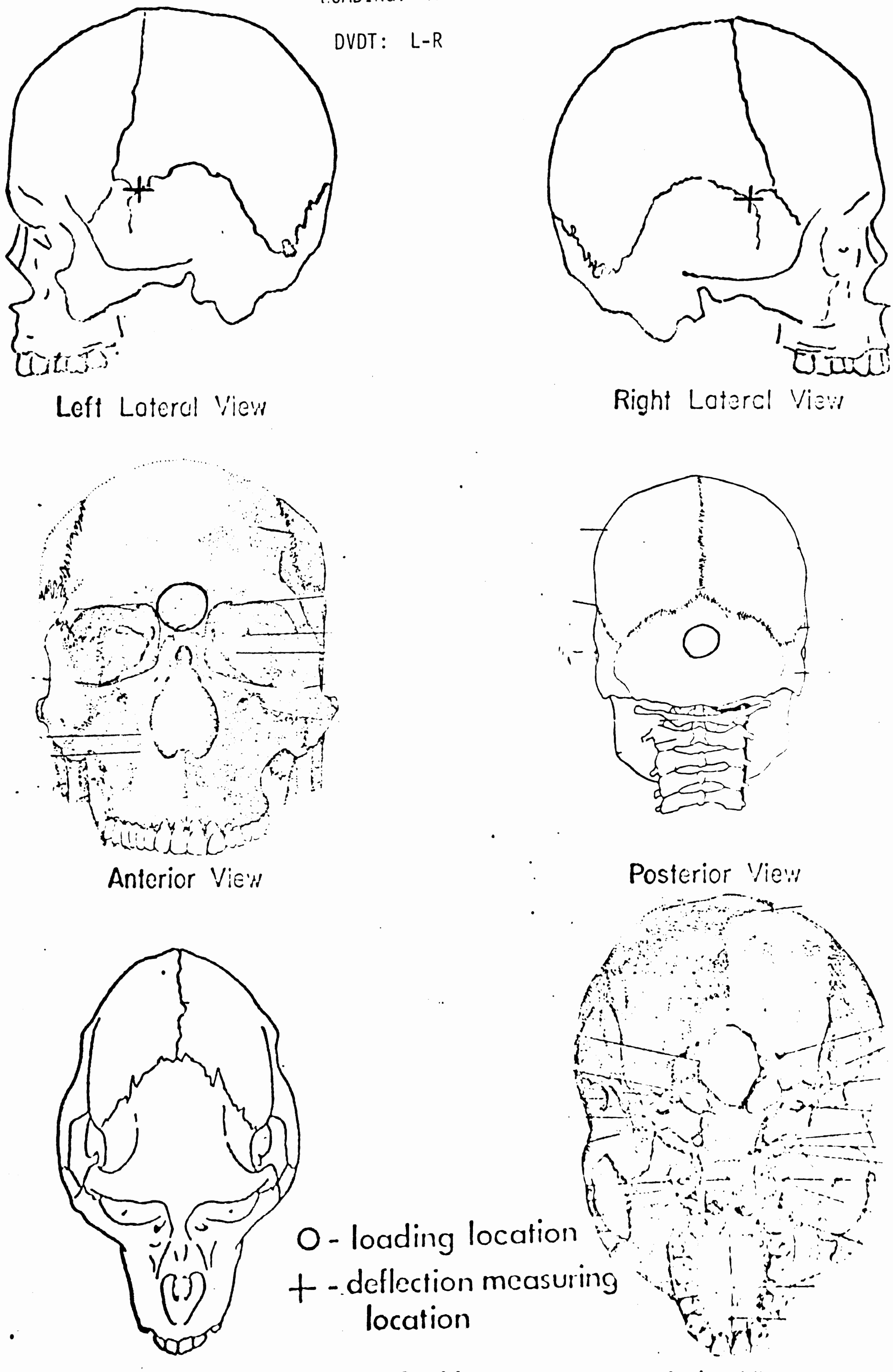


FIG 11

Loading Deflection Measuring Location; 3B

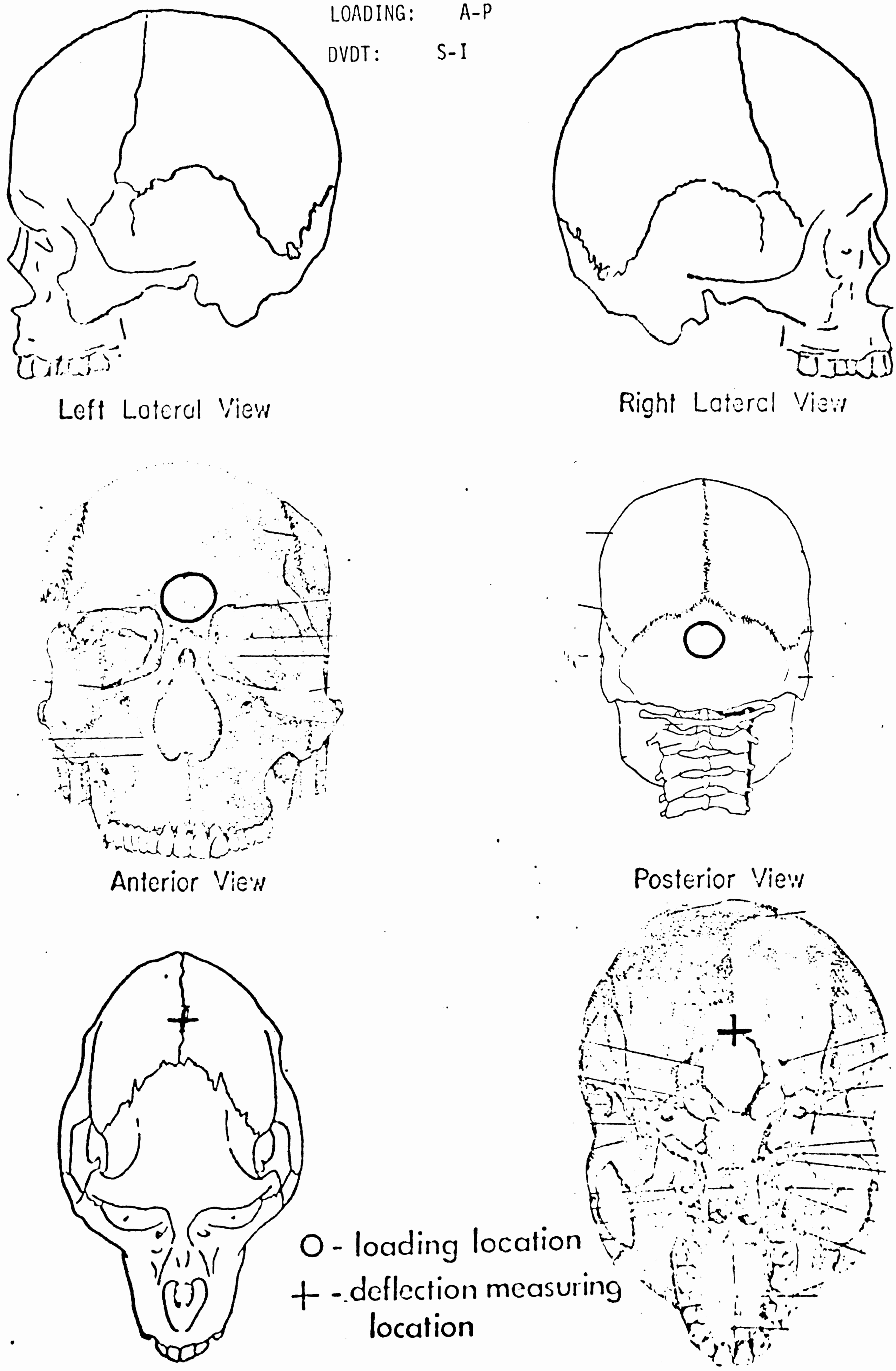
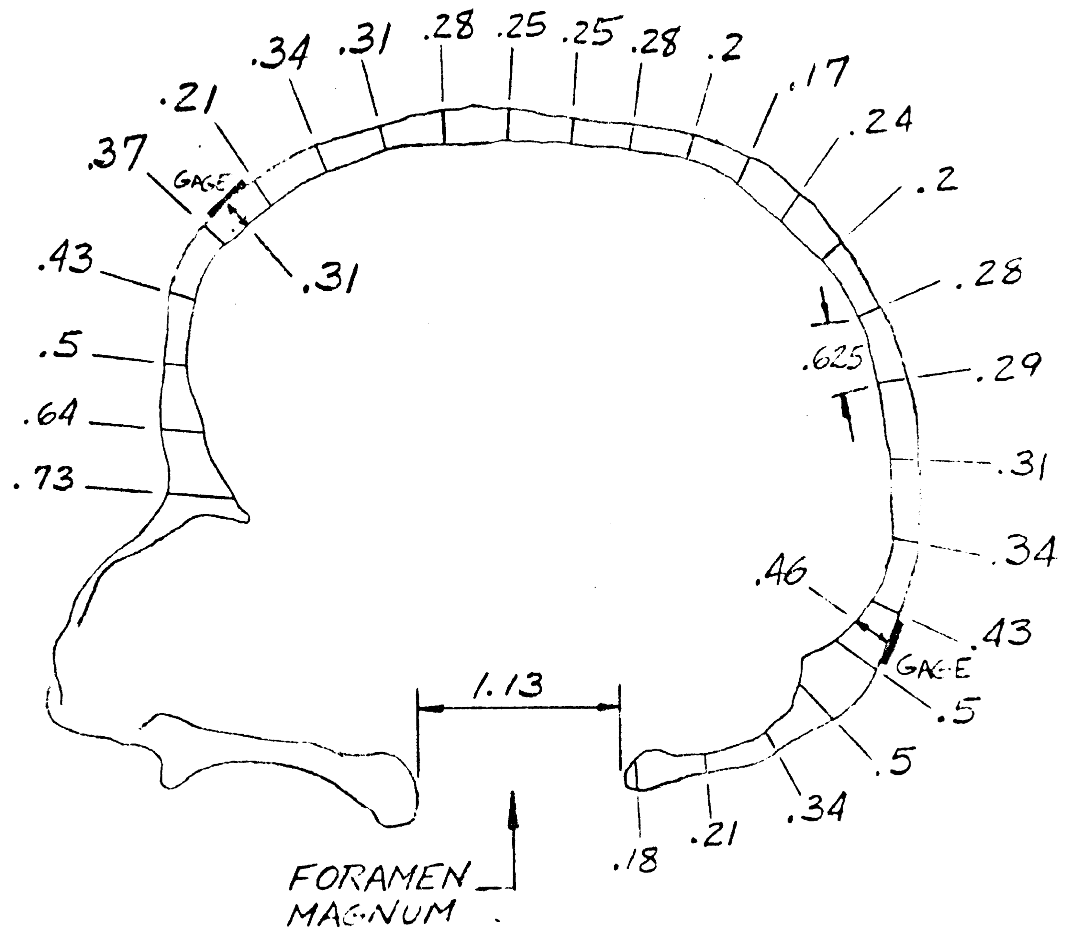


FIG 12

MAXIMUM WIDTH IN: (INCH)

L-R: 5.25
A-P: 7.25
S-I: 6.0

THICKNESS AT PARIETAL GAGE LOCATIONS: 0.3



MIDSAGITTAL VIEW

FIG 13

HSRI - BIOMECHANICS DEPARTMENT

HUMAN SKULL COMPRESSION TEST

RUN NO. 1 A 1 LOADING S-I (Vertical)

LVDT DIRECTION: A-P (Horizontal)

RDG.	LOAD (LBS)	HORIZONTAL (INCH x 10^{-3})	VERTICAL (INCH x 10^{-3})
1	30		-2.5
2	60		-5.
3	90		-7.5
4	120		-10.
5	150		-11.5
6	180		-12.5
7	210		-13.5
8	240		-16.25
9	270		-17.5
10	300		-20.
11	330		-22.5
12	360		-25.
13	390		-27.5

RIGHT ROSETTE

PRINCIPAL STRAINS E1,E2, (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0
2	6.7	-0.1	-4.8
3	18.4	-4.0	-3.1
4	21.8	-6.0	-3.6
5	26.8	-5.8	-2.5
6	32.0	-5.8	-2.4
7	32.5	-3.5	-1.8
8	35.1	-1.6	-1.3
9	40.2	0.2	-1.0
10	45.4	0.9	0.2
11	50.6	1.8	1.1
12	53.3	2.7	1.7
13	58.7	3.7	2.5

RUN 1 A 1 (Continued)

LEFT ROSETTE

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0
2	7.6	0.9	-4.6
3	15.4	1.1	-6.0
4	26.4	2.0	-4.2
5	33.4	0.2	-1.5
6	40.7	-2.2	-0.6
7	48.1	-3.0	-0.6
8	49.7	-4.7	1.1
9	41.2	-3.8	3.1
10	38.2	-5.2	4.9
11	36.0	-6.6	7.3
12	27.9	-6.4	12.0
13	24.2	-7.2	16.6

FRONT ROSETTE

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0
2	0.9	-2.6	0
3	-1.0	-5.8	-6.7
4	-2.0	-8.8	-9.4
5	-0.6	-12.9	-1.4
6	-0.8	-12.9	1.8
7	1.8	-17.3	6.0
8	0.4	-15.8	7.5
9	4.6	-21.7	7.0
10	2.1	-21.3	6.3
11	1.9	-24.6	4.9
12	-2.2	-25.9	2.4
13	-4.0	-27.6	1.3
14	-0.9	-29.4	1.1

REAR ROSETTE

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0
2	8.2	-0.1	-2.6
3	15.8	1.6	-3.0
4	25.4	2.5	-0.8

RUN 1 A 1 (Continued)

REAR ROSETTE (Continued)

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
5	39.0	3.3	2.8
6	47.5	1.6	1.7
7	57.1	3.6	0
8	59.5	3.5	-1.0
9	62.7	-1.3	-4.1
10	69.0	-0.1	-4.8
11	71.2	-3.1	-5.9
12	77.2	-4.5	-6.8
13	80.2	-5.3	-7.2
14	86.3	-7.0	8.0

HSRI - BIOMECHANICS DEPARTMENT

HUMAN SKULL COMPRESSION TEST

RUN NO. 1 A2 LOADING S-I (Vertical)

LVDT DIRECTION: A-P (Horizontal)

RDG.	LOAD (LBS)	HORIZONTAL (INCH x 10^{-3})	VERTICAL (INCH x 10^{-3})
1	30		-2.5
2	60		-3.75
3	85		-6.25
4	110		-7.5
5	140		-10.
6	160		-11.25
7	190		-12.5
8	220		-16.25
9	240		-18.75
10	260		-21.25
11	280		-25.
12	310		-27.5
13	340		-30.
14	370		-33.75

PRINCIPAL STRAINS E1,E2, (MICRO-IN/IN)

RIGHT ROSETTE

RDG	E1	E2	PHI
1	0.0	0.0	0.0
2	6.9	-5.0	-5.2
3	10.7	-9.0	-6.3
4	13.2	-7.0	-3.0
5	19.6	-7.9	-2.5
6	24.0	-8.0	0.0
7	22.9	-6.2	2.7
8	26.1	-7.2	2.4
9	29.4	-8.3	2.1
10	33.5	-4.6	4.8
11	40.6	-3.3	5.7
12	47.3	-2.8	5.8
13	54.1	-1.8	5.8
14	60.9	-2.6	5.8

RUN NO. 1A2 (Continued)

LEFT ROSETTE

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0.0
2	3.7	-1.7	-2.2
3	11.4	-4.0	-3.8
4	15.4	-4.8	-5.1
5	26.8	-7.9	-4.7
6	23.7	-7.0	-6.4
7	16.1	-4.6	-14.7
8	14.2	-5.6	-11.7
9	8.0	-5.8	-17.0
10	5.8	-6.2	-12.4
11	4.6	-6.4	-13.8
12	3.9	-6.9	-11.6
13	0.1	-8.5	-3.5
14	-2.3	-7.5	-15.4
15	7.5	-2.5	-15.0

FRONT ROSETTE

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0.0
2	1.0	-5.6	3.4
3	8.9	-24.5	-22.1
4	7.8	-7.1	14.3
5	5.5	-7.3	16.1
6	4.8	-8.9	14.9
7	7.5	-10.7	16.2
8	5.9	-10.8	13.5
9	4.4	-16.3	8.1
10	1.8	-17.3	6.0
11	3.4	-22.6	4.4
12	1.5	-25.9	2.7
13	1.5	-29.6	2.4
14	-0.4	-25.9	2.7
15	-2.9	-22.1	2.2

REAR ROSETTE

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0.0
2	7.6	1.7	-3.6
3	16.4	-0.1	-2.6
4	28.1	-0.0	1.0

RUN NO. 1A2 (Continued)

REAR ROSETTE (Continued)

PRINCIPAL STRAINS E1, E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
5	33.3	-0.3	2.6
6	41.8	3.6	0.5
7	45.9	5.1	-2.3
8	43.8	7.3	-6.1
9	48.1	5.1	-10.7
10	54.2	5.8	-12.4
11	60.7	6.3	-13.8
12	53.9	9.1	-15.9
13	54.4	9.2	-18.2
14	54.4	9.2	-18.2
15	57.5	7.1	-17.3

HSRI - BIOMECHANICS DEPARTMENT

HUMAN SKULL COMPRESSION TEST

RUN NO. 1 B 1 LOADING S-I (Vertical)

LVDT DIRECTION: L-R (Horizontal)

RDG.	LOAD (LBS)	HORIZONTAL (INCH x 10^{-3})	VERTICAL (INCH x 10^{-3})
1	20		-0.50
2	40		-1.25
3	55		-1.75
4	75		-2.50
5	90		-3.25
6	108		-3.75
7	130		-5.50
8	165		-7.00
9	190		-8.75
10	205		-10.50
11	230		-12.5
12	260		-13.75
13	280		-15.50
14	300		-17.00

PRINCIPAL STRAINS E1,E2, (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0.0
2	4.2	0.9	-8.5
3	4.7	-0.0	-16.9
4	9.1	-4.4	-13.1
5	13.0	-4.6	-8.1
6	20.6	-9.2	-5.7
7	23.5	-8.4	-6.2
8	29.0	-7.8	-5.2
9	37.5	-9.5	-3.1
10	40.6	-8.7	-2.6
11	44.2	-7.3	-1.3
12	48.6	-6.3	-0.8
13	51.8	-4.2	0.2
14	58.3	-4.4	-0.1
15	65.0	-4.1	1.5

RIGHT ROSETTE

RUN NO. 1 B 1 (Continued)

LEFT ROSETTE

PRINCIPAL STRAINS E1, E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0.0
2	8.3	-6.5	7.1
3	15.6	-9.0	4.9
4	17.5	-7.3	3.6
5	21.1	-10.8	5.1
6	27.4	-13.6	5.2
7	30.7	-13.0	4.3
8	23.8	-10.4	6.1
9	10.8	- 7.3	12.8
10	8.6	-11.4	20.5
11	10.2	-15.0	19.8
12	15.7	-14.3	15.8
13	17.6	-16.2	16.6
14	16.2	-12.2	18.5
15	14.6	-15.1	22.3

FRONT ROSETTE

PRINCIPAL STRAINS E1, E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0.0
2	3.3	-1.7	18.0
3	7.6	-1.4	11.7
4	12.5	-18.3	-18.0
5	10.3	-3.6	20.9
6	6.1	-4.5	-14.3
7	3.5	-5.6	-19.2
8	-0.3	-5.9	-15.7
9	-2.0	-6.4	-19.2
10	-5.4	-7.7	5.1
11	-6.6	-9.4	15.9
12	-6.6	-7.9	-2.9

REAR ROSETTE

PRINCIPAL STRAINS E1, E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0.0
2	8.0	0.6	-2.8
3	15.2	0.7	-4.8
4	20.0	1.3	-2.8
5	26.8	-1.8	-0.6
6	31.3	-0.1	-1.6
7	49.6	0.6	-1.2
8	56.4	-4.8	-1.5

REAR ROSETTE (Continued)

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
9	60.6	-0.1	-0.9
10	70.6	-0.0	-0.5
11	81.1	-1.8	-0.1
12	86.4	-0.0	0.4
13	96.3	1.4	-0.5

HSRI - BIOMECHANICS DEPARTMENT

HUMAN SKULL COMPRESSION TEST

RUN NO. 1 B 2 **LOADING** S-I (Vertical)

LVDT DIRECTION: L-R (Horizontal)

RDG.	LOAD (LBS)	HORIZONTAL (INCH x 10^{-3})	VERTICAL (INCH x 10^{-3})
1	17		-0.75
2	34		-1.75
3	50		-2.5
4	70		-3.0
5	85		-3.5
6	105		-4.0
7	130		-6.25
8	160		-7.5
9	180		-9.5
10	210		-11.25
11	230		-13.25
12	260		-14.0
13	290		-16.25
14	320		-17.5

PRINCIPAL STRAINS E1,E2, (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0.0
2	6.6	-1.1	4.0
3	9.9	-0.3	4.1
4	13.4	-0.1	4.9
5	18.0	-0.3	5.0
6	19.5	1.6	8.0
7	21.8	3.3	10.5
8	27.9	4.5	8.5
9	30.0	5.7	10.0
10	35.2	6.4	9.2
11	42.1	5.8	8.6
12	49.2	5.4	8.6
13	55.2	6.2	7.6
14	58.3	7.7	7.3
15	55.2	6.2	7.6

RIGHT ROSETTE

RUN NO. 1 B 2 (Continued)

LEFT ROSETTE

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0.0
2	3.0	-3.8	2.7
3	6.9	-14.9	0.6
4	4.8	-3.9	4.2
5	6.1	-7.5	2.2
6	3.8	0.0	0.0
7	3.6	1.5	-18.5
8	4.3	-2.2	-17.7
9	5.8	-4.7	-9.0
10	8.9	-3.0	-1.5
11	7.5	-5.1	-19.8
12	10.5	-5.6	18.9
13	10.6	-4.6	-22.5
14	10.8	-4.8	-16.9
15	11.0	-9.3	-8.7

FRONT ROSETTE

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0.0
2	5.6	0.4	-18.8
3	8.7	0.4	-21.9
4	10.3	0.7	22.5
5	8.3	0.4	20.0
6	8.1	-0.3	15.1
7	7.6	-4.2	6.1
8	7.7	-4.1	5.4
9	7.7	-0.5	7.4
10	7.3	-1.9	1.8
11	8.3	-7.4	-2.3
12	8.0	-9.9	-6.0
13	8.7	-11.1	-5.8
14	9.1	-6.9	-3.7
15	8.6	-7.9	-5.3

REAR ROSETTE

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0.0
2	8.2	-0.1	-2.6
3	14.7	0.7	-0.6
4	20.1	-0.1	2.5

RUN NO. 1 B 2 (Continued)

REAR ROSETTE (Continued)

PRINCIPAL STRAINS E1, E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
5	26.1	-3.6	0.6
6	34.9	-2.6	1.7
7	42.5	-3.7	1.4
8	53.9	-5.5	1.1
9	61.3	-4.0	2.3
10	74.2	-0.4	2.2
11	82.0	0.2	3.0
12	81.8	0.9	3.0
13	100.4	-0.0	0.4
14	109.3	-0.8	-0.7
15	112.0	-2.0	-1.2

HSRI - BIOMECHANICS DEPARTMENT

HUMAN SKULL COMPRESSION TEST

RUN NO. 2A1 LOADING L-R (vertical)

LVDT DIRECTION A-P (horizontal)

RDG.	LOAD (LBS)	HORIZONTAL (INCH x 10^{-3})	VERTICAL (INCH x 10^{-3})
1	12	.1	-2.5
2	20	.15	-6.25
3	30	.025	-8.75
4	40	.025	-11.25
5	50	.05	-13.75
6	60	.05	-20.
7	70	.075	-22.5
8	80	.175	-25.
9	95	.175	-27.5
10	105	.2	-31.25
11	115	.25	-33.75
12	125	.35	-36.25
13	140	.35	-38.75
14	150	.425	-41.25
15	165	.55	-43.75
16	175	.75	-46.25
17	185	.85	-48.75
18	200	.975	-50.0
19	210	1.05	-52.5
20	225	1.1	-55.0
21	240	1.125	-56.25

RUN 2A 1 (Continued)

RIGHT ROSETTE

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0.0
2	10.0	4.1	-3.4
3	13.1	3.0	4.6
4	17.6	6.1	5.5
5	22.7	7.6	5.3
6	27.8	10.5	6.3
7	32.8	12.0	3.4
8	40.3	13.6	3.3
9	40.3	13.6	3.3
10	43.6	14.1	3.9
11	51.0	13.1	4.3
12	58.9	7.6	7.9
13	51.0	13.1	4.3
14	59.7	4.6	7.3
15	65.7	4.5	7.0
16	71.9	5.8	7.1
17	76.6	10.1	7.5
18	83.0	12.7	7.9
19	87.2	14.2	9.0
20	90.9	13.1	9.4
21	95.1	12.7	9.3
22	100.7	11.4	10.4
23	107.6	8.9	10.3

LEFT ROSETTE

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0.0
2	2.5	0.7	-10.9
3	3.8	-0.6	4.1
4	6.0	-0.1	-2.0
5	7.7	0.6	-5.4
6	12.6	-1.8	0.0
7	9.7	0.8	-2.0
8	15.3	1.3	-5.2
9	22.8	0.2	-4.3
10	22.8	0.2	-4.3
11	30.3	-1.0	-3.8
12	32.5	-1.4	-3.4
13	30.5	0.5	-4.6
14	27.4	2.6	-6.7
15	27.9	3.5	-8.0
16	30.1	0.5	-3.0
17	33.5	-3.8	0.2
18	37.2	-3.6	-0.5
19	37.2	-3.6	-0.5

RUN 2A 1 (Continued)

LEFT ROSETTE (Continued)

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
20	37.4	-1.1	-1.9
21	39.4	1.9	-4.0
22	41.8	2.6	-4.3
23	46.1	3.5	-5.3

FRONT ROSETTE

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0.0
2	7.8	-0.7	-6.5
3	7.5	-0.1	-12.0
4	10.7	-0.9	-9.1
5	5.3	-0.9	-15.6
6	3.9	-1.5	-19.3
7	5.1	-1.4	-13.9
8	3.9	-1.5	-19.3
9	8.9	-2.0	-11.2
10	7.9	-2.3	-14.5
11	12.9	-2.7	-10.1
12	13.0	-3.1	-10.3
13	12.3	-3.5	- 8.4
14	11.7	-3.7	- 6.1
15	11.2	-5.6	- 2.7
16	10.2	-4.0	- 7.8
17	15.1	-6.6	- 4.0
18	15.4	-5.9	- 5.4
19	16.4	-4.7	- 8.4
20	13.1	-7.3	- 3.3
21	16.7	-8.4	- 2.7
22	14.9	-7.8	- 3.0

REAR ROSETTE

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0.0
2	4.0	-2.0	-5.7
3	3.4	-1.1	-15.0
4	3.6	-4.6	-10.5
5	4.4	-5.8	- 5.6
6	5.1	-1.4	14.4
7	0.1	-1.9	-5.0
8	3.0	-2.0	4.6
9	4.8	-2.8	-3.7

RUN 2A 1 (Continued)

REAR ROSETTE (Continued)

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
10	3.6	-2.8	1.0
11	5.5	-1.0	-3.6
12	7.3	-1.6	-2.6
13	7.3	-3.6	-2.6
14	3.6	-3.2	-0.8
15	7.2	-6.5	-0.8
16	7.2	-8.5	-1.0
17	13.0	-7.2	18.9
18	3.6	0.4	1.3
19	3.7	-21.7	-2.2
20	3.0	-22.5	-6.2
21	2.9	-26.5	-5.7
22	5.3	-30.0	-6.4

HSRI - BIOMECHANICS DEPARTMENT

HUMAN SKULL COMPRESSION TEST

RUN NO. 2 A 2 LOADING L-R (Vertical)

LVDT DIRECTION A-P (Horizontal)

RDG.	LOAD (LBS)	HORIZONTAL (INCH x 10^{-3})	VERTICAL (INCH x 10^{-3})
1	15		-1.25
2	30		-3.
3	42		-5.
4	55		-6.25
5	68		-8.
6	80		-10.
7	93		-11.25
8	106		-13.
9	120		-15.
10	130		-16.75
11	143		-18.25
12	157		-20.25
13	165		-21.75
14	180		-23.75
15	190		-25.5
16	202		-27.5
17	213		-28.75
18	225		-30.
19	238		-31.25
20	250		-32.75
21	260		-36.25
22	270		-37.5
23	280		-40.

RUN NO. 2 A 2 (Continued)

RIGHT ROSETTE

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0.0
2	5.7	0.1	-21.0
3	9.1	1.3	-21.4
4	12.0	2.3	-20.6
5	18.1	0.3	-15.3
6	23.5	0.8	-15.0
7	30.9	-1.9	-13.5
8	38.0	-2.7	-14.2
9	41.6	-2.4	-14.6
10	47.1	-2.6	-15.0
11	47.2	2.4	-16.9
12	50.8	3.6	-16.7
13	51.2	7.3	-18.2
14	55.4	6.8	-19.4
15	57.6	8.8	-20.1
16	58.3	10.8	-21.2
17	62.5	14.0	-22.0
18	64.7	16.4	-22.5
19	68.8	16.1	-22.4
20	71.3	14.4	-22.1
21	76.3	15.4	-22.3
22	78.3	16.1	-22.4
23	84.5	17.6	22.2

LEFT ROSETTE

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0.0
2	5.9	0.9	-20.6
3	7.9	2.8	-18.9
4	13.0	4.6	-14.1
5	33.4	7.3	2.3
6	27.1	3.9	-6.1
7	30.7	4.8	-5.6
8	52.5	0.5	-2.7
9	56.1	0.4	-2.0
10	78.4	-0.9	-1.7
11	74.5	-3.4	-0.8
12	85.8	-0.9	-1.6
13	89.6	-0.0	-1.6
14	97.0	-0.4	-1.5
15	111.8	-3.4	-1.2
16	119.3	-4.3	-1.5
17	119.2	-1.7	-1.0
18	134.0	-4.3	-0.9

RUN 2 A 2 (Continued)

LEFT ROSETTE (Continued)

PRINCIPAL STRAINS E1, E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
19	137.8	-3.2	-0.9
20	145.2	-3.7	-0.7
21	145.2	-0.9	-0.8
22	148.9	0.3	-0.8
23	151.1	0.8	-0.6
24	148.9	3.9	-0.6

FRONT ROSETTE

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0.0
2	0.9	-1.8	-2.8
3	1.2	-1.7	-20.2
4	3.2	-1.6	16.6
5	4.5	-2.4	10.7
6	2.6	-1.5	21.4
7	8.2	-3.8	8.7
8	8.8	-2.6	6.5
9	10.8	-0.5	2.3
10	8.8	-2.6	6.5
11	10.8	-0.5	2.3
12	15.5	2.6	-9.0
13	14.4	-1.4	2.1
14	16.8	0.3	-0.8
15	16.1	0.6	-0.9
16	21.6	1.0	-2.9
17	22.7	0.7	-2.7
18	22.7	0.7	-2.7
19	23.3	-0.5	-1.4
20	25.0	-2.1	-0.2
21	23.2	-1.5	-0.3
22	23.2	-2.6	0.8

REAR ROSETTE

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0.0
2	2.9	-1.4	-2.6
3	4.7	-8.2	-5.2
4	3.8	-8.6	-3.5

RUN NO. 2 A 2 (Continued)

REAR ROSETTE (Continued)

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
5	3.2	-11.2	-4.6
6	4.0	-14.1	-4.6
7	3.1	-14.5	-7.9
8	2.4	-14.3	-8.8
9	1.5	-14.1	-9.0
10	3.1	-14.5	-7.9
11	4.0	-17.2	-10.9
12	1.5	-14.1	-9.0
13	4.2	-13.8	-10.8
14	5.3	-17.1	-11.6
15	9.3	-18.4	-8.0
16	6.1	-17.7	-9.5
17	10.1	-18.8	-11.9
18	12.8	-23.2	-9.5
19	11.5	-20.6	-11.6
20	10.1	-20.4	-12.5
21	12.8	-27.1	-12.8
22	12.9	-25.8	-11.3
23	10.6	-27.7	-10.9
24	11.5	-28.3	-9.6

HSRI - BIOMECHANICS DEPARTMENT

HUMAN SKULL COMPRESSION TEST

RUN NO. 2 B 1 LOADING L-R (Vertical)

LVDT DIRECTION: S-I (Horizontal)

RDG.	LOAD (LBS)	HORIZONTAL (INCH x 10^{-3})	VERTICAL (INCH x 10^{-3})
1	15		-2.5
2	25		-3.75
3	40		-5.5
4	50		-7.5
5	60		-8.75
6	70		-11.25
7	85		-12.5
8	95		-13.75
9	110		-16.25
10	120		-18.75
11	135		-20.
12	145		-21.25
13	160		-23.75

REAR ROSETTE

PRINCIPAL STRAINS E1,E2, (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0
2	0.0	-5.5	13.2
3	-0.6	-8.3	11.6
4	0.1	-10.0	2.5
5	0.1	-10.0	2.5
6	0.4	-9.2	5.7
7	2.0	-6.7	4.1
8	2.4	-6.0	7.8
9	4.1	-6.4	6.2
10	5.8	-7.0	5.1
11	7.5	-7.5	4.3
12	6.5	-7.2	4.7
13	7.2	-9.4	0.5
14	9.1	-12.0	2.5
15	10.8	-13.6	1.0

RUN NO. 2 B 1 (Continued)

FRONT ROSETTE

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0
2	0.8	-3.7	-2.4
3	1.8	-7.4	-1.8
4	2.8	-7.3	-0.8
5	2.8	-7.3	-0.8
6	0.9	-0.3	-15.0
7	0.9	-3.0	-16.8
8	1.3	-1.9	-4.7
9	3.8	-0.5	5.4
10	1.9	0.9	6.5
11	4.2	1.3	-12.5
12	8.3	1.2	-10.6
13	13.5	0.2	-6.6
14	17.4	-0.1	-6.6
15	21.8	0.1	-8.0

LEFT ROSETTE

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0.0
2	2.4	-0.2	7.2
3	7.7	-1.1	4.8
4	12.8	-0.3	3.2
5	13.4	2.2	1.1
6	14.9	4.6	0.0
7	16.4	6.4	0.0
8	22.6	8.9	-4.4
9	26.3	10.1	-3.7
10	30.3	12.1	-5.0
11	30.3	12.1	-5.0
12	34.4	13.8	-6.2
13	40.6	17.5	-11.4
14	42.1	19.6	-13.9
15	49.1	21.1	-11.8
16	49.1	21.1	-11.8
17	53.9	23.1	-13.4

RUN NO. 2 B 1 (Continued)

RIGHT ROSETTE

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0.0
2	1.5	-1.8	-15.6
3	2.7	1.4	12.5
4	9.7	3.0	-5.7
5	10.2	4.9	-1.1
6	12.7	6.5	1.3
7	12.7	6.5	1.3
8	15.8	8.0	-2.7
9	21.2	7.5	-6.0
10	23.1	9.2	-5.8
11	26.6	10.4	-6.9
12	30.5	12.0	-6.5
13	31.7	16.1	-2.7
14	37.8	14.7	-7.3
15	41.4	16.0	-7.9

HSRI - BIOMECHANICS DEPARTMENT

HUMAN SKULL COMPRESSION TEST

RUN NO. 2 B 2 LOADING L-R (Vertical)

LVDT DIRECTION S-I (Horizontal)

RDG.	LOAD (LBS)	HORIZONTAL (INCH x 10^{-3})	VERTICAL (INCH x 10^{-3})
1	15	.05	-2.5
2	25	.2	-3.75
3	35	.35	-5.
4	45	.45	-7.5
5	60	.55	-8.75
6	70	.6	-11.25
7	85	.65	-12.5
8	95	.7	-15.
9	115	.75	-16.25
10	125	.8	-17.5
11	135	.85	-20.
12	145	.875	-21.25
13	160	.775	-23.75
14	170	.725	-25.
15	180	.725	-26.25
16	195	.65	-28.75
17	210	.6	-30.
18	225	.55	-32.
19	235	.5	-33.75
20	245	.475	-35.
21	255	.45	-37.5
22	270	.425	-40.

RUN NO. 2 B 2 (Continued)

RIGHT ROSETTE

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0
2	3.7	-0.6	-10.6
3	7.2	0.9	-14.0
4	12.8	-0.7	-12.4
5	16.6	-0.9	-11.1
6	22.0	-0.3	-11.8
7	25.6	-1.5	-12.4
8	29.3	1.9	-12.2
9	32.9	5.3	-11.8
10	38.4	8.2	-11.7
11	36.7	11.0	-11.0
12	36.8	13.2	-10.4
13	38.6	12.7	-10.8
14	38.8	17.1	-9.5
15	39.2	21.5	-7.6
16	40.2	29.6	-9.8
17	45.3	32.6	-14.7
18	43.5	36.6	-17.6
19	48.9	39.5	-16.0
20	51.2	42.9	-22.3
21	55.8	45.2	18.9
22	60.1	49.1	16.9
23	60.5	51.0	14.3

LEFT ROSETTE

RDG	E1	E2	PHI
1	0.0	0.0	0
2	7.0	1.8	-13.1
3	15.3	1.3	-5.2
4	22.7	1.0	-3.6
5	30.0	0.7	-2.8
6	41.1	-0.2	-1.8
7	41.2	1.6	-2.3
8	45.1	3.7	-2.9
9	52.3	2.7	-1.8
10	59.8	3.7	-2.1
11	59.8	6.0	-2.2
12	67.2	5.5	-1.8
13	74.5	4.8	-1.3
14	74.5	7.2	-1.3
15	89.4	4.6	-1.1
16	100.5	2.9	-0.8
17	111.7	2.0	-0.8
18	119.1	2.4	-0.7
19	126.5	2.5	-0.6
20	134.0	2.9	-0.5
21	137.7	4.1	-0.5

RUN NO. 2 B 2 (Continued)

LEFT ROSETTE (Continued)

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
22	145.1	4.0	-0.4
23	145.1	6.3	-0.5

FRONT ROSETTE

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0
2	0.9	-0.3	-15.0
3	3.3	0.6	20.9
4	4.3	0.9	-12.9
5	5.5	-0.2	-2.1
6	5.5	-0.2	-2.1
7	7.5	0.4	-4.5
8	11.4	0.1	-5.3
9	11.7	1.1	-7.6
10	11.3	0.5	-4.8
11	9.2	-0.8	.3
12	9.3	-1.7	3.4
13	9.3	-1.7	3.4
14	11.6	-5.0	5.6
15	9.6	-3.0	5.2
16	13.0	-2.9	2.4
17	11.2	-2.1	3.4
18	16.5	-2.6	1.0
19	18.4	-2.2	-0.5
20	20.2	-2.5	-0.1
21	22.0	-3.1	-0.1
22	23.9	-3.4	0.2
23	23.9	-2.3	-0.8

REAR ROSETTE

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0
2	2.5	-4.0	21.1
3	0.0	-2.3	14.2
4	0.0	-2.1	-11.8
5	-0.7	-5.3	-8.9

RUN No. 2 B 2 (Continued)

REAR ROSETTE (Continued)

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
6	-0.7	-6.8	-12.4
7	1.7	-5.0	-15.0
8	0.1	-8.2	-2.5
9	-0.8	-10.1	-16.5
10	-2.9	-6.7	-12.8
11	1.0	-12.5	-8.1
12	-0.3	-10.7	-7.7
13	1.0	-12.5	-8.1
14	2.6	-15.4	-11.2
15	1.0	-12.5	-8.1
16	3.5	-16.1	-8.7
17	4.7	-14.9	-7.0
18	5.1	-18.5	-7.3
19	7.7	-18.0	-8.7
20	7.7	-18.0	-8.7
21	6.4	-19.5	-5.7
22	20.6	-10.2	22.4
23	7.1	-22.4	-7.0
24	4.3	-23.6	-4.7
25	5.8	-27.5	-7.4

HSRI - BIOMECHANICS DEPARTMENT

HUMAN SKULL COMPRESSION TEST

RUN NO. 3 A 1 LOADING A-P (Vertical)

LVDT DIRECTION S-I (Horizontal)

RDG.	LOAD (LBS)	HORIZONTAL (INCH x 10^{-3})	VERTICAL (INCH x 10^{-3})
1	15	-.05	-0.5
2	30	-.05	-0.75
3	45	-.04	-1.75
4	55	-.01	-2.0
5	70	.04	-2.75
6	85	.09	-3.25
7	100	.125	-3.75
8	115	.16	-4.5
9	130	.2	-5.0
10	145	.225	-5.75
11	160	.265	-6.25
12	175	.31	-6.75
13	190	.34	-7.5
14	200	.365	-8.
15	220	.385	-8.5
16	235	.425	-9.
17	240	.475	-9.25

RUN NO. 3 A 1

REAR ROSETTE

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0.0
2	2.5	-17.3	-10.4
3	7.2	-42.0	-9.7
4	10.7	-71.4	-8.6
5	11.5	-88.3	-9.1
6	11.3	-105.9	-9.1
7	12.1	-125.9	-8.0
8	19.3	-144.4	-7.9
9	22.3	-162.9	-7.8
10	26.9	-181.8	-7.6
11	30.7	-201.7	-7.3
12	37.0	-221.1	-7.1
13	38.3	-241.6	-6.7
14	44.7	-261.0	-6.6
15	45.2	-280.1	-6.5
16	48.4	-301.2	-6.2
17	51.6	-322.3	-5.9
18	56.3	-341.3	-6.0

FRONT ROSETTE

RDG	E1	E2	PHI
1	0.0	0.0	0
2	3.7	-0.9	1.6
3	0.9	-1.6	18.0
4	0.9	-1.6	18.0
5	3.9	-2.2	5.7
6	3.0	-0.7	2.1
7	1.0	-6.0	-17.8
8	1.6	-5.6	-20.3
9	2.1	-7.6	-19.9
10	3.2	-9.3	-21.0
11	3.6	-9.2	-16.3
12	11.6	-5.3	5.2
13	4.7	-8.5	-18.6
14	5.0	-9.6	-16.1
15	5.1	-13.1	-17.2
16	5.5	-13.3	-17.1
17	6.1	-11.4	-20.9
18	6.3	-15.9	-19.2

RUN NO. 3 A 1 (Continued)

RIGHT ROSETTE

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0.0
2	4.5	-1.1	14.0
3	2.3	-0.0	16.4
4	4.0	1.9	18.0
5	4.1	1.5	17.5
6	4.9	-0.7	-20.0
7	5.8	0.4	22.0
8	2.8	0.7	8.7
9	3.5	-4.5	-5.3
10	0.0	-2.5	0.6
11	-0.8	-4.9	-0.4
12	-0.3	-6.5	-0.2
13	-1.8	-7.4	11.9
14	-1.9	-4.0	18.0
15	-0.3	-9.8	3.1
16	-0.3	-9.8	3.1
17	3.2	-13.0	1.9
18	5.4	-16.2	0.0
19	5.6	-13.0	-1.6

LEFT ROSETTE

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0.0
2	2.0	-2.2	5.7
3	3.8	-1.7	-2.2
4	2.2	-4.1	6.9
5	1.9	-2.8	1.3
6	0.8	-5.5	10.2
7	0.0	-10.8	18.0
8	1.2	-4.4	10.3
9	2.0	-12.8	19.2
10	0.4	-14.3	16.0
11	-1.9	-14.8	20.6
12	-3.3	-10.0	-9.5
13	-1.0	-11.2	0.0
14	-1.8	-13.1	-2.1
15	-0.5	-14.9	2.3
16	-1.3	-13.1	2.0
17	-5.1	-11.9	-9.4
18	-4.9	-13.2	-21.7

HSRI - BIOMECHANICS DEPARTMENT

HUMAN SKULL COMPRESSION TEST

RUN NO. 3 A 2 LOADING A-P (Vertical)

LVDT DIRECTION L-R (Horizontal)

RDG.	LOAD (LBS)	HORIZONTAL (INCH x 10^{-3})	VERTICAL (INCH x 10^{-3})
1	15		-0.5
2	30		-1.0
3	40		-1.5
4	55		-2.
5	70		-2.5
6	82		-3.
7	95		-3.5
8	110		-4.25
9	125		-4.75
10	140		-5.25
11	155		-5.75
12	170		-6.25
13	185		-6.75
14	200		-7.25
15	215		-7.75
16	230		-8.25
17	250		-8.75

RIGHT ROSETTE

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0
2	3.7	-0.7	-12.2
3	7.3	0.9	-18.5
4	7.5	2.6	-21.5
5	9.1	1.7	-13.8
6	14.6	-1.3	-12.8
7	12.8	1.5	-11.4
8	5.7	3.1	-6.0
9	4.4	1.6	1.0
10	3.3	-0.2	-21.9
11	3.7	0.6	-10.0
12	5.2	-4.3	-3.1
13	5.9	-6.6	-2.3
14	10.4	-10.0	-3.5
15	11.8	-13.1	-2.3
16	15.2	-15.1	-3.9
17	15.3	-16.8	-4.1
18	12.3	-18.1	-2.9

LEFT ROSETTE

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0
2	4.7	-0.8	-12.4
3	6.6	-1.2	-10.2
4	7.5	-3.5	-2.2
5	9.5	-8.1	3.4
6	7.5	-6.3	1.7
7	10.0	-11.4	5.1
8	5.1	-11.6	8.3
9	4.9	-8.8	4.9
10	0.6	-7.7	7.5
11	-1.7	-5.7	6.0
12	0.8	-4.4	-18.7
13	-1.7	-5.0	-5.6
14	-2.8	-6.1	12.1
15	1.8	-5.4	-15.0
16	3.2	-5.8	-18.3
17	0.9	-6.2	-19.4
18	0.4	-7.0	-6.6

RUN NO. 3 A 2 (Continued)

FRONT ROSETTE

PRINCIPAL STRAINS E1,E2, (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0
2	0.5	-2.5	-13.8
3	1.4	-3.4	20.8
4	0.9	-7.2	-13.7
5	1.4	-13.8	-14.4
6	2.2	-12.5	-21.8
7	1.8	-12.7	-16.4
8	1.8	-10.9	-16.0
9	2.0	-8.9	-11.2
10	2.6	-7.4	- 9.9
11	4.3	-5.8	- 5.3
12	3.7	-2.4	-19.4
13	4.7	-1.8	-19.5
14	5.5	-1.5	-6.6
15	6.4	-2.7	-3.2
16	5.9	-2.1	-5.0
17	5.5	-0.9	-11.8
18	7.1	-3.8	-3.3

REAR ROSETTE

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0
2	-3.4	-19.4	-3.3
3	2.6	-54.9	-6.9
4	-5.2	-70.6	-8.5
5	-7.3	-95.7	-8.2
6	-6.5	-112.6	-8.8
7	2.3	-141.2	-8.8
8	6.3	-158.9	-8.9
9	12.4	-178.1	-8.5
10	15.4	-196.5	-8.3
11	22.5	-214.9	-8.2
12	30.3	-244.4	-8.1
13	35.6	-258.9	-7.5
14	39.3	-284.4	-7.5
15	38.9	-304.3	-7.2
16	43.4	-331.3	-7.0
17	44.8	-351.8	-6.7
18	41.3	-373.5	-6.3

HSRI - BIOMECHANICS DEPARTMENT

HUMAN SKULL COMPRESSION TEST

RUN NO. 3 B 1 LOADING A-P (Vertical)

LVDT DIRECTION: S-I (Horizontal)

RDG.	LOAD (LBS)	HORIZONTAL (INCH x 10^{-3})	VERTICAL (INCH x 10^{-3})
1	15	.075	-1.25
2	37	.2	-2.5
3	55	.35	-3.75
4	78	.35	-5.0
5	98	.35	-6.75
6	118	.375	-8.75
7	139	.525	-10.00
8	155	1.000	-12.50
9	175	1.35	-14.50
10	193	1.625	-16.25

RIGHT ROSETTE

PRINCIPAL STRAINS E1,E2, (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0.0
2	4.4	-3.6	-6.2
3	5.8	-8.3	-3.4
4	3.1	-9.8	-2.4
5	1.0	-13.1	2.5
6	4.5	-16.3	-2.4
7	-2.7	-17.1	7.2
8	-4.3	-20.2	6.4
9	-4.1	-22.3	3.8
10	-2.6	-23.3	-0.9
11	0.3	-22.9	-2.8

RUN NO. 3 B 1 (Continued)

FRONT ROSETTE

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0.0
2	2.2	-0.0	11.3
3	3.8	-3.7	-1.4
4	6.1	-5.5	0.1
5	5.5	-0.0	0.5
6	8.6	1.4	7.5
7	13.1	4.0	18.6
8	13.5	4.8	-22.5
9	16.5	3.9	20.1
10	9.7	4.0	15.3
11	10.6	-0.6	6.6

REAR ROSETTE

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0.0
2	7.3	-38.1	20.9
3	14.7	-76.2	20.9
4	22.0	-114.3	20.9
5	28.9	-155.9	20.1
6	34.0	-199.0	19.4
7	49.2	-221.8	22.1
8	50.7	-263.2	21.4
9	50.4	-306.0	20.6
10	47.1	-349.9	19.9
11	41.9	-403.1	20.2

LEFT ROSETTE

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0.0
2	0.4	-5.5	19.3
3	10.9	-6.7	12.2
4	-0.4	-13.6	-21.6
5	-1.5	-17.8	-18.6
6	0.7	-18.0	14.8
7	0.5	-16.1	15.2
8	0.9	-17.9	14.8
9	-1.8	-14.3	16.7
10	-0.9	-12.5	14.7
11	-4.1	-20.6	-18.0

HSRI - BIOMECHANICS DEPARTMENT

HUMAN SKULL COMPRESSION TEST

RUN NO. 3 B 2 LOADING A-P (Vertical)

LVDT DIRECTION: S-I (Horizontal)

RDG.	LOAD (LBS)	HORIZONTAL (INCH x 10^{-3})	VERTICAL (INCH x 10^{-3})
1	15	.200	-1.25
2	30	.300	-2.5
3	45	.350	-5.0
4	60	.525	-6.25
5	75	.750	-8.25
6	90	1.000	-10.0
7	105	1.175	-12.5
8	125	1.300	-14.25
9	140	1.350	-15.75
10	160	1.350	-17.5

RIGHT ROSETTE

PRINCIPAL STRAINS E1,E2, (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0
2	0.0	0.0	0
3	1.3	-1.3	22.3
4	1.7	-0.7	-15.3
5	2.0	-0.0	-15.5
6	2.6	0.8	- 4.1
7	2.9	0.7	- 3.2
8	4.5	0.8	-21.5
9	4.4	0.5	-18.0
10	7.3	0.5	9.5
11	7.9	-0.1	7.8

RUN NO. 3 B 2 (Continued)

LEFT ROSETTE

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0
2	1.8	-1.1	19.1
3	4.2	-1.1	-14.7
4	7.0	-2.1	-5.9
5	7.0	-2.1	-5.9
6	11.1	-1.8	-8.3
7	9.0	-1.5	-17.5
8	10.0	-2.0	-21.4
9	10.0	-3.5	19.6
10	8.7	-2.0	-18.6
11	9.9	-2.1	-15.6
12	9.4	-3.4	-8.9

FRONT ROSETTE

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0
2	0.8	-2.7	-5.3
3	3.7	-2.2	6.8
4	5.9	-3.5	7.0
5	6.2	-2.7	8.9
6	6.7	1.3	20.9
7	6.7	1.3	20.9
8	9.9	2.3	20.2
9	16.3	4.0	-16.0
10	17.3	3.8	-21.6

REAR ROSETTE

PRINCIPAL STRAINS E1,E2 (MICRO-IN/IN)

RDG	E1	E2	PHI
1	0.0	0.0	0
2	6.0	-37.7	21.1
3	13.4	-75.8	21.0
4	18.8	-94.6	21.2
5	22.8	-123.5	20.4
6	28.1	-152.1	21.9
7	32.4	-187.5	20.0
8	39.0	-205.8	19.6
9	40.6	-242.6	18.9
10	40.6	-242.6	18.9
11	46.5	-284.1	18.7
12	49.8	-324.8	18.7

APPENDIX B-2

MONKEY TYPE I

HEAD IMPACT TEST SUMMARY

TEST NO. 002

TEST DATE 12/12/74

TEST SUBJECT

SPECIES Rhesus

Body Weight 11.44 lb.

Sitting Height (Top of Head to bottom of Buttocks) 19.00 in.

Head Weight 1.14 lbs

Brain Weight 0.225 lbs

Brain Volume 6.35 in^3

Skull Inside Length A 3.02 in

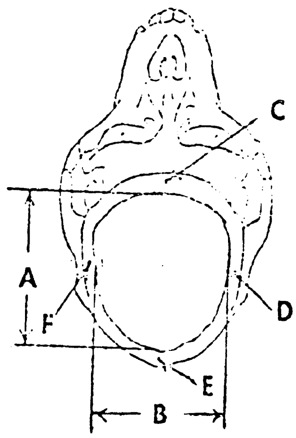
Skull Inside Width B 2.49 in

Skull Thickness at Pt. C 0.096 in

Skull Thickness at Pt. D 0.084 in

Skull Thickness at Pt. E 0.124 in

Skull Thickness at Pt. F 0.094 in



IMPACT CONDITIONS

Location of Impact Back of Head

Type of Impact One and one quarter inches diameter, 0.25 inch wall thickness, round cap

Impact Velocity 31.28 ft/sec

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site ----

Opposite to Impact Site GOOD

Epidural Pressures in Direction of Impact:

At Impact Site ---

Opposite to Impact Site Good

Strain Gage Rosettes:

Right Parietal Gage Good

Left Parietal Gage ----

Frontal Gage ----

Force: Good

High Speed Motion Pictures:

Side Camera Good

Frame Rate 3000 fps

Type II

Accelerations in Direction of Impact:

At Impact Site ______

Opposite to Impact Site ______

Rigid Body Head Motion Analysis: ______

EEG DATA: Pre-Impact ______

Post Impact ______

- NOT ANALYZED -

Force: ______

TEST NO. 002

High Speed Motion Pictures

Side Camera __________

Framing Rate __________

Front Camera __________

Framing Rate __________

INJURY:

Condition Prior to Impact Slight muscle tone, slight eye reflex, and some shivering.

		Time After Impact	Condition
Consciousness	1.	0 min	Unconscious
	2.	20 min	Unconscious
	3.		
	4.		
	5.		
	6.		
	7.		
	8.		
	9.		
	10.		

AUTOPSY SUMMARY:

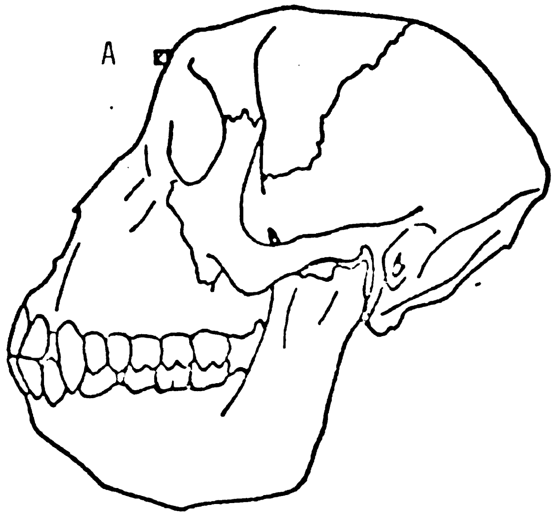
1. Compound and simple fractures of occipital bone
2. Simple fractures of Lt. parietal bone
3. Simple fractures of Rt. parietal bone
4. Simple fractures of Rt. temporal bone
5. Simple fractures of Lt. temporal bone
6. Subdural hemorrhage (massive)
7. Tear of major vessels
8. Focussed injury under front pressure gage
9. Focussed injury under rear pressure gage
10.
11.
12.
13.
14.
15.

Injuries Due to Impact only (not instrumentation)

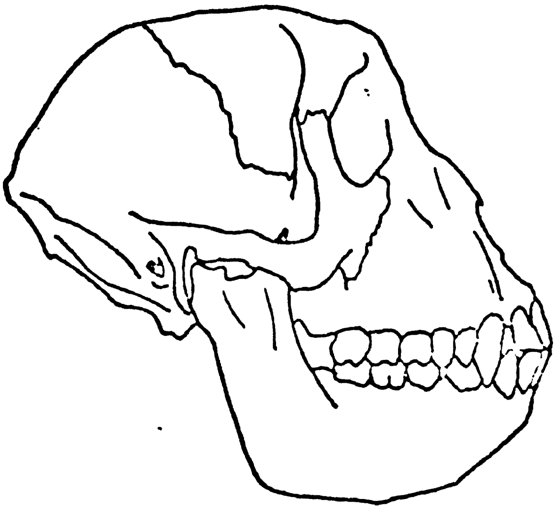
	Injury	AIS
1.	Compound and simple fractures of occipital	4
2.	Simple fractures of Lt. parietal bone	3
3.	Simple fractures of Rt. parietal bone	2
4.	Simple fractures of Lt. temporal bone	2
5.	Simple fractures of Rt. temporal bone	2
6.	Subdural hemorrhage (massive)	5
7.	Tear of major vessels	5
8.		
9.		
10.		

AIS Overall 6

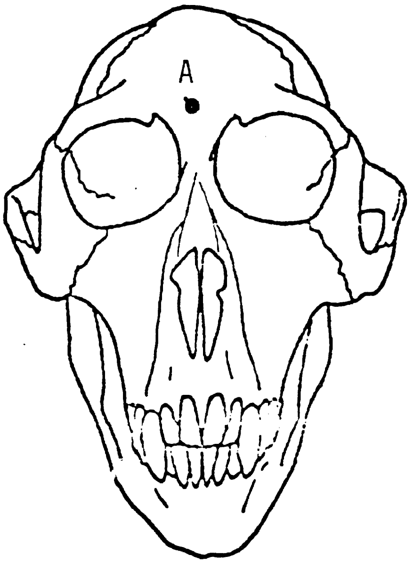
Run Number 002



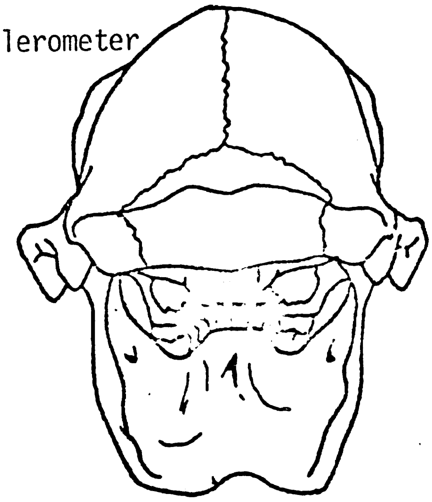
Left Lateral View



Right Lateral View



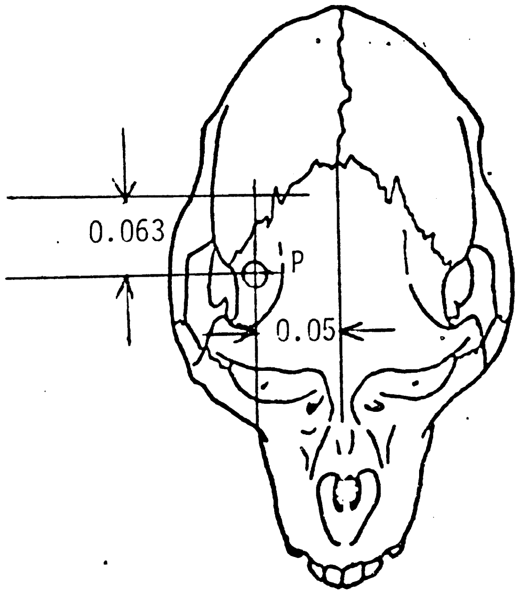
A - location of accelerometer



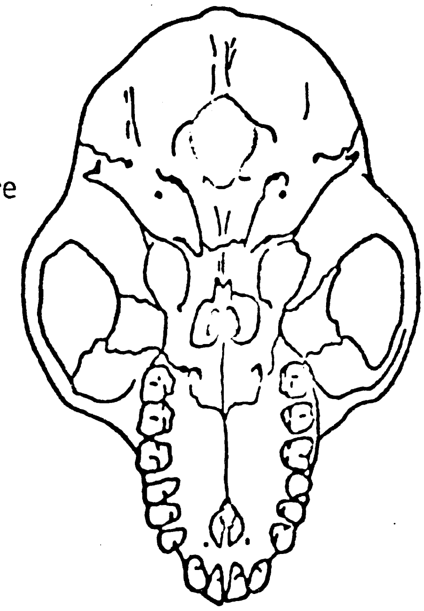
Anterior View

Posterior View

Distances measured along surface of skull

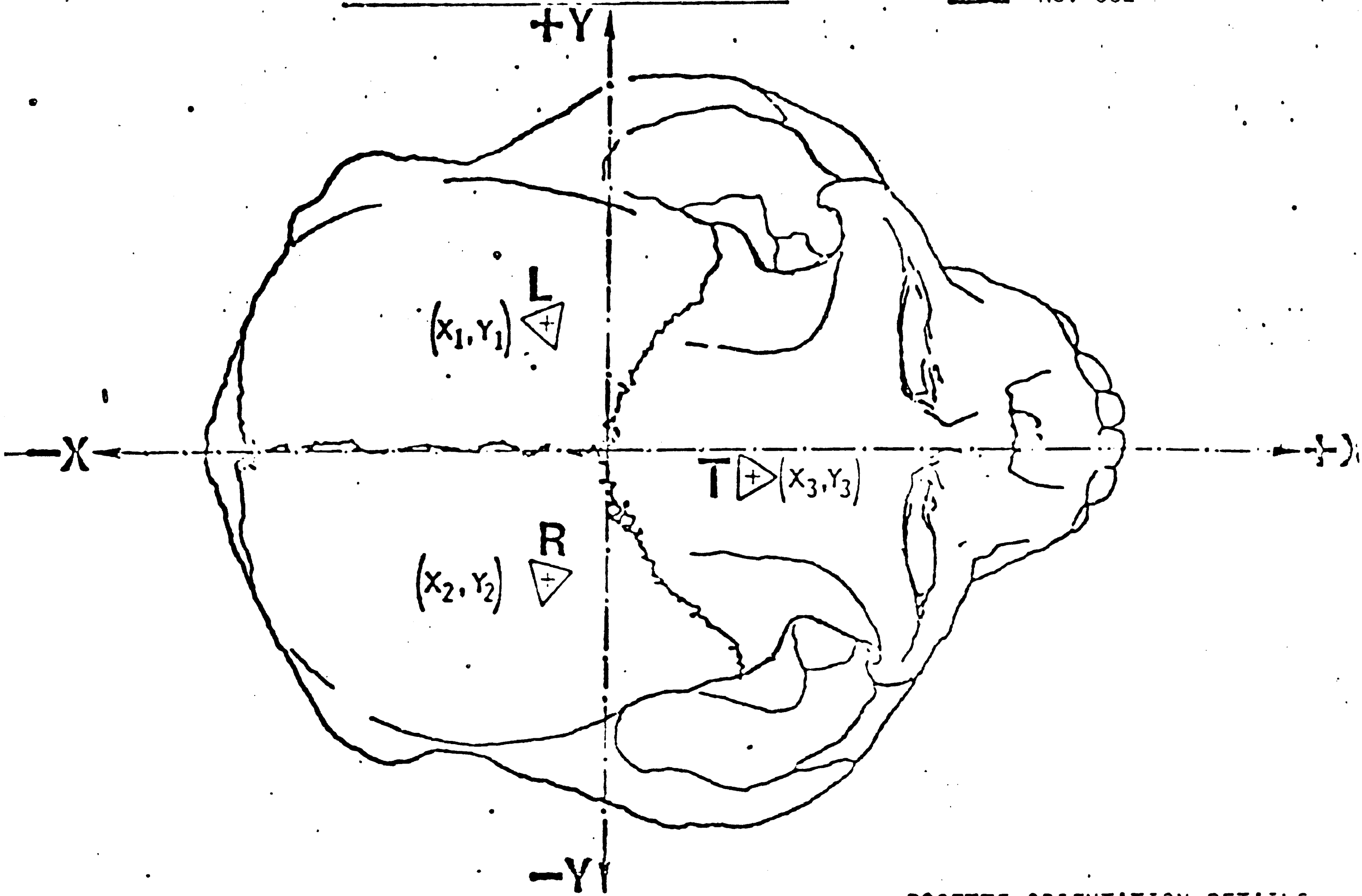


P - location of pressure transducer

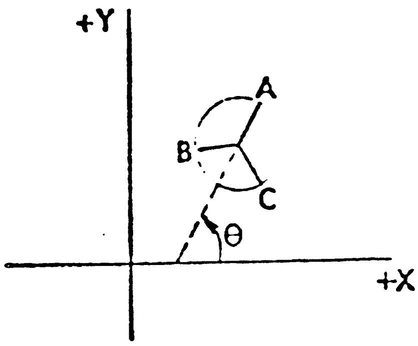


Superior View

Inferior View



ROSETTE ORIENTATION DETAILS



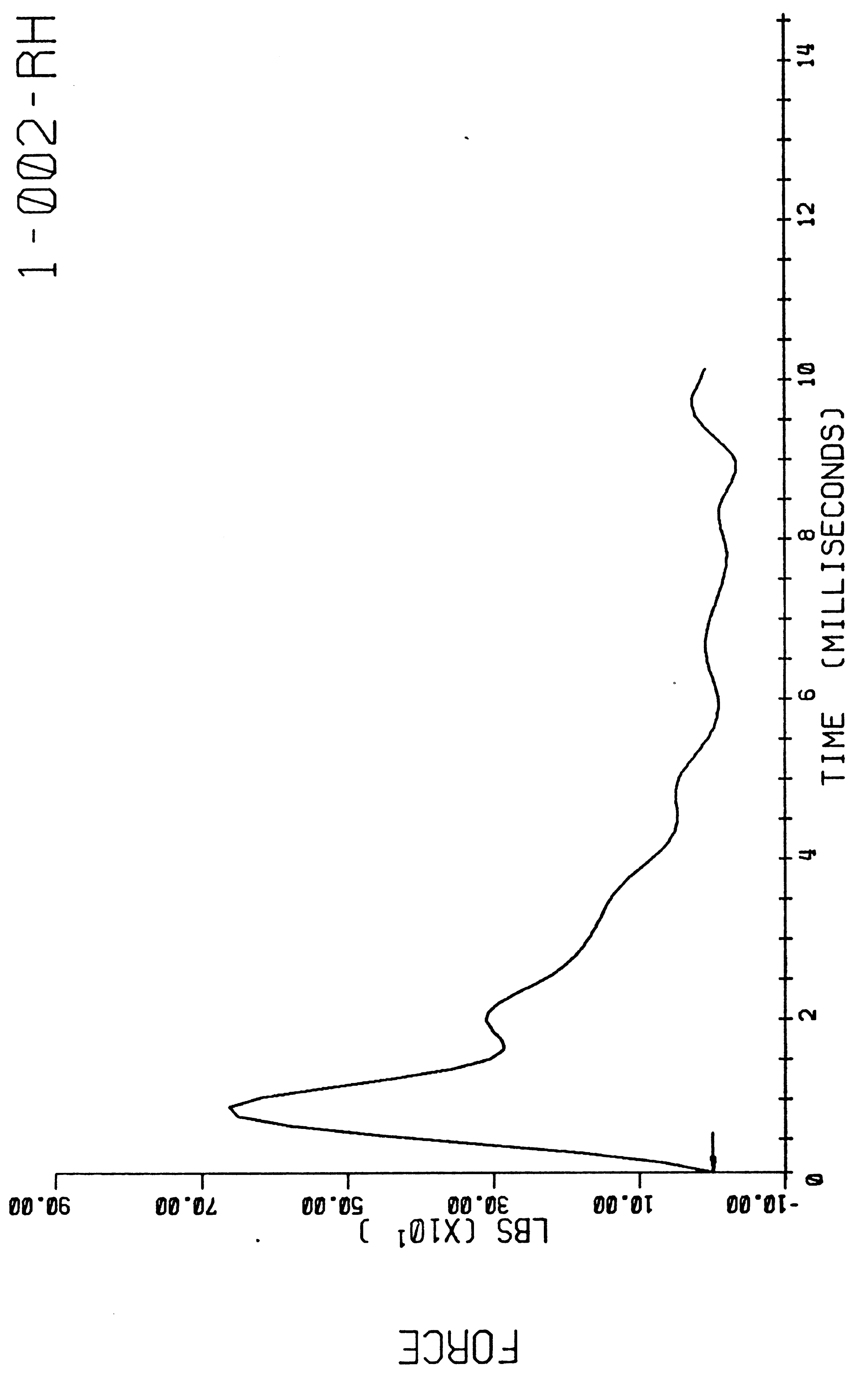
a. △ -- Location of strain rosettes.

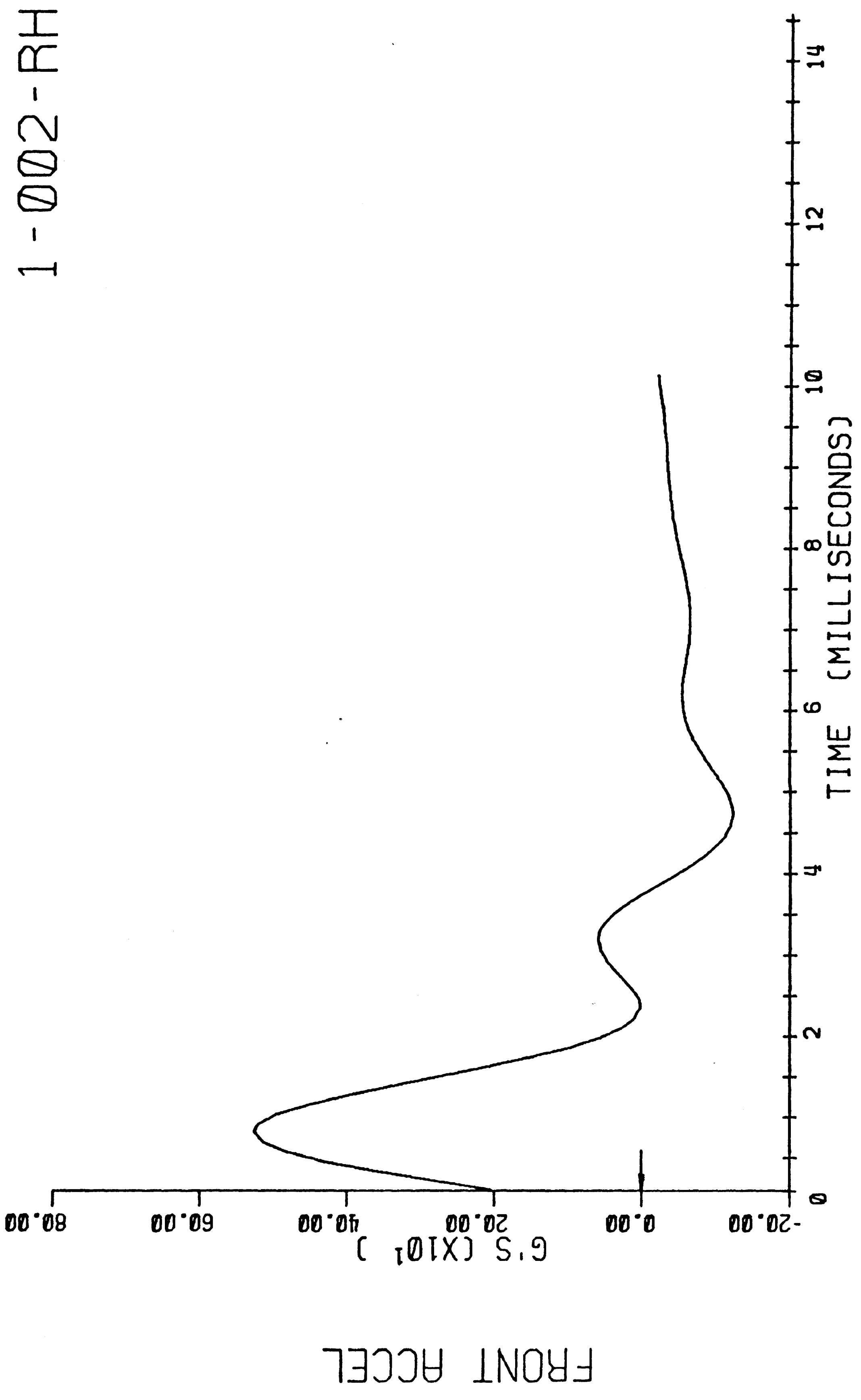
b. R -- Right L -- Left T -- Top

c. θ is the angle (measured anti-clockwise) arm 'A' of the rosette makes with the positive direction of the X-axis.
Note: Arm 'A' corresponds to arm '1' as printed on rosette.

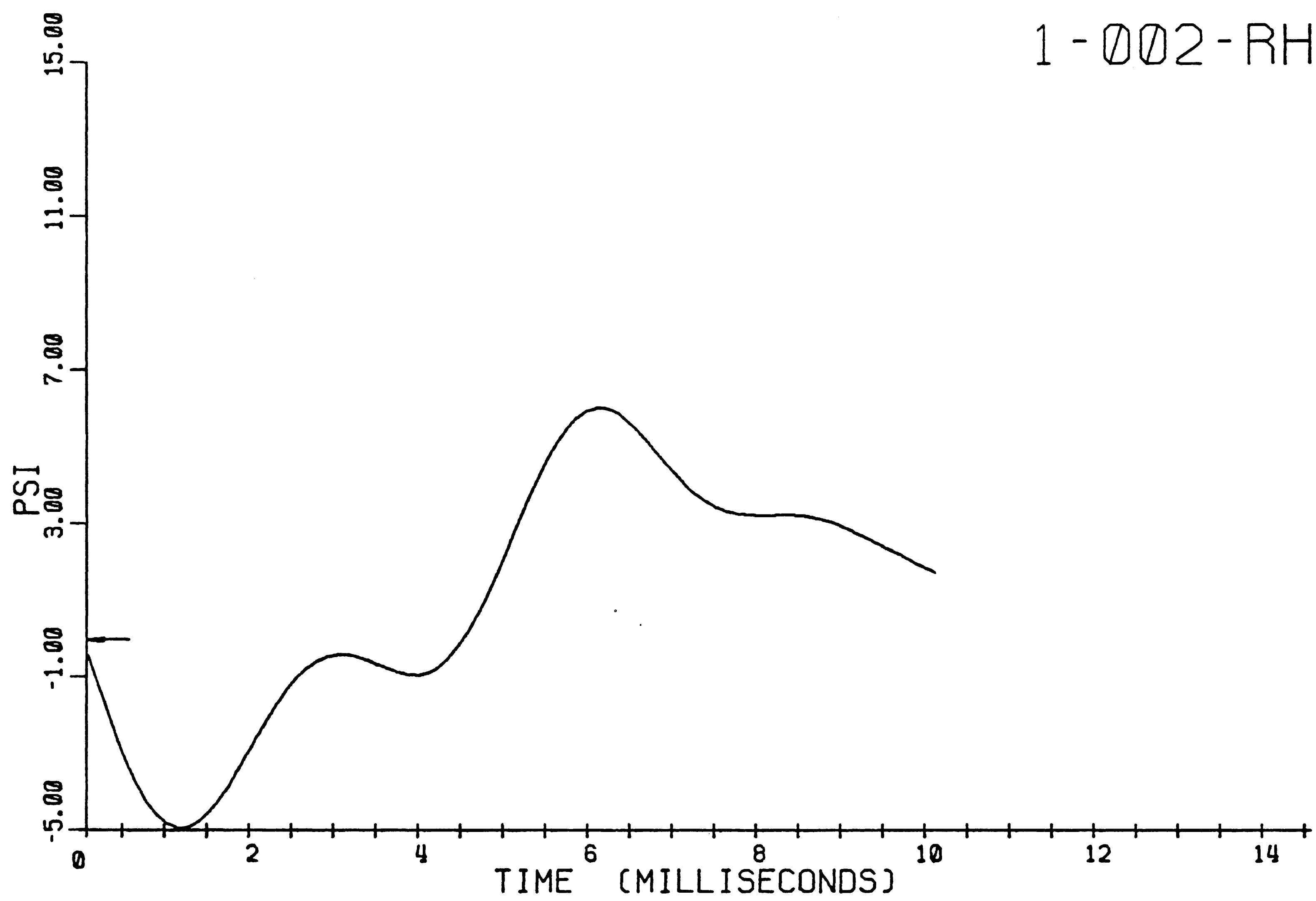
d. All distances are measured along the surface of the skull.

LEFT ROSETTE	RIGHT ROSETTE	TOP ROSETTE
x_1 =	x_2 = -0.29	x_3 =
y_1 =	y_2 = -1.08	y_3 =
θ_1 =	θ_2 = 3.7°	θ_3 =

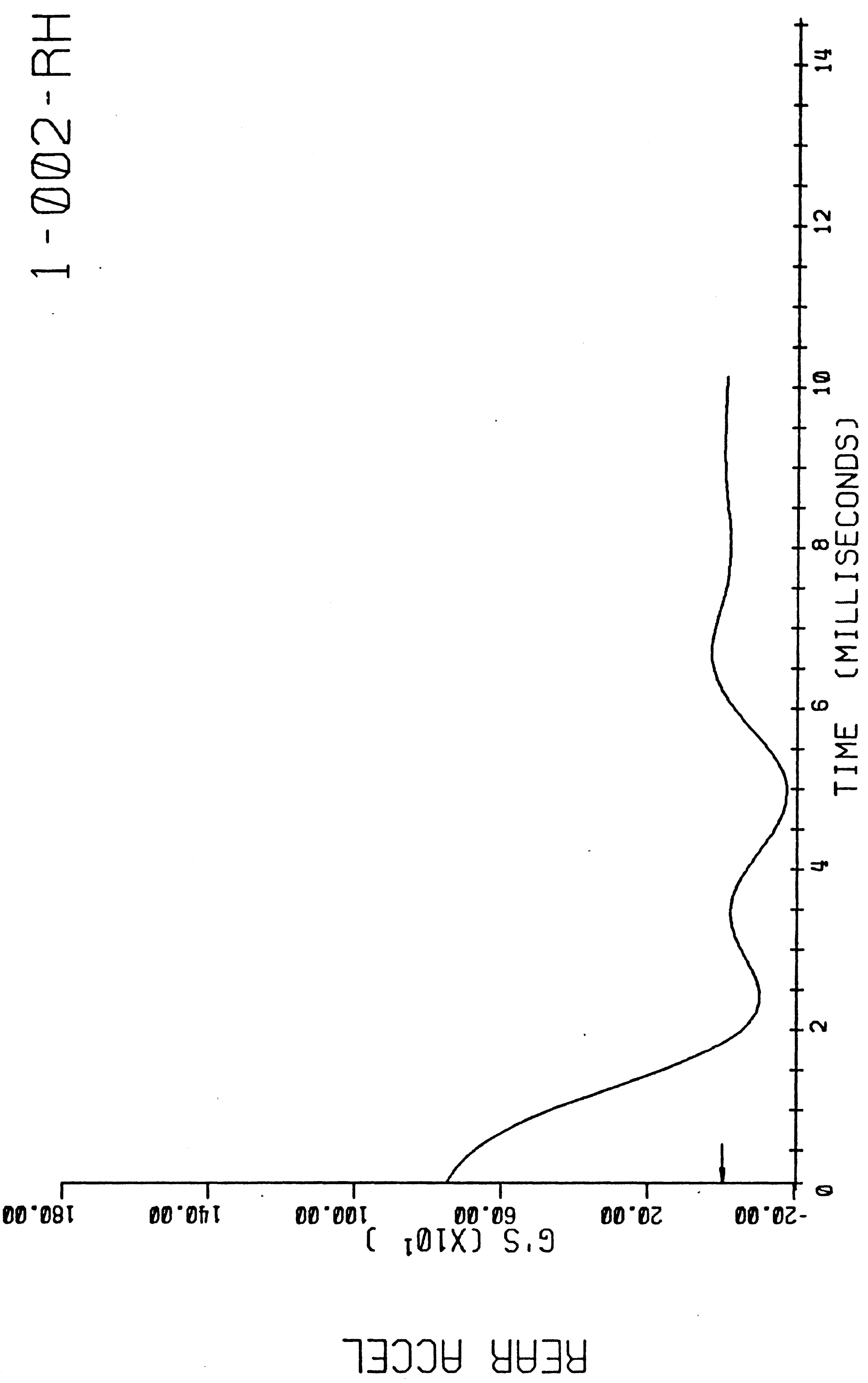

1-002-RH
FORCE
LBS (X10¹)
-10.00
10.00
30.00
50.00
70.00
90.00
TIME (MILLISECONDS)
0
2
4
6
8
10
12
14

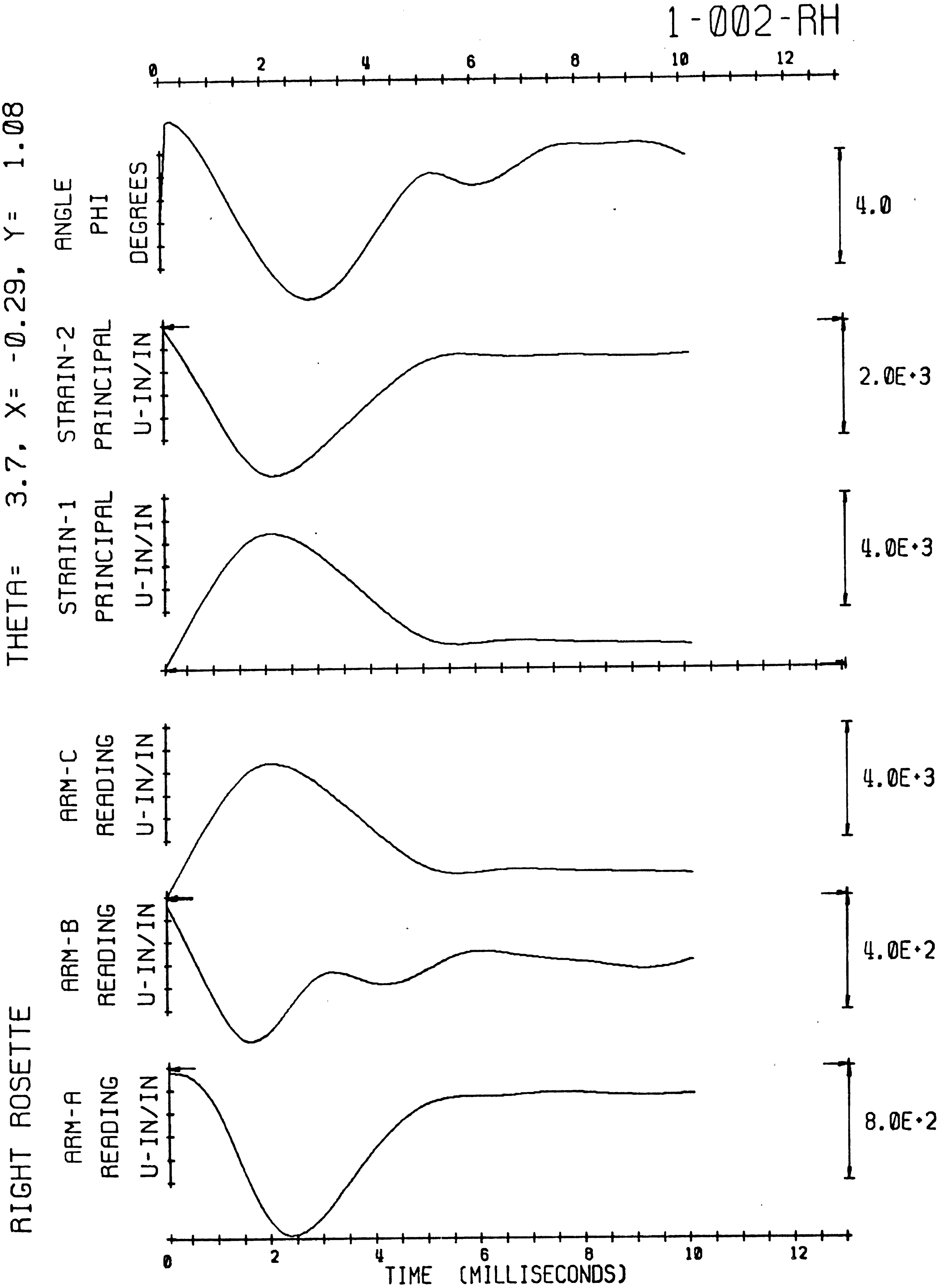


1-ØØ2-RH
TIME (MILLISECONDS)
0
2
4
6
8
10
12
14
G'S (X1Ø1)
-20.00
0.00
20.00
40.00
60.00
80.00
FRONT ACCEL



FRONT PRESSURE


1-ØØ2-RH
TIME (MILLISECONDS)
0
2
4
6
8
10
12
14
G'S (X10¹)
-20.00
20.00
60.00
100.00
140.00
180.00
REAR ACCEL



DELTA ROSETTE STRAIN GAGE

HEAD IMPACT TEST SUMMARY

TEST NO. 003 TEST DATE 12-17-74

TEST SUBJECT

SPECIES Rhesus

Body Weight 11.70 lb.

Sitting Height (Top of Head to bottom of Buttocks) 20.00 in.

Head Weight 1.17 lbs

Brain Weight 0.188 lbs

Brain Volume 6.16 in^3

Skull Inside Length A 3.35 in

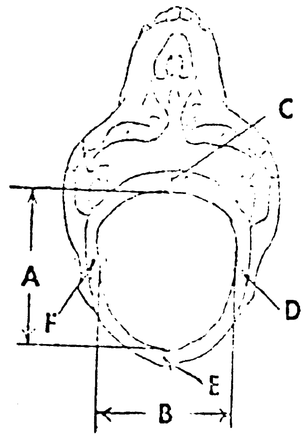
Skull Inside Width B 2.47 in

Skull Thickness at Pt. C 0.104 in

Skull Thickness at Pt. D 0.069 in

Skull Thickness at Pt. E 0.150 in

Skull Thickness at Pt. F 0.065 in



IMPACT CONDITIONS

Location of Impact Back of Head

Type of Impact One and one-quarter inches diameter, 0.25 inch wall thickness, round cap

Impact Velocity 21.12 ft/sec

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site Good

Opposite to Impact Site ----

Epidural Pressures in Direction of Impact:

At Impact Site ----

Opposite to Impact Site Good

Strain Gage Rosettes:

Right Parietal Gage Good

Left Parietal Gage ---

Frontal Gage ---

Force: Good

High Speed Motion Pictures:

Side Camera Good

Frame Rate 3000 fps

Type II

Accelerations in Direction of Impact:

At Impact Site ____

Opposite to Impact Site ____

Rigid Body Head Motion Analysis: ____

EEG DATA: Pre-Impact ____

Post Impact ____

- NOT ANALYZED -

Force: ____

High Speed Motion Pictures

Side Camera ____________________

Framing Rate ____________________

Front Camera ____________________

Framing Rate ____________________

INJURY:

Condition Prior to Impact Slight muscle tone, slight eye reflex, and some shivering

		Time After Impact	Condition
Consciousness	1.	0 min	Unconscious
	2.	60 min	Unconscious
	3.		
	4.		
	5.		
	6.		
	7.		
	8.		
	9.		
	10.		

TEST NO. 003

Autopsy Summary

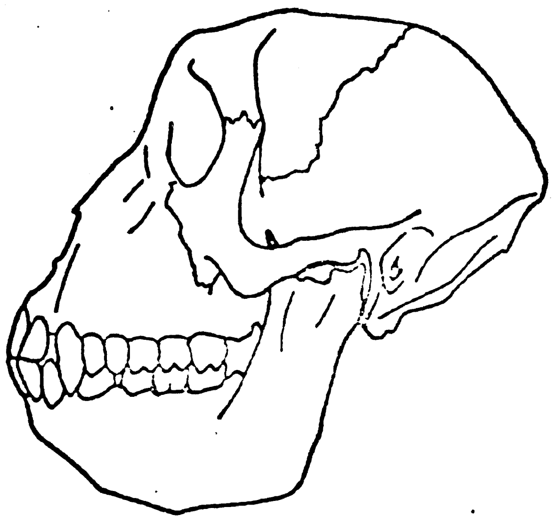
1. Simple fracture of occipital bone
2. Simple fracture of Lt. Parietal bone
3. Simple fracture of Lt. Temporal bone
4. Focussed injury under front pressure gage
5. Focussed injury under rear pressure gage
6. Subdural hemorrhage Rt. tip of frontal lobe
7. Highly localized contre-coup injury tip of Rt. frontal lobe
8.
9.
10.
11.
12.
13.
14.
15.

Injuries Due to Impact only (not instrumentation)

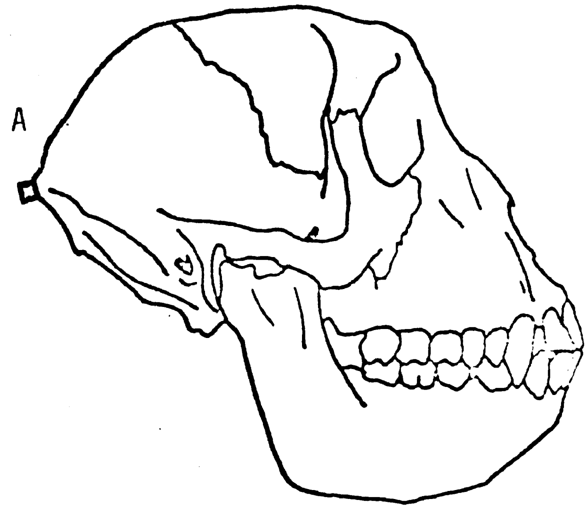
1.	Simple fracture of occipital bone	3
2.	Simple fracture of Lt. Parietal bone	2
3.	Simple fracture of Lt. Temporal bone	2
4.	Subdural hemorrhage Rt. tip of frontal lobe	4
5.	Highly localized contre coup injury tip of Rt. Frontal Lobe	3
6.	Unconscious for more than 15 minutes	4
7.		
8.		
9.		
10.		

AIS OVERALL 6

Run Number 003

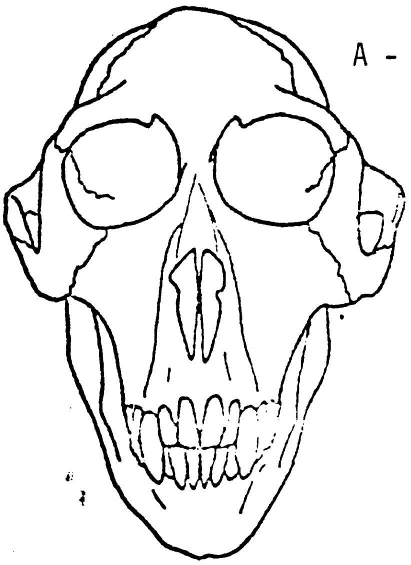


Left Lateral View

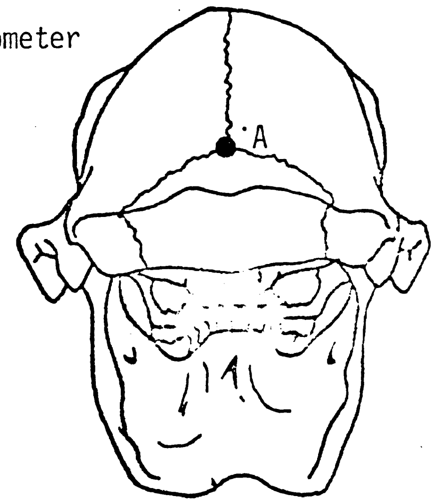


Right Lateral View

A - location of accelerometer



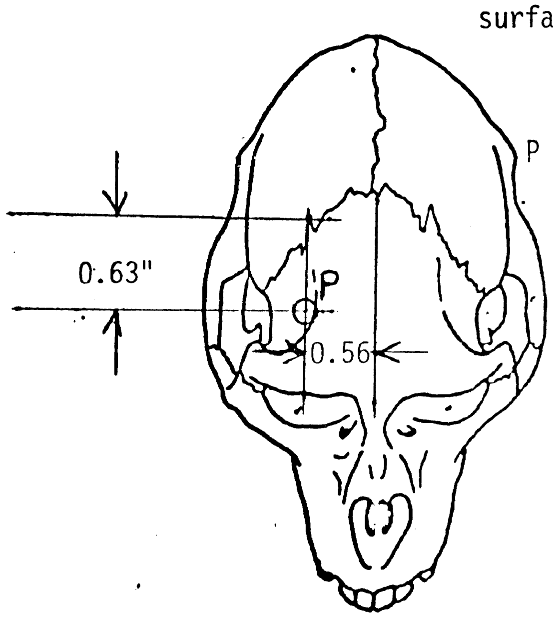
Anterior View



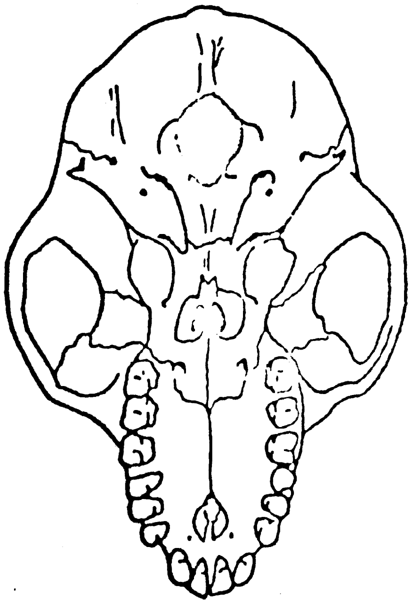
Posterior View

Distances measured along surface of skull

P - location of pressure transducer

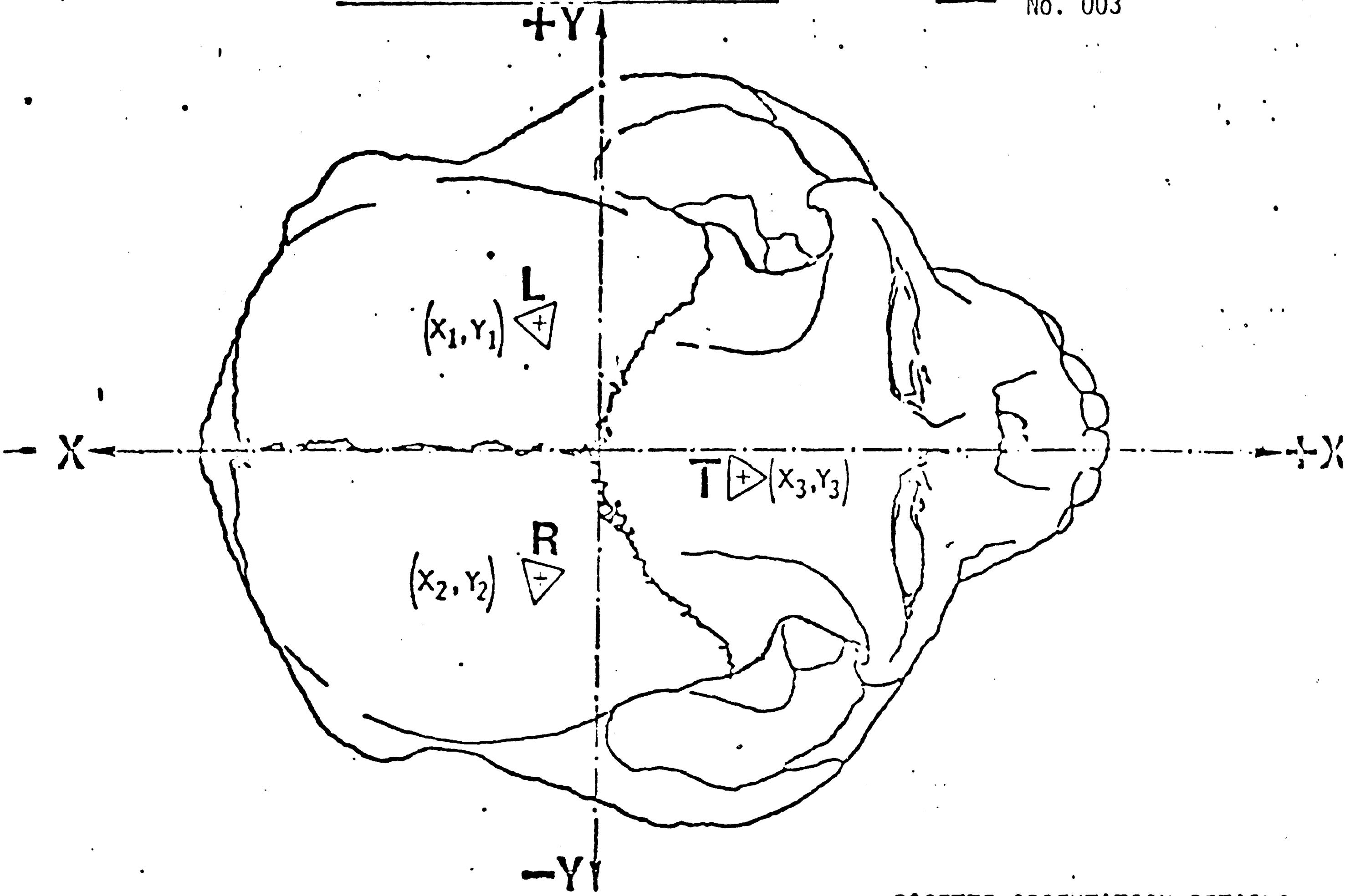


Superior View

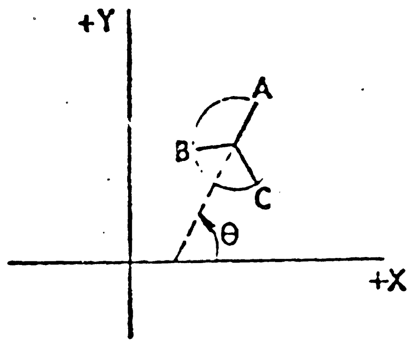


Inferior View

HSRI STRAIN ROSETTE DATA SHEET TEST No. 003



ROSETTE ORIENTATION DETAILS



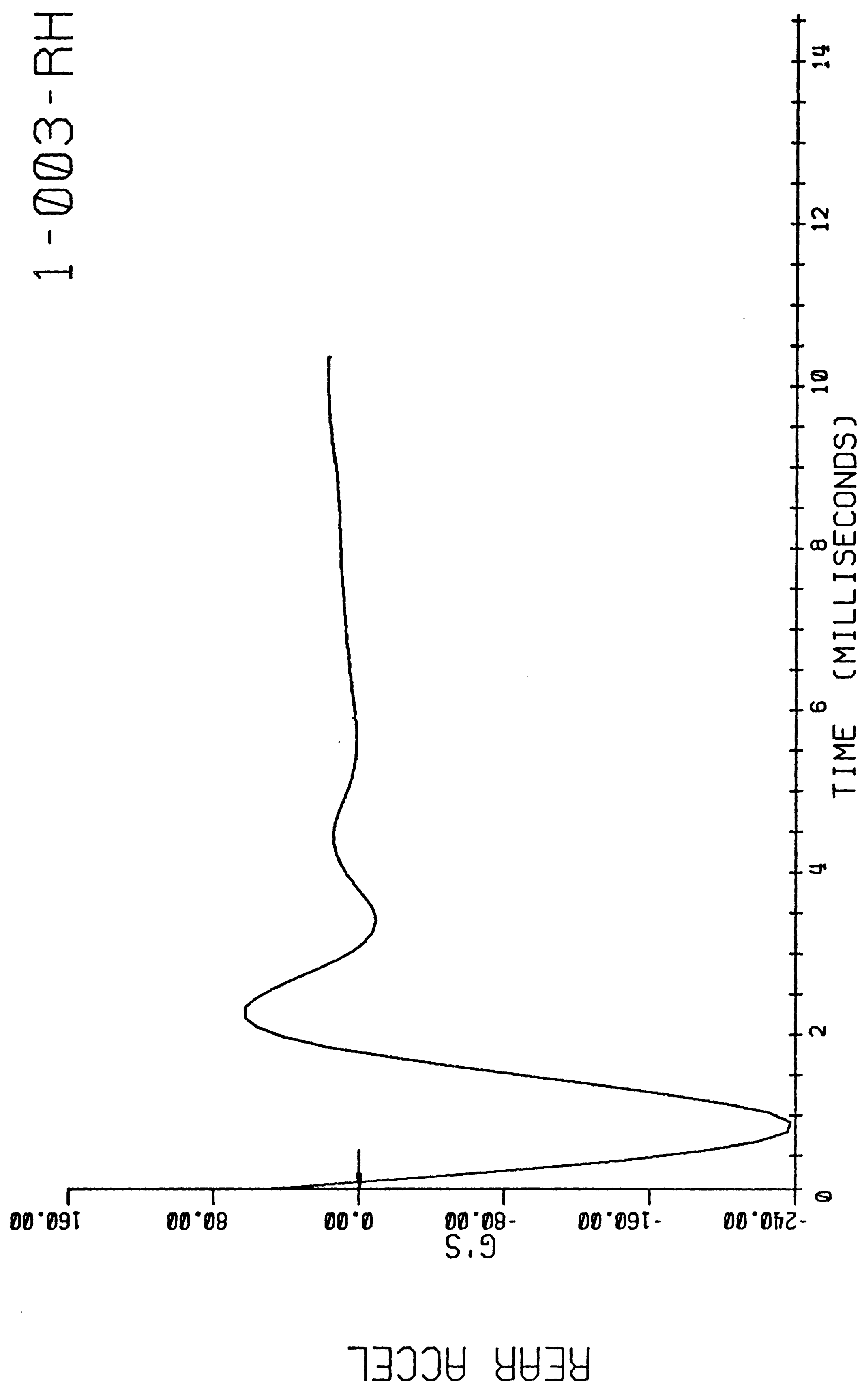
a. △ -- Location of strain rosettes.

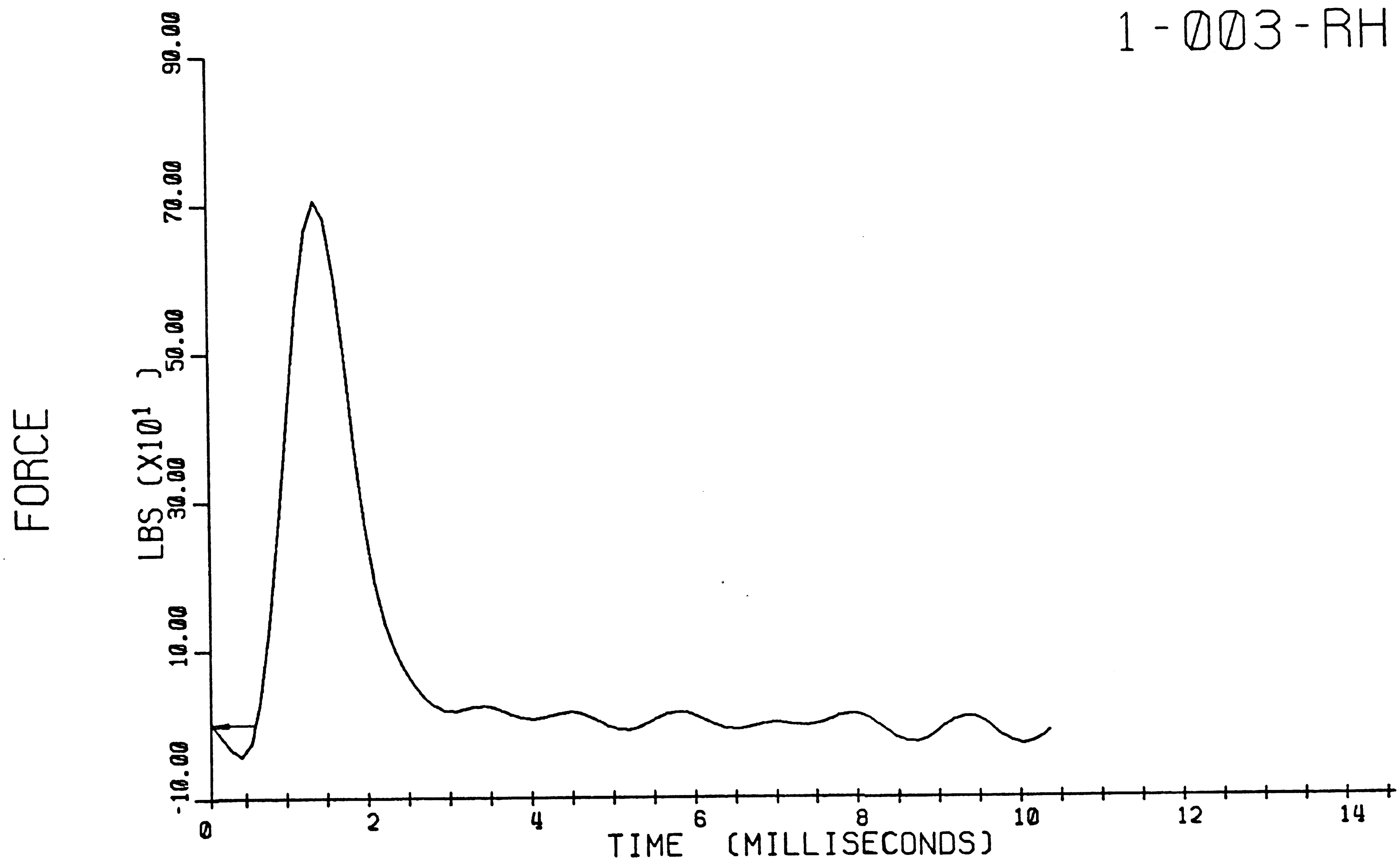
b. R -- Right L -- Left T -- Top

c. θ is the angle (measured anti-clockwise) arm 'A' of the rosette makes with the positive direction of the X-axis.
Note: Arm 'A' corresponds to arm '1' as printed on rosette.

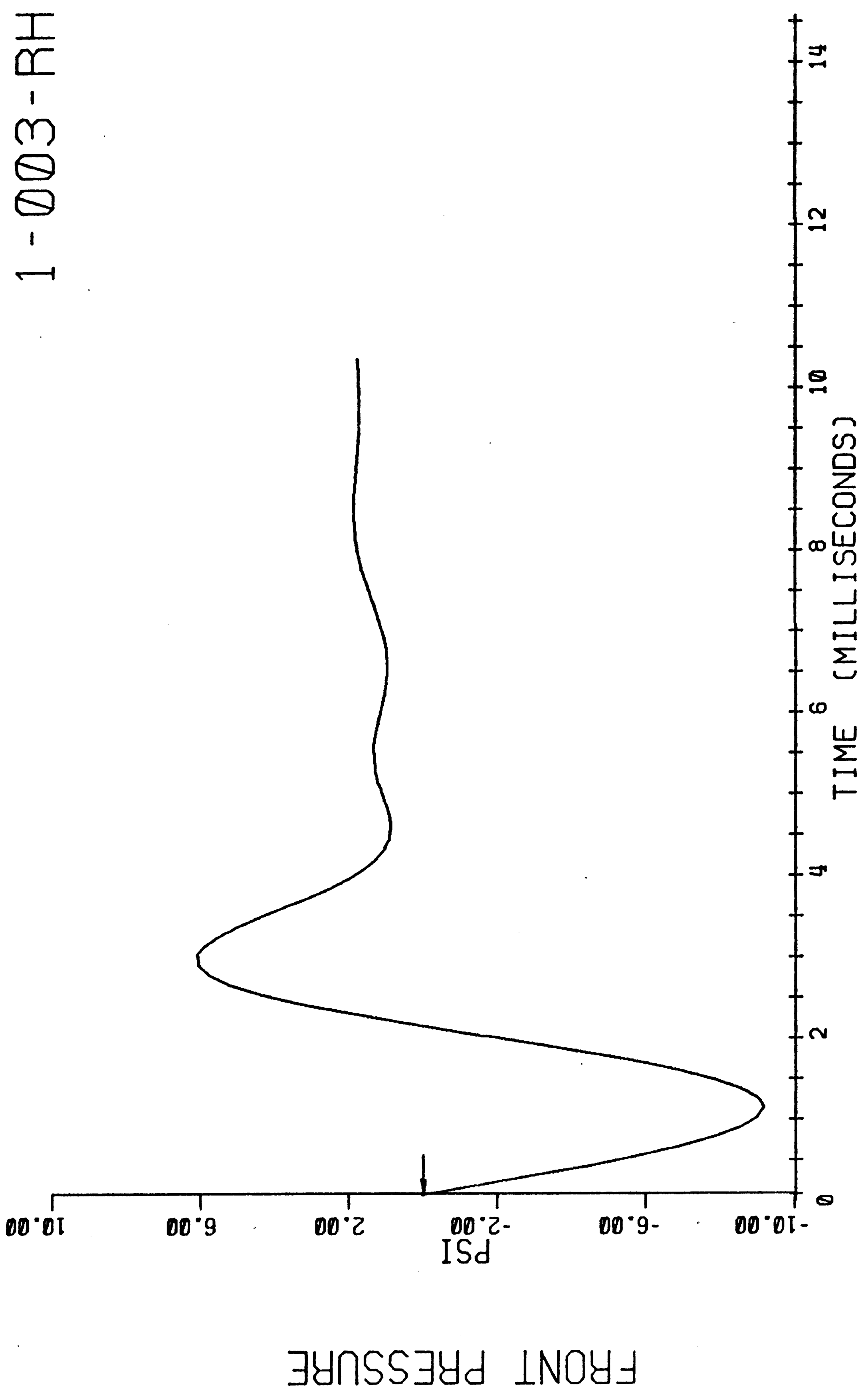
d. All distances are measured along the surface of the skull.

LEFT ROSETTE	RIGHT ROSETTE	TOP ROSETTE
x_1 =	x_2 = -0.16	x_3 =
y_1 =	y_2 = -0.79	y_3 =
θ_1 =	θ_2 = 0°	θ_3 =

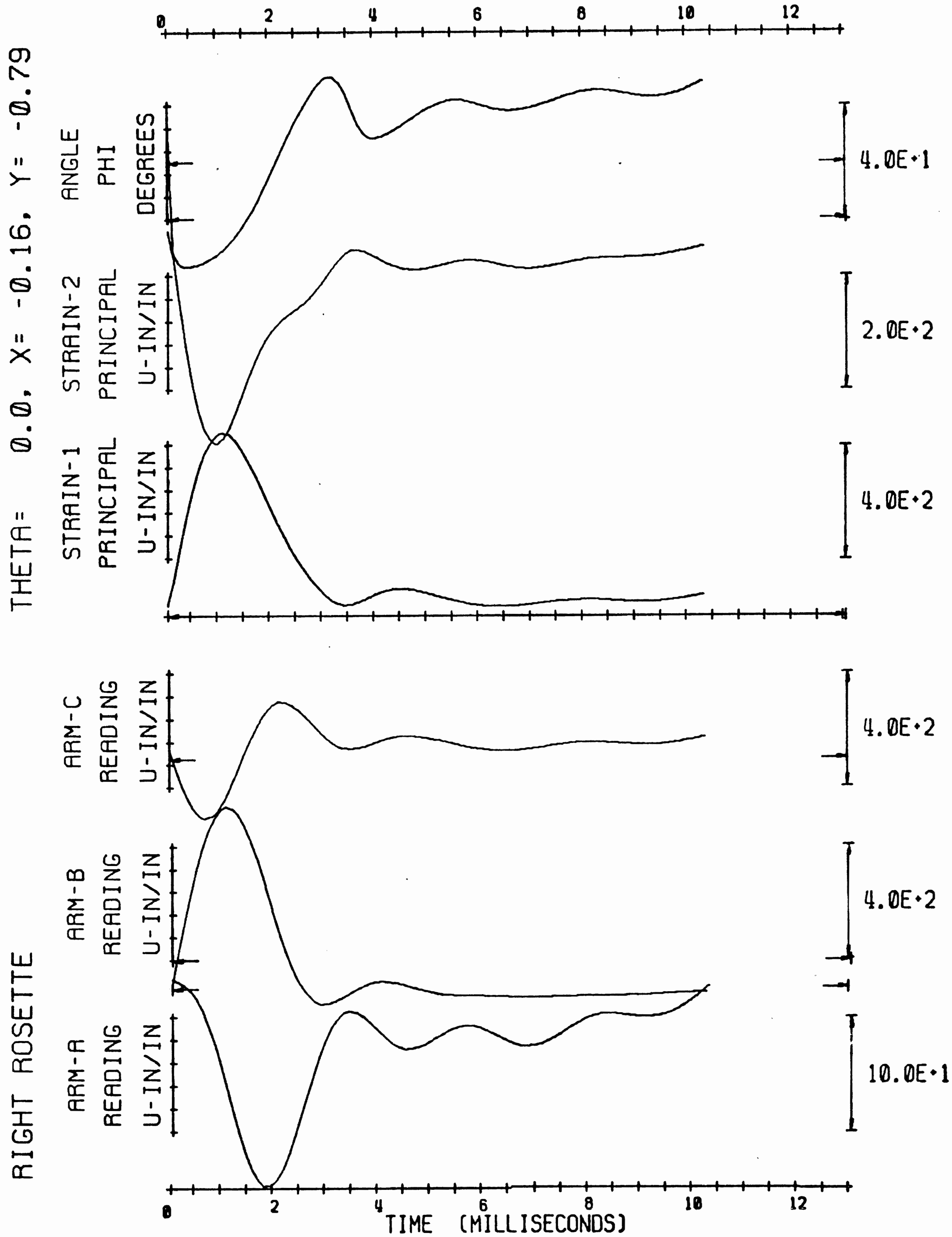

1-003-RH
REAR ACCEL
G'S
TIME (MILLISECONDS)
160.00
80.00
0.00
-80.00
-160.00
-240.00
0
2
4
6
8
10
12
14



1-003-RH
FORCE
LBS (X10¹)
90.00
70.00
50.00
30.00
10.00
-10.00
0
2
4
6
8
10
12
14
TIME (MILLISECONDS)


1-Ø03-RH
FRONT PRESSURE
PSI
-10.00
-6.00
-2.00
2.00
6.00
10.00
TIME (MILLISECONDS)
0
2
4
6
8
10
12
14

1-003-RH



DELTA ROSETTE STRAIN GAGE

HEAD IMPACT TEST SUMMARY

TEST NO. 010 TEST DATE 1/14/75

TEST SUBJECT

SPECIES Rhesus

Body Weight 11.44 lb.

Sitting Height (Top of Head to bottom of Buttocks) 20.00 in.

Head Weight 1.15 lbs

Brain Weight 0.256 lbs

Brain Volume 6.77 in^3

Skull Inside Length A 3.08 in

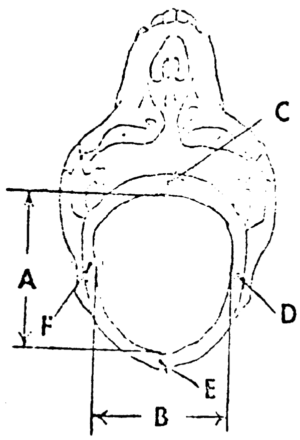
Skull Inside Width B 2.37 in

Skull Thickness at Pt. C 0.105 in

Skull Thickness at Pt. D 0.091 in

Skull Thickness at Pt. E 0.112 in

Skull Thickness at Pt. F 0.088 in



IMPACT CONDITIONS

Location of Impact Back of head

Type of Impact One and one quarter inches diameter, 0.25 inch wall thickness, round cap

Impact Velocity 14.52 ft/sec

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site Good

Opposite to Impact Site ----

Epidural Pressures in Direction of Impact:

At Impact Site Good

Opposite to Impact Site Good

Strain Gage Rosettes:

Right Parietal Gage Good

Left Parietal Gage Good

Frontal Gage ----

Force: Good

High Speed Motion Pictures:

Side Camera Good

Frame Rate 3000 fps

Type II

Accelerations in Direction of Impact:

At Impact Site ______

Opposite to Impact Site ______

Rigid Body Head Motion Analysis: ______

EEG DATA: Pre-Impact ______

Post Impact ______

- NOT ANALYZED -

Force: ______

High Speed Motion Pictures

Side Camera ____________________

Framing Rate ____________________

Front Camera ____________________

Framing Rate ____________________

INJURY:

Condition Prior to Impact Slight muscle tone, slight eye reflex, and some shivering

		Time After Impact	Condition
Consciousness	1.	0 min	conscious
	2.		
	3.		
	4.		
	5.		
	6.		
	7.		
	8.		
	9.		
	10.		

Autopsy Summary

1. Epidural hemorrhage under front pressure gage
2. Epidural hemorrhage under rear pressure gage
3. Focussed injury under front pressure gage
4.
5.
6.
7.
8.
9.
10.
11.
12.
13.
14.
15.

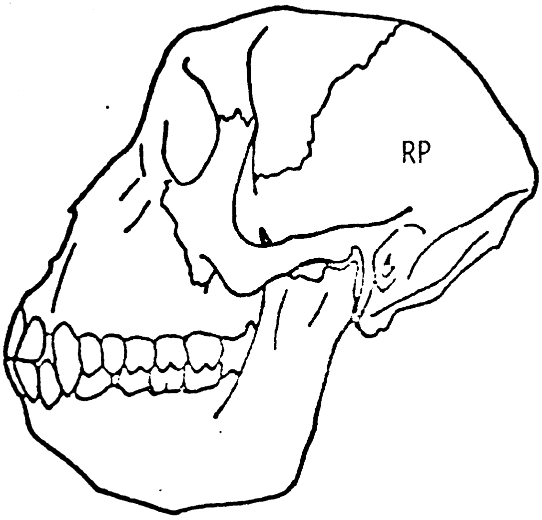
Injuries Due to Impact only (not instrumentation)

AIS

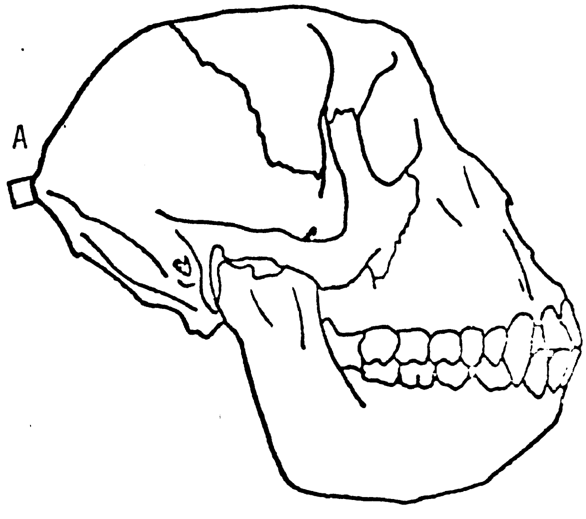
1.
2.
3.
4.
5.
6.
7.
8.
9.
10.

AIS Overall 0

Run Number 010

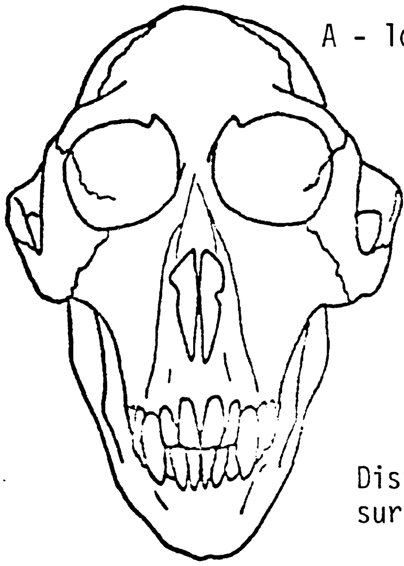


Left Lateral View

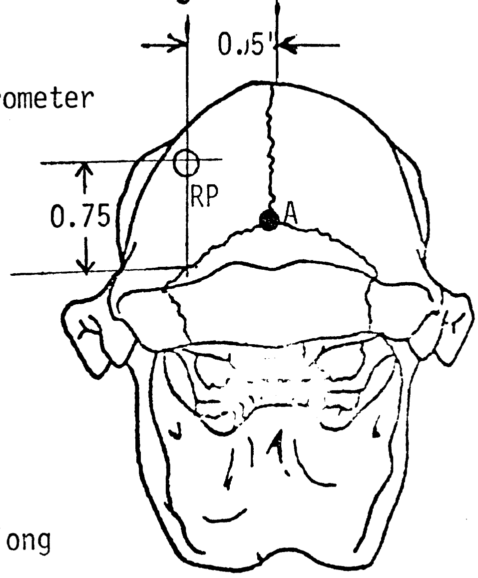


Right Lateral View

A - location of accelerometer



Anterior View

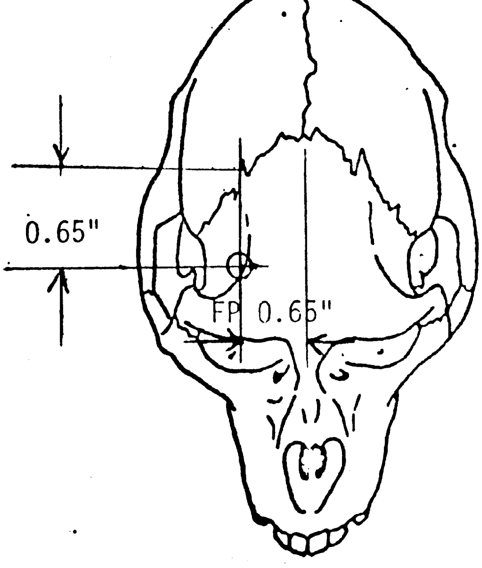


Posterior View

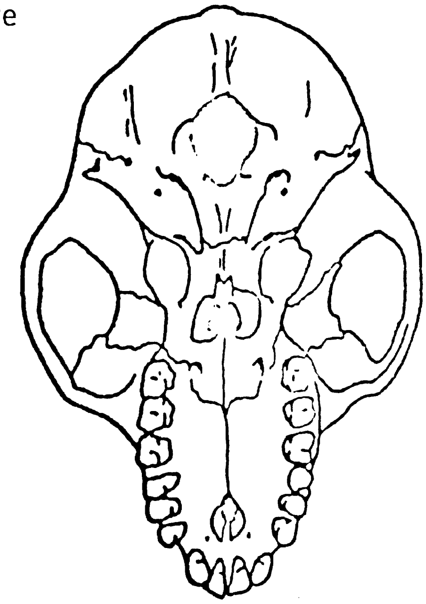
Distances measured along surface of skull

RP - rear pressure gage

FP - front pressure gage

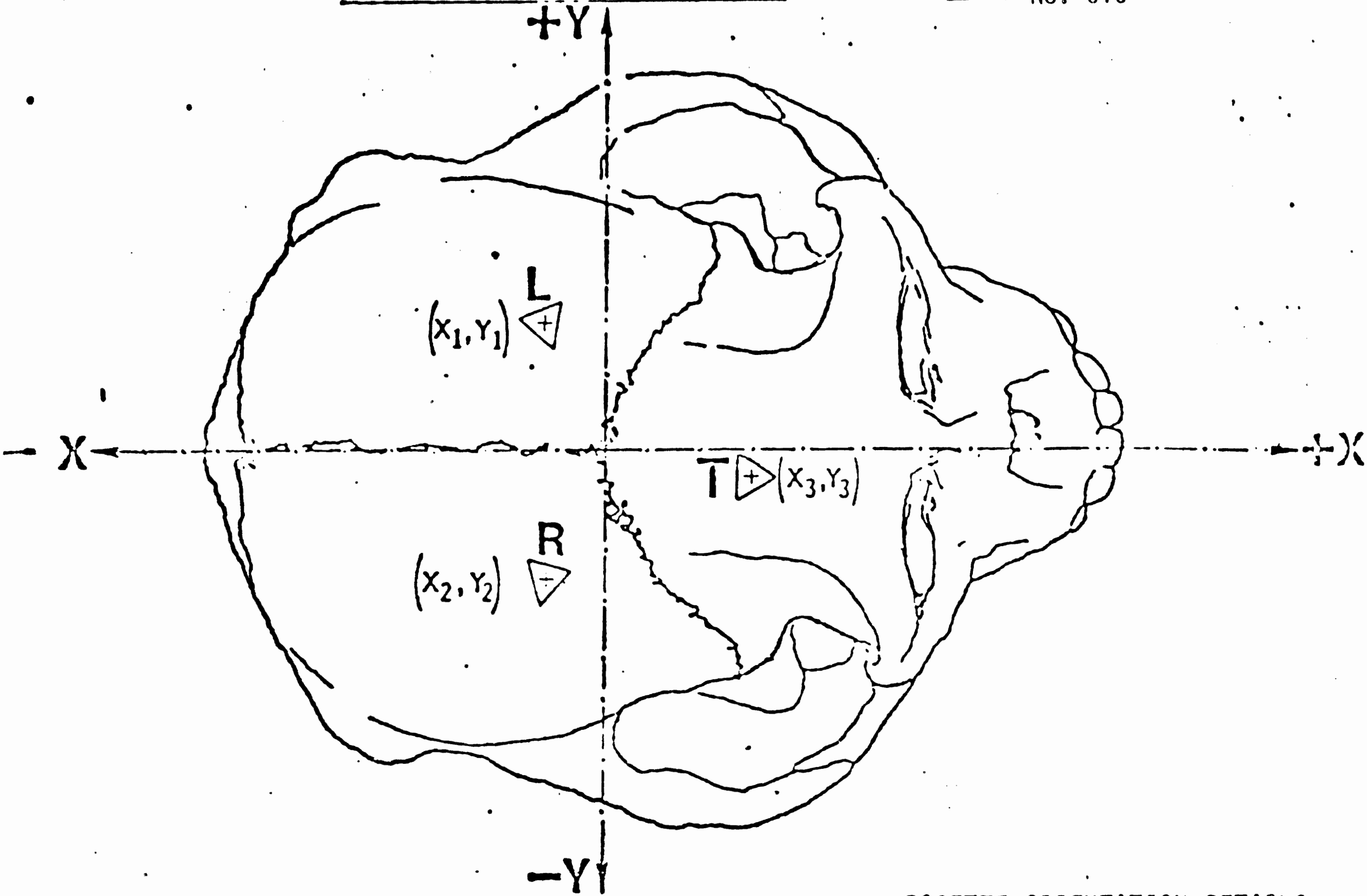


Superior View

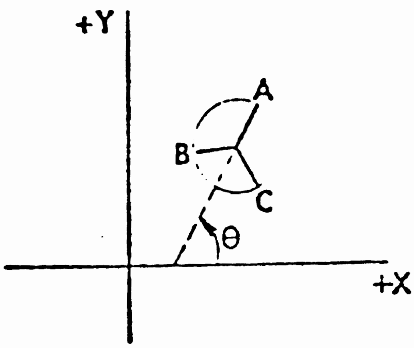


Inferior View

HSRI STRAIN ROSETTE DATA SHEET TEST No. 010



ROSETTE ORIENTATION DETAILS



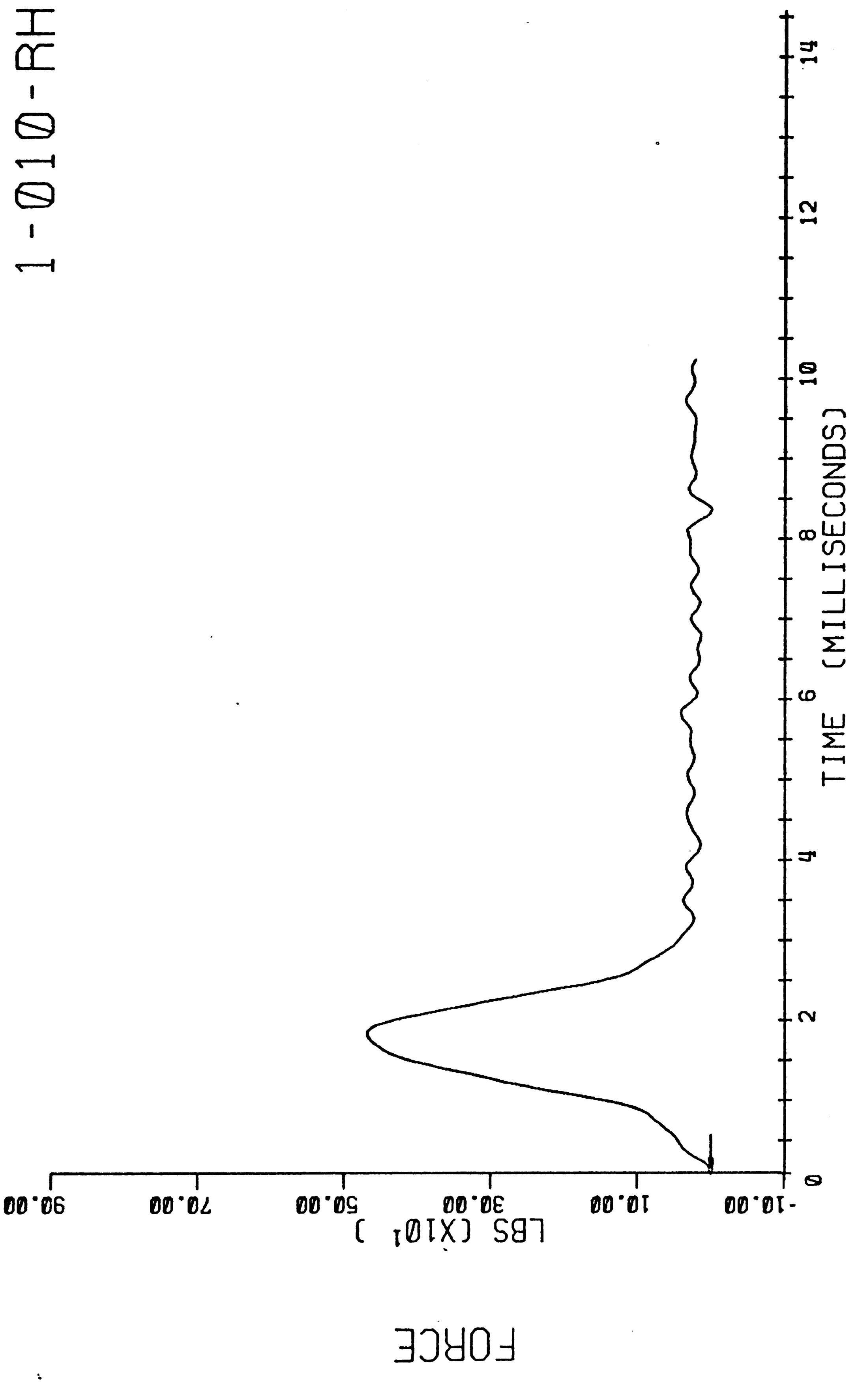
a. △ -- Location of strain rosettes..

b. R -- Right L -- Left T -- Top

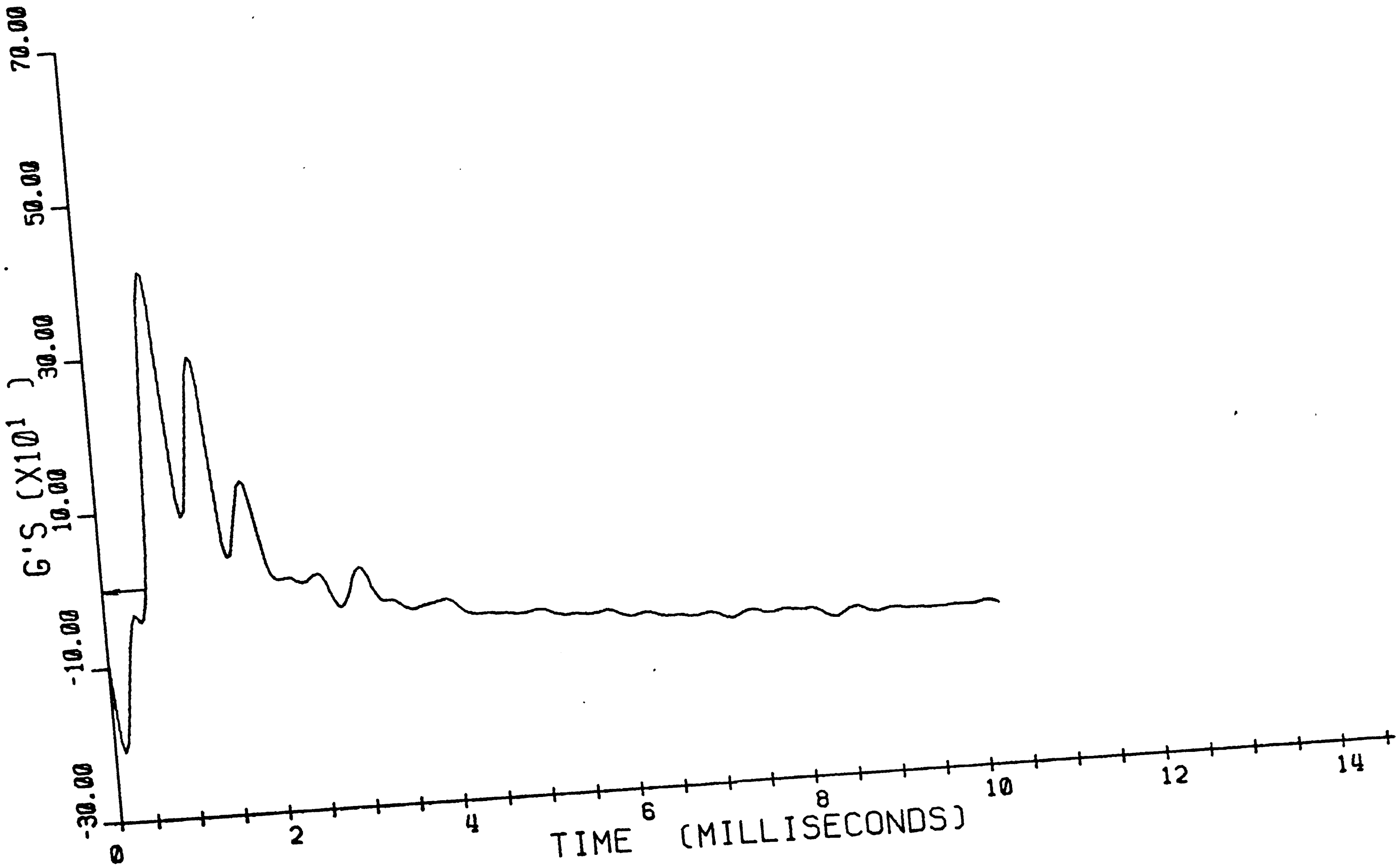
c. θ is the angle (measured anti-clockwise) arm 'A' of the rosette makes with the positive direction of the X-axis.
Note: Arm 'A' corresponds to arm '1' as printed on rosette.

d. All distances are measured along the surface of the skull.

LEFT ROSETTE		RIGHT ROSETTE		TOP ROSETTE	
x_1 =	-0.28	x_2 =	-0.47	x_3 =	
y_1 =	-0.79	y_2 =	0.75	y_3 =	
θ_1 =	84°	θ_2 =	3.0°	θ_3 =	

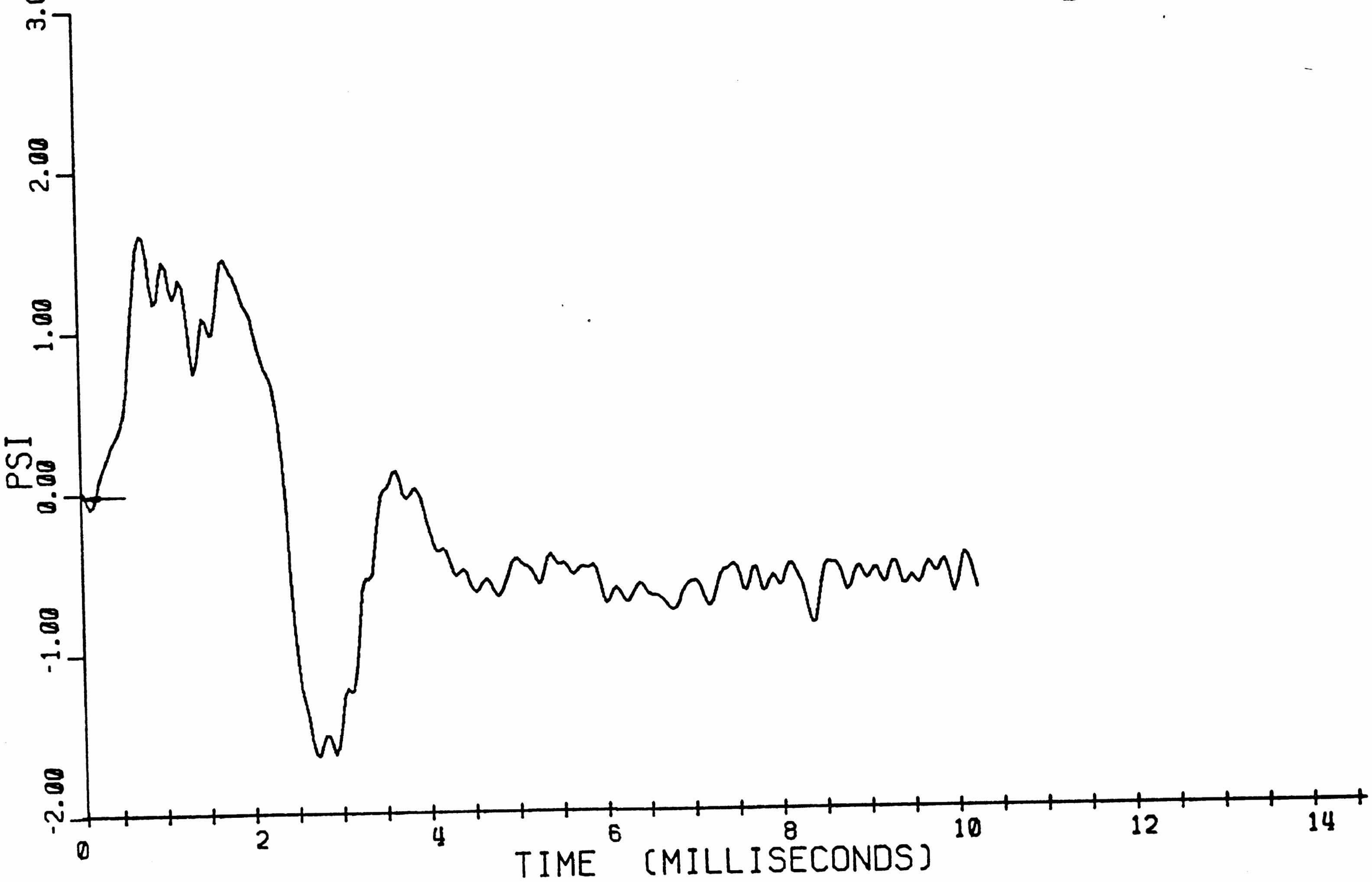

1-Ø10-RH
FORCE
LBS (X1Ø1)
-10.00
10.00
30.00
50.00
70.00
90.00
0
2
4
6
8
10
12
14
TIME (MILLISECONDS)

1-010-RH



REAR ACCEL

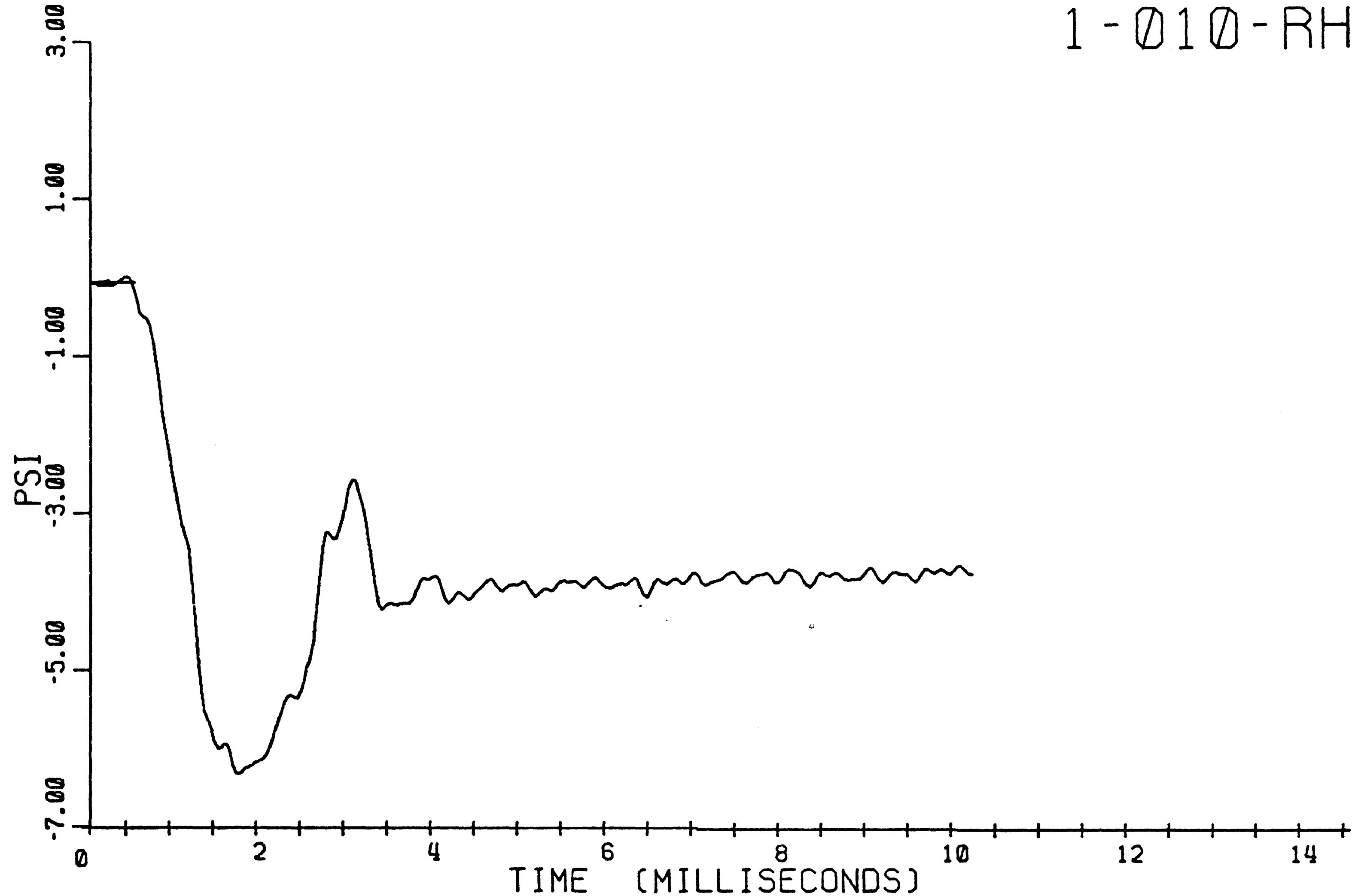
1-Ø10-RH

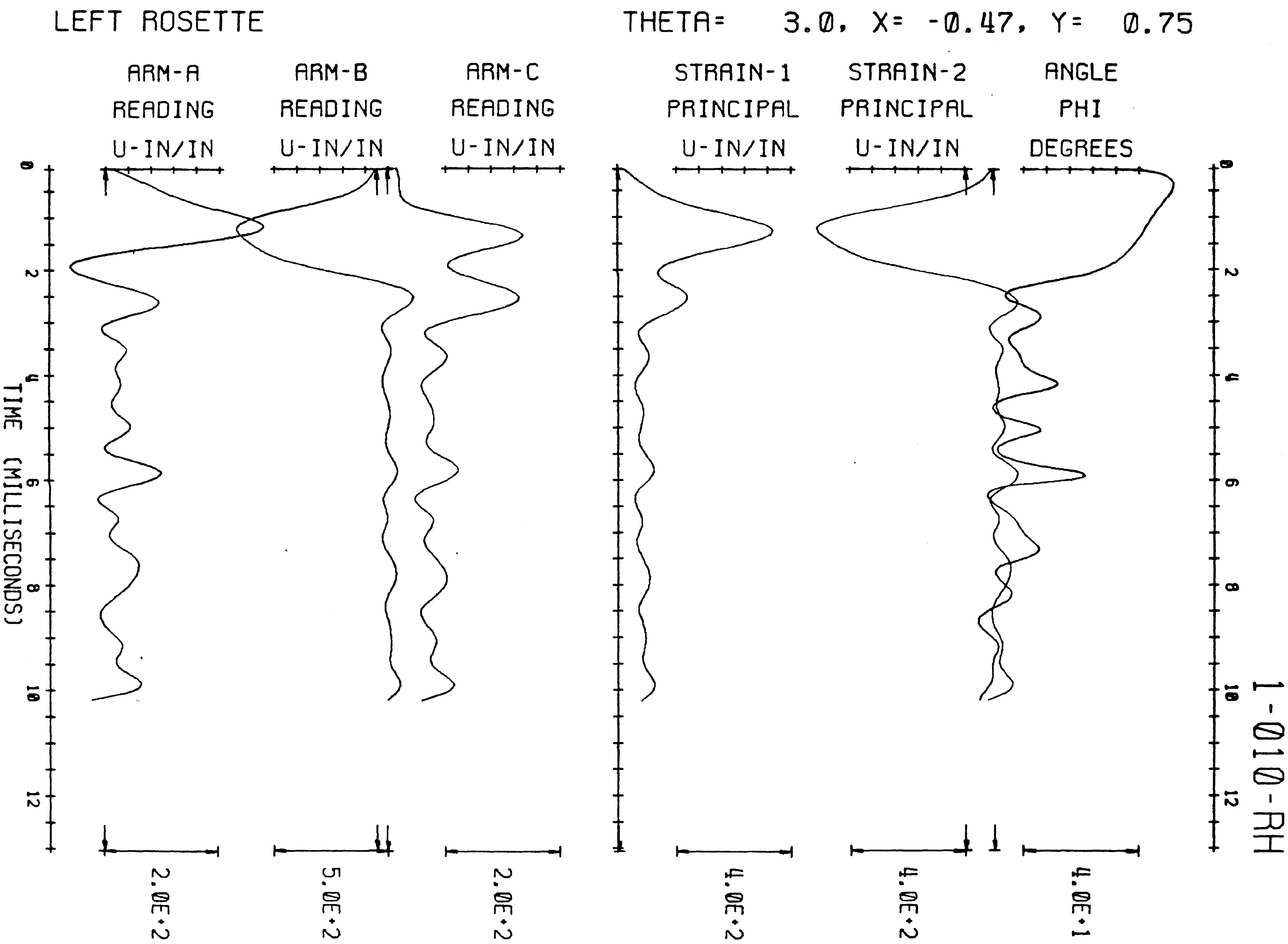


REAR PRESSURE

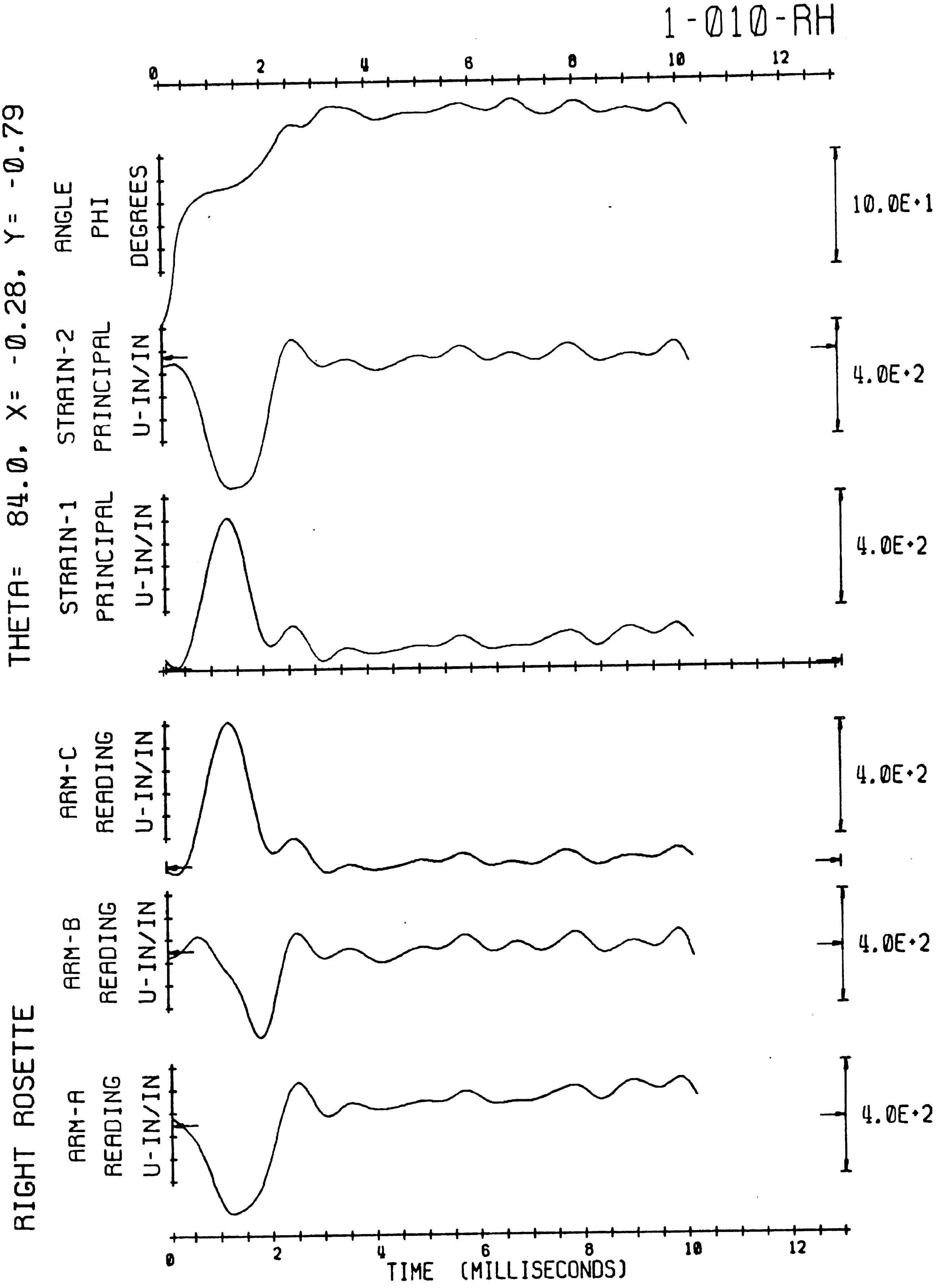
1-Ø1Ø-RH

FRONT PRESSURE





DELTA ROSETTE STRAIN GAGE



DELTA ROSETTE STRAIN GAGE

HEAD IMPACT TEST SUMMARY

TEST NO. 028 TEST DATE 2/12/75

TEST SUBJECT

SPECIES Rhesus

Body Weight 14.30 lb.

Sitting Height (Top of Head to bottom of Buttocks) 23.00 in.

Head Weight 1.33 lbs

Brain Weight 0.253 lbs

Brain Volume 7.02 in^3

Skull Inside Length A 2.800 in

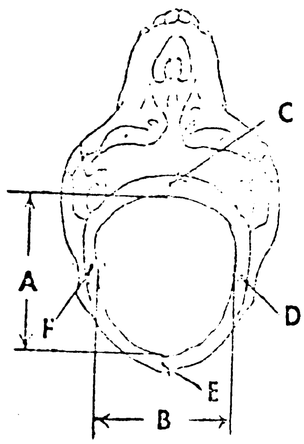
Skull Inside Width B 2.300 in

Skull Thickness at Pt. C 0.090 in

Skull Thickness at Pt. D 0.069 in

Skull Thickness at Pt. E 0.123 in

Skull Thickness at Pt. F 0.067 in



IMPACT CONDITIONS

Location of Impact Right side of head

Type of Impact One inch square, one half inch thick padding

Impact Velocity 32.15 ft/sec

TEST NO. 028

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site ----

Opposite to Impact Site ----

Epidural Pressures in Direction of Impact:

At Impact Site ----

Opposite to Impact Site Good

Strain Gage Rosettes:

Right Parietal Gage Good

Left Parietal Gage Good

Frontal Gage ______

Force: Good

High Speed Motion Pictures:

Side Camera Good

Frame Rate 3000 fps

Type II

Accelerations in Direction of Impact:

At Impact Site ______

Opposite to Impact Site ______

Rigid Body Head Motion Analysis: ______

EEG DATA: Pre-Impact ______

Post Impact ______

- NOT ANALYZED -

Force: ______

TEST NO. 028

High Speed Motion Pictures:

Side Camera ______________

Framing Rate ______________

Front Camera ______________

Framing Rate ______________

INJURY:

Condition Prior to Impact Slight muscle tone, slight eye reflex, and some shivering

		Time After Impact	Condition
Consciousness	1.	0 min	unconscious
	2.	1 min	conscious
	3.		
	4.		
	5.		
	6.		
	7.		
	8.		
	9.		
	10.		

Autopsy Summary:

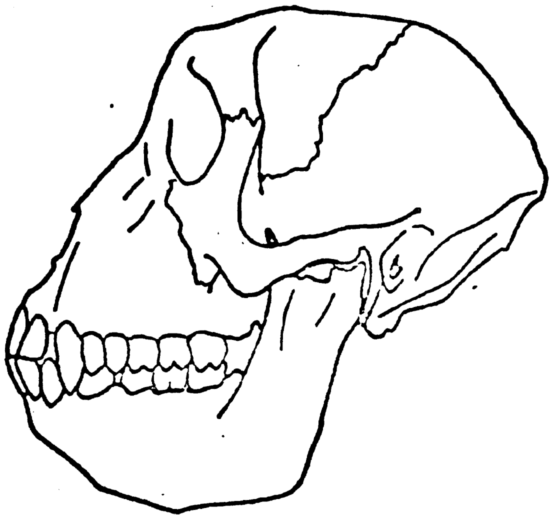
1. Subdural hemorrhage on Lt. Temporal lobe
2. Epidural hemorrhage at pressure gage
3.
4.
5.
6.
7.
8.
9.
10.
11.
12.
13.
14.
15.

Injuries Due to Impact only (not instrumentation)

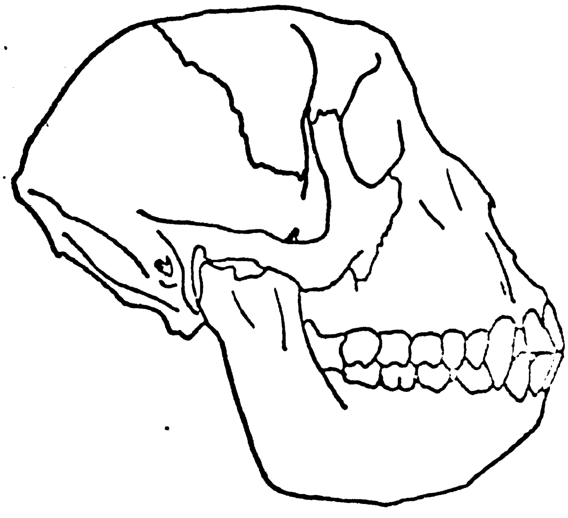
		AIS
1.	Subdural hemorrhage on Lt. Temporal Lobe	4
2.	Dazed one minute	1
3.		
4.		
5.		
6.		
7.		
8.		
9.		
10.		

AIS Overall 4

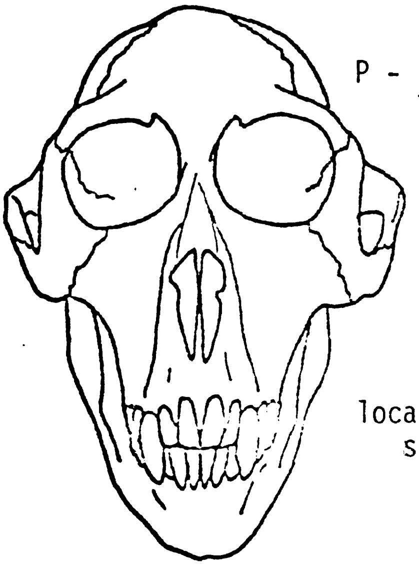
Run Number 028



Left Lateral View



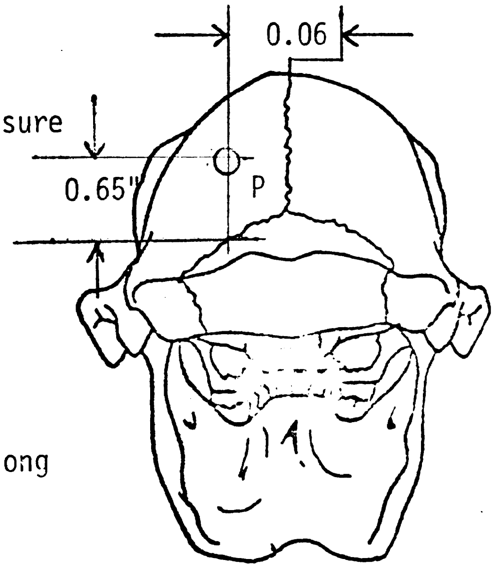
Right Lateral View



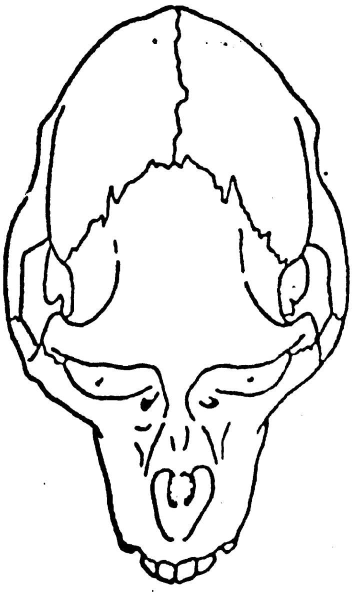
Anterior View

P - location of Pressure Transducer

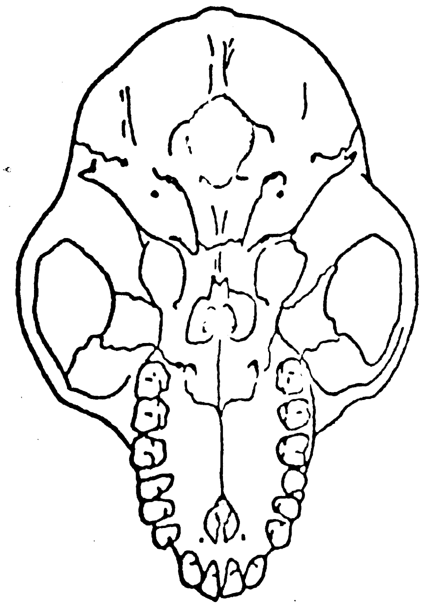
location measured along surface of skull



Posterior View

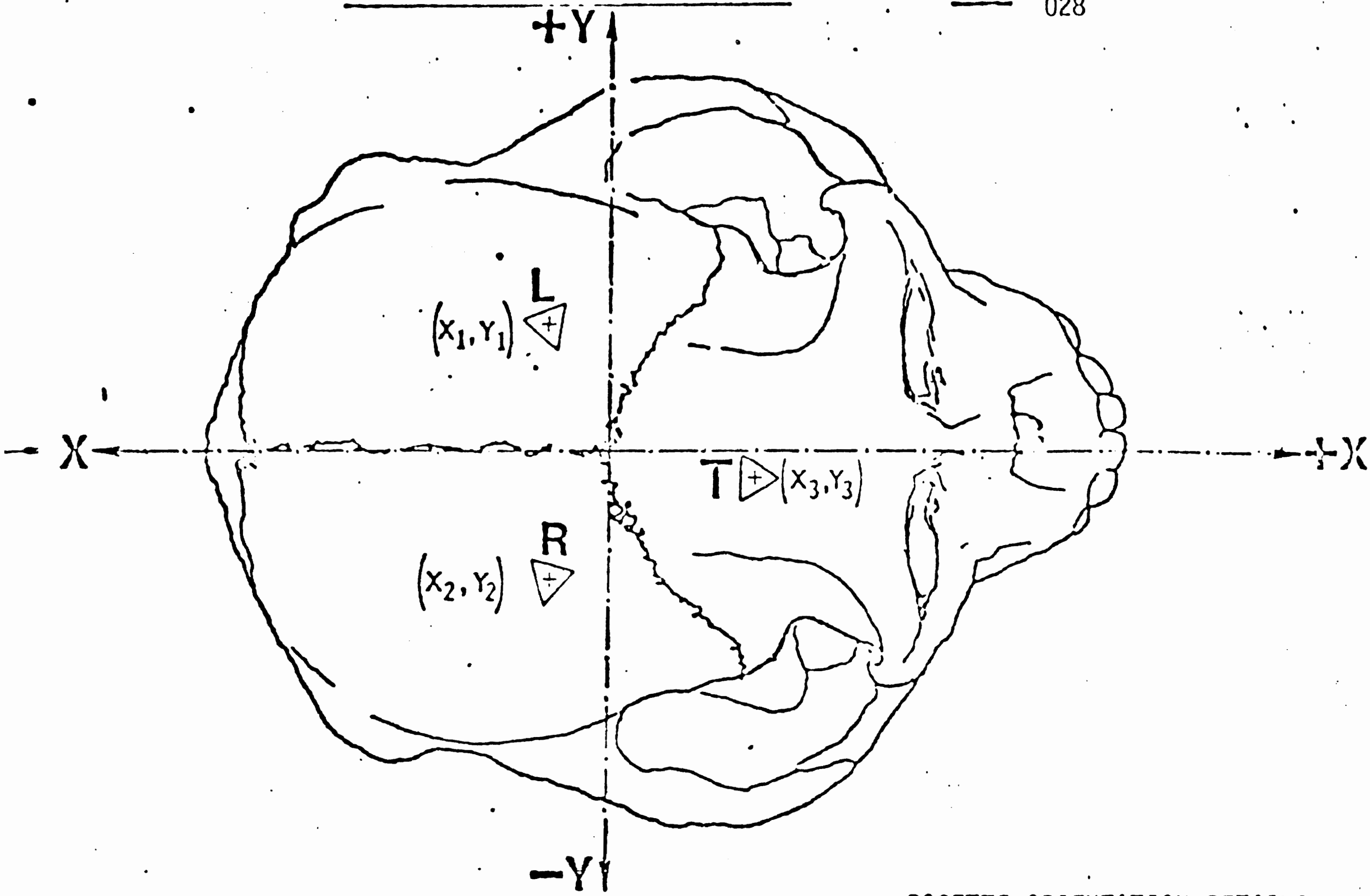


Superior View



Inferior View

HSRI STRAIN ROSETTE DATA SHEET TEST 028



a. △ -- Location of strain rosettes.

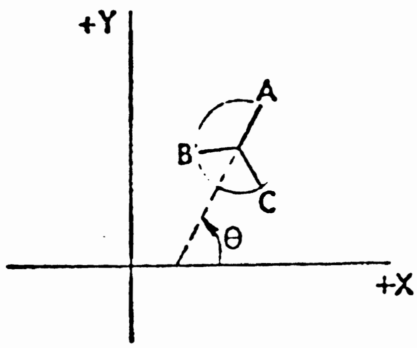
b. R -- Right L -- Left T -- Top

c. θ is the angle (measured anti-clockwise) arm 'A' of the rosette makes with the positive direction of the X-axis.

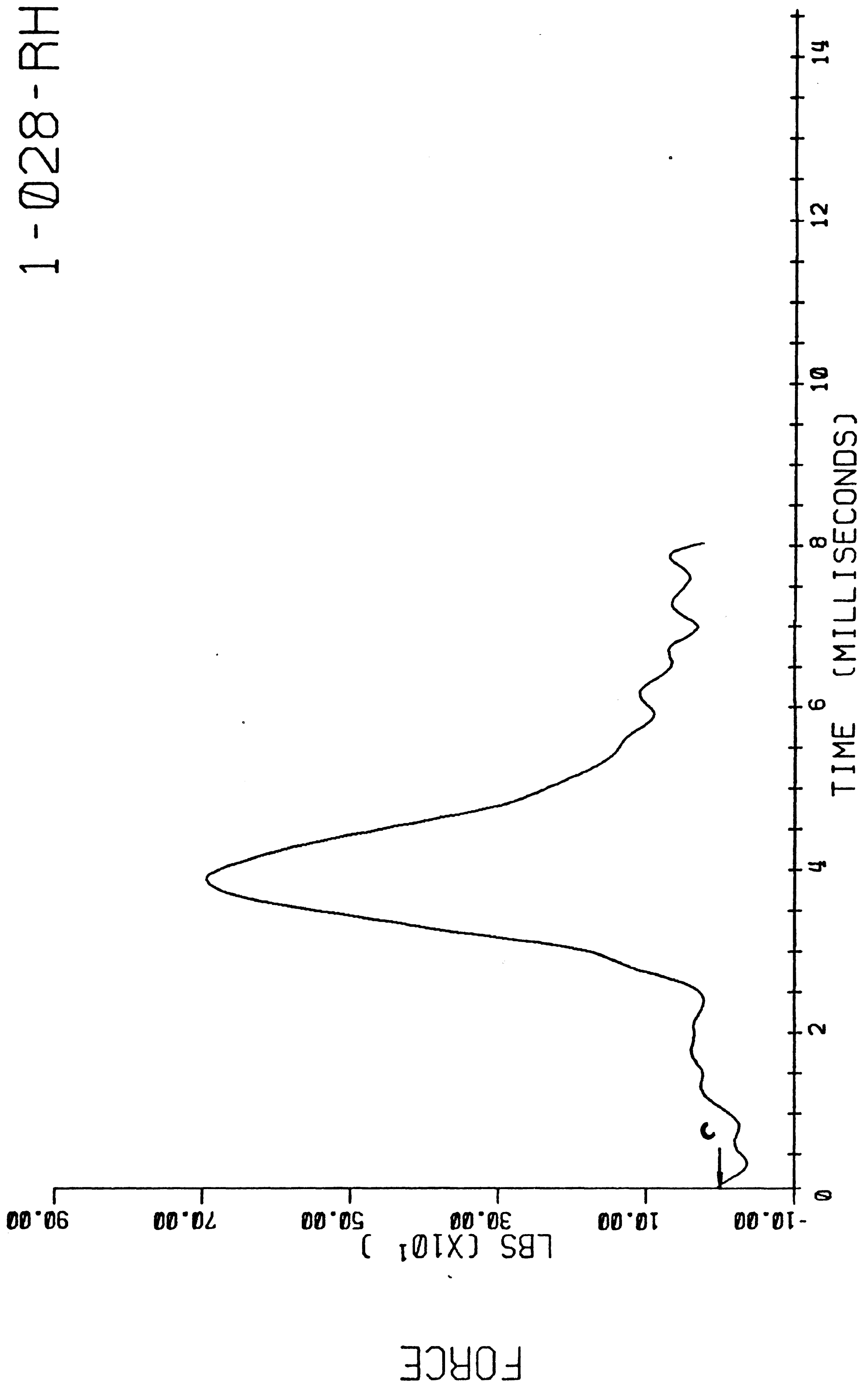
Note: Arm 'A' corresponds to arm '1' as printed on rosette.

d. All distances are measured along the surface of the skull.

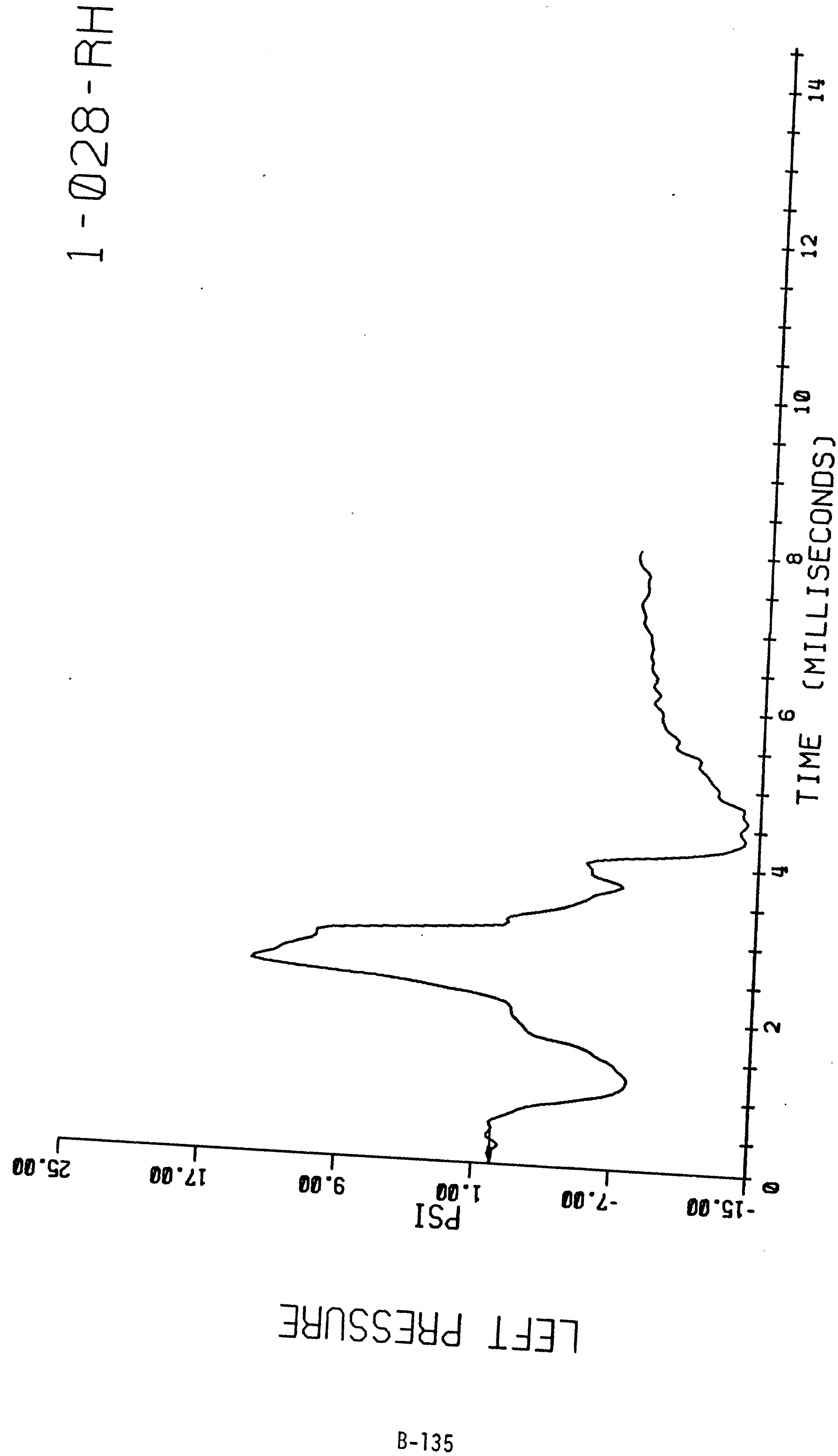
ROSETTE ORIENTATION DETAILS



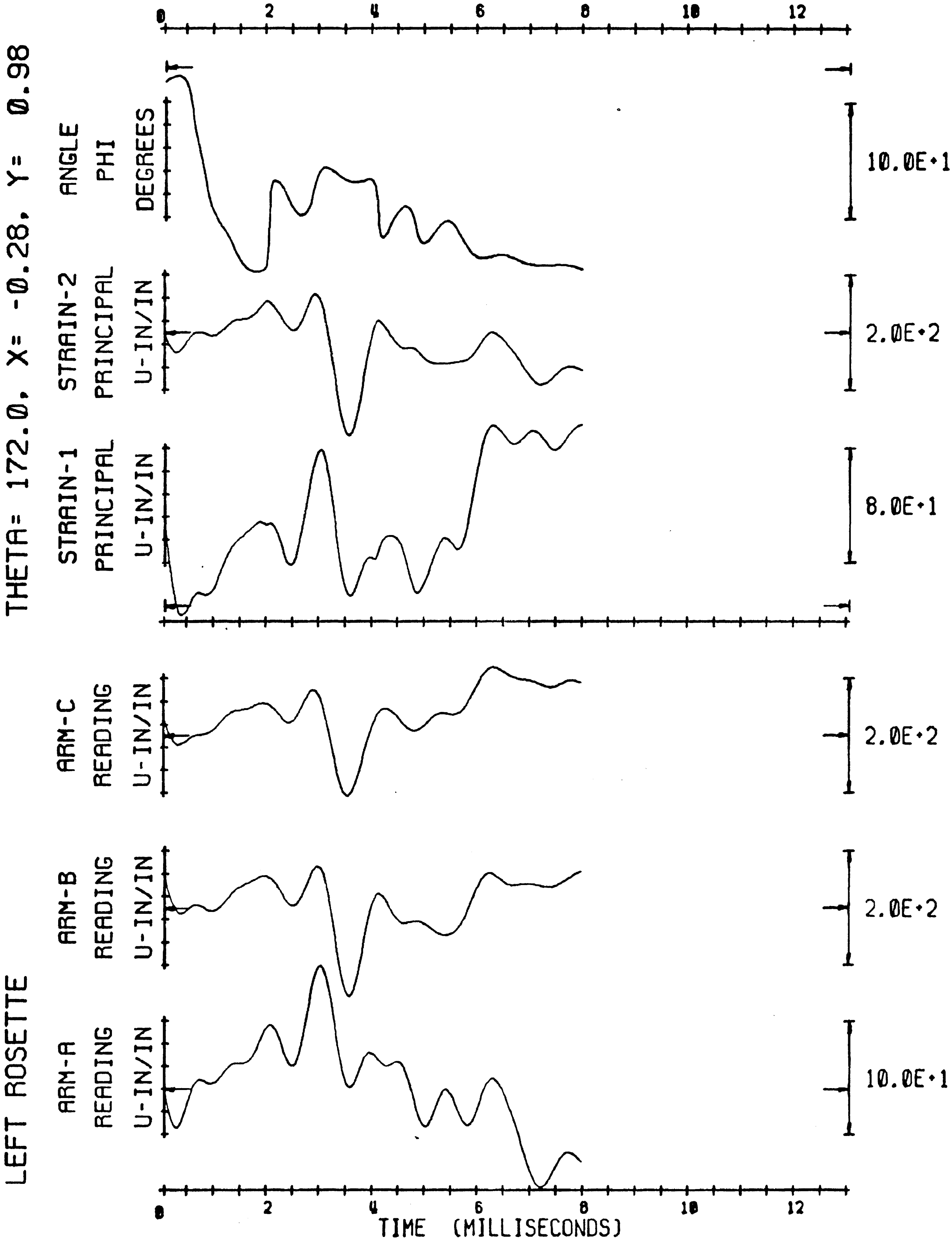
LEFT ROSETTE		RIGHT ROSETTE		TOP ROSETTE	
x_1 =	-0.28"	x_2 =	-0.38	x_3 =	
y_1 =	0.98"	y_2 =	-1.03	y_3 =	
θ_1 =	172°	θ_2 =	173.5°	θ_3 =	



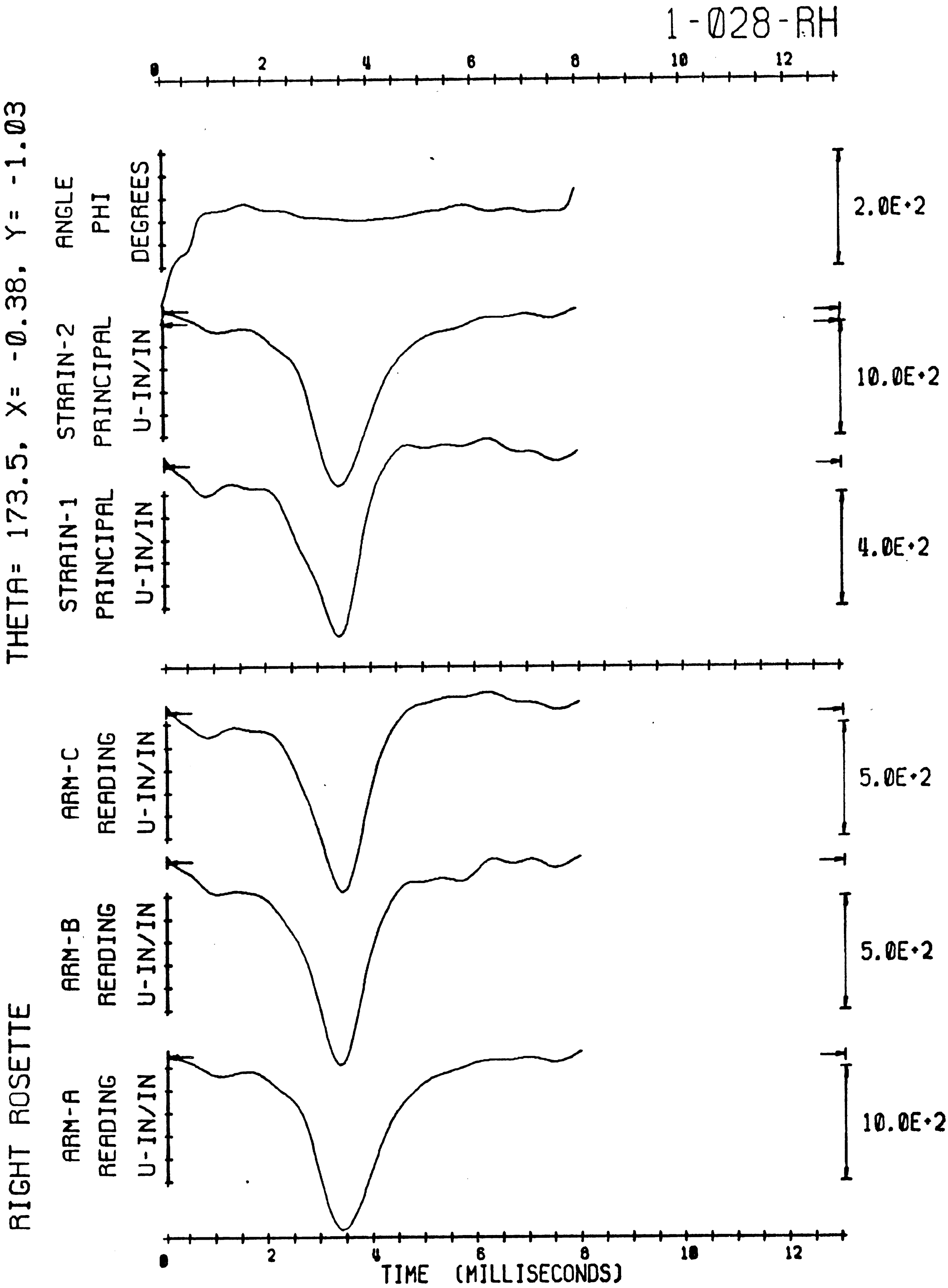
1-Ø28-RH
TIME (MILLISECONDS)
Ø
2
4
6
8
1Ø
12
14
FORCE
LBS (X1Ø¹)
-1Ø.ØØ
1Ø.ØØ
3Ø.ØØ
5Ø.ØØ
7Ø.ØØ
9Ø.ØØ


1-Ø28-RH
LEFT PRESSURE
PSI
-15.00
-7.00
1.00
9.00
17.00
25.00
TIME (MILLISECONDS)
0
2
4
6
8
10
12
14

1-028-RH



DELTA ROSETTE STRAIN GAGE



DELTA ROSETTE STRAIN GAGE

HEAD IMPACT TEST SUMMARY

TEST NO. 029 TEST DATE 2/12/75

TEST SUBJECT

SPECIES Rhesus

Body Weight 14.69 lb.

Sitting Height (Top of Head to bottom of Buttocks) 19.00 in.

Head Weight 1.47 lbs

Brain Weight 0.266 lbs

Brain Volume 7.44 in^3

Skull Inside Length A 2.900 in

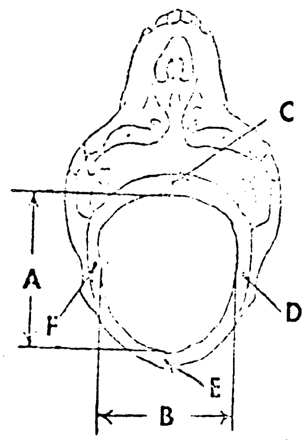
Skull Inside Width B 2.300 in

Skull Thickness at Pt. C 0.175 in

Skull Thickness at Pt. D 0.076 in

Skull Thickness at Pt. E 0.155 in

Skull Thickness at Pt. F 0.094 in



IMPACT CONDITIONS

Location of Impact Lt. Side of Head

Type of Impact One inch square, one-half inch thick padding

Impact Velocity 36.33 ft/sec

TEST NO. 029

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site ----

Opposite to Impact Site ----

Epidural Pressures in Direction of Impact:

At Impact Site ----

Opposite to Impact Site Good

Strain Gage Rosettes:

Right Parietal Gage Good

Left Parietal Gage Good

Frontal Gage ______

Force: Good

High Speed Motion Pictures:

Side Camera Good

Frame Rate 3000 fps

Type II

Accelerations in Direction of Impact:

At Impact Site ______

Opposite to Impact Site ______

Rigid Body Head Motion Analysis: ______

EEG DATA: Pre-Impact ______

Post Impact ______

- NOT ANALYZED -

Force: ______

TEST NO. 029

High Speed Motion Pictures

Side Camera ____________

Framing Rate ____________

Front Camera ____________

Framing Rate ____________

INJURY:

Condition Prior to Impact Slight muscle tone, slight eye reflex, and some shivering

		Time After Impact	Condition
Consciousness	1.	0 min.	Unconscious
	2.	2 min.	Conscious
	3.		
	4.		
	5.		
	6.		
	7.		
	8.		
	9.		
	10.		

Autopsy Summary

1. Epidural hemorrhage under pressure gage
2. Minor haematome over zygomatic arch
3.
4.
5.
6.
7.
8.
9.
10.
11.
12.
13.
14.
15.

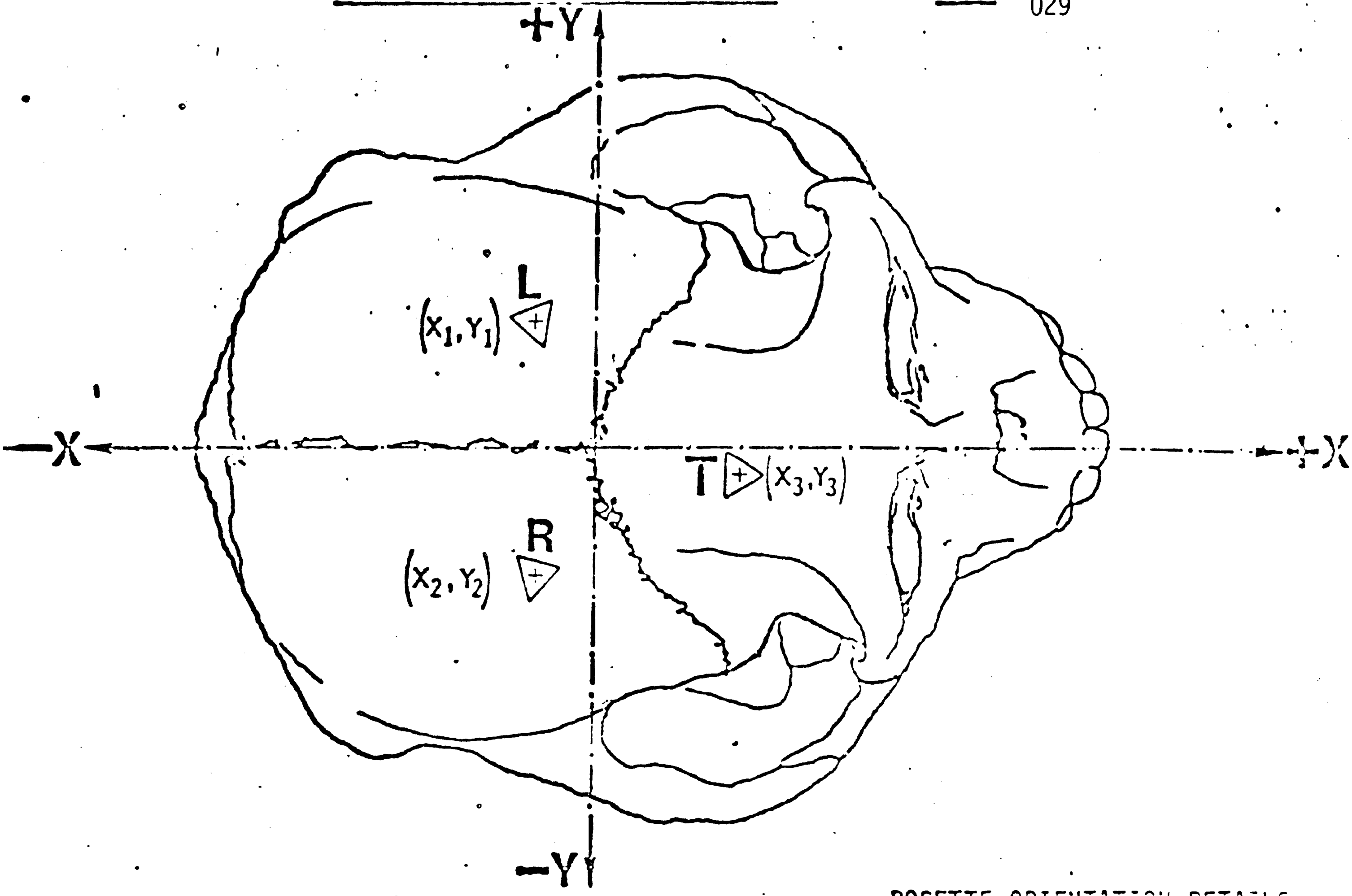
Injuries Due to Impact only (not instrumentation)

		AIS
1.	Minor haematome over zygomatic arch	1
2.	Unconscious one minute	1
3.		
4.		
5.		
6.		
7.		
8.		
9.		
10.		

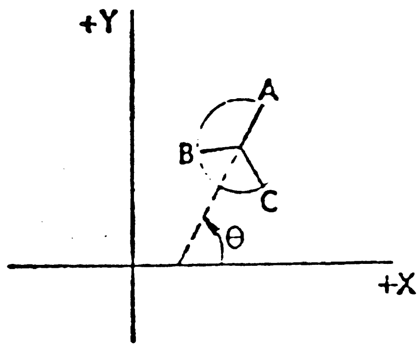
AIS Overall 1

HSRI STRAIN ROSETTE DATA SHEET

TEST 029



ROSETTE ORIENTATION DETAILS



a. △ -- Location of strain rosettes.

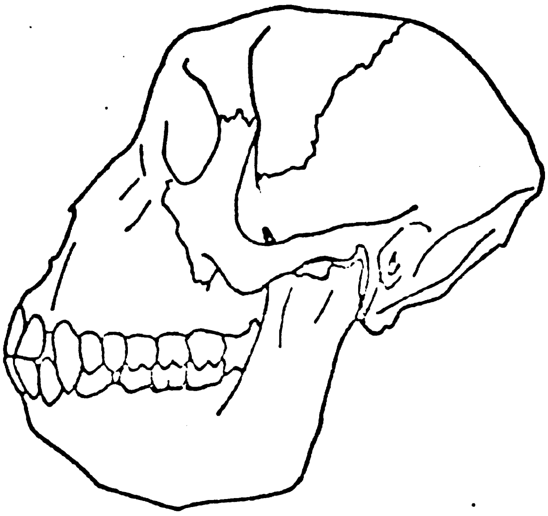
b. R -- Right L -- Left T -- Top

c. θ is the angle (measured anti-clockwise) arm 'A' of the rosette makes with the positive direction of the X-axis.
Note: Arm 'A' corresponds to arm '1' as printed on rosette.

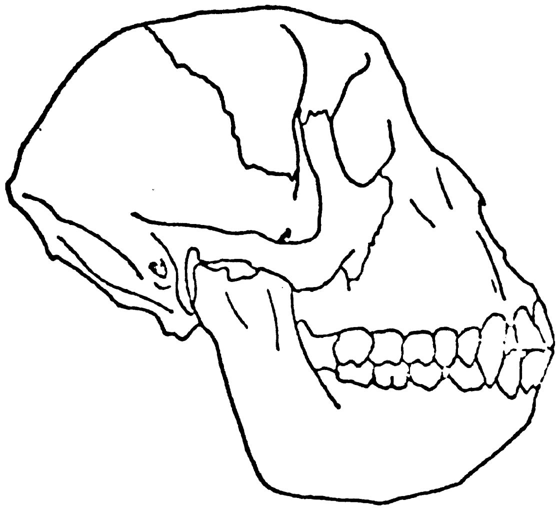
d. All distances are measured along the surface of the skull.

LEFT ROSETTE		RIGHT ROSETTE		TOP ROSETTE	
x_1 =	-0.39"	x_2 =	-0.38"	x_3 =	
y_1 =	0.79"	y_2 =	-0.76"	y_3 =	
θ_1 =	6°	θ_2 =	176.5°	θ_3 =	

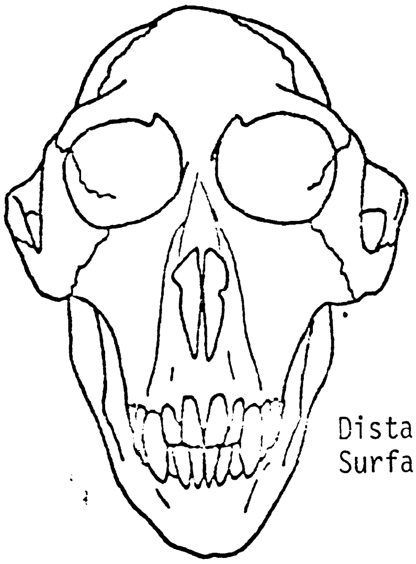
Run Number 029



Left Lateral View

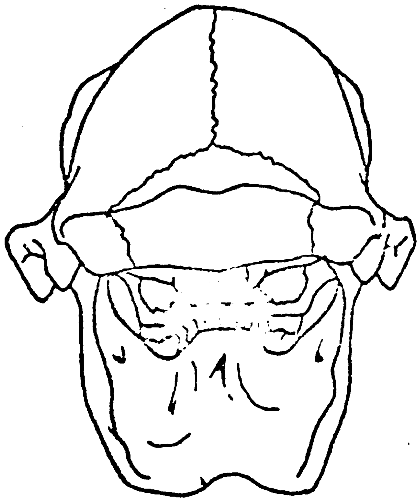


Right Lateral View

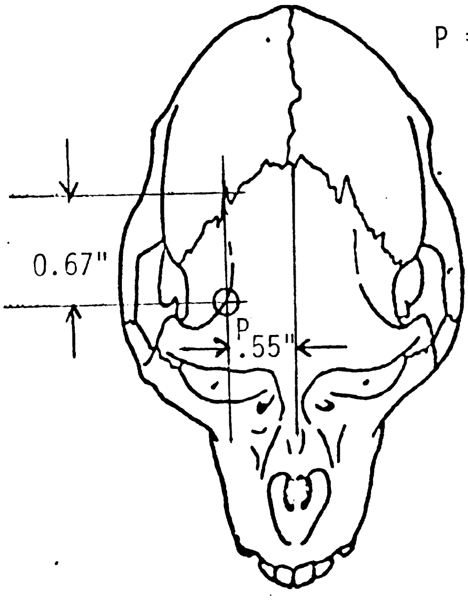


Distances measured along
Surface of skull

Anterior View

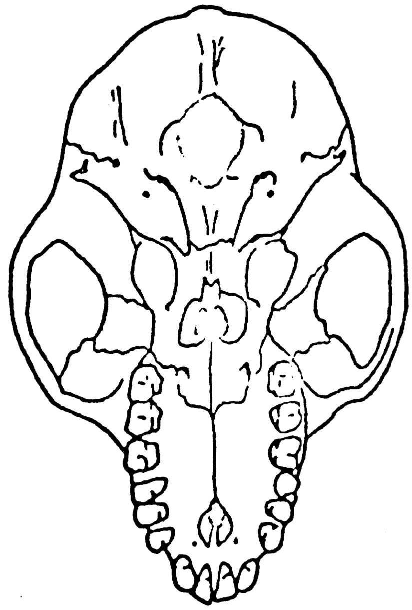


Posterior View

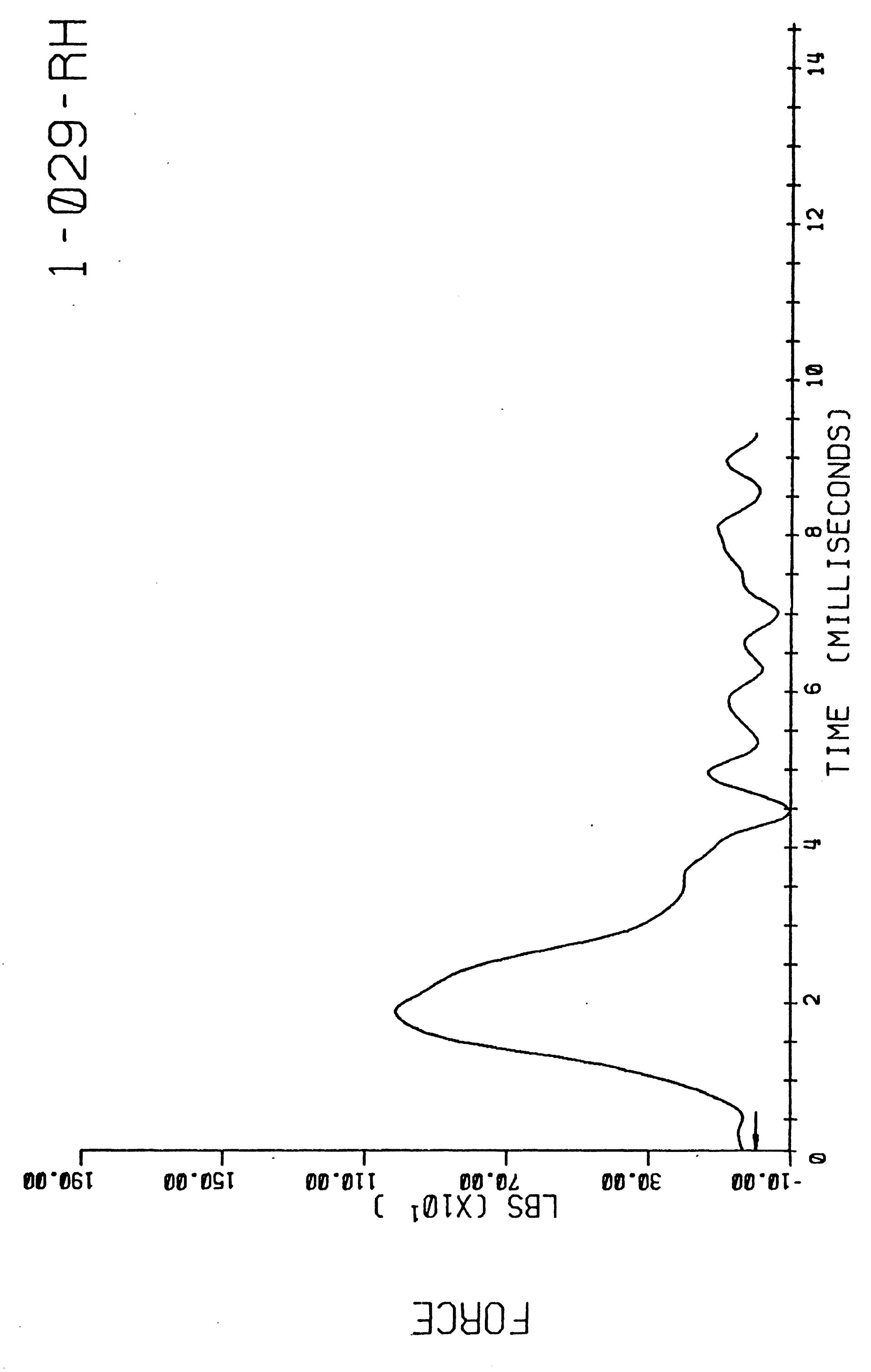


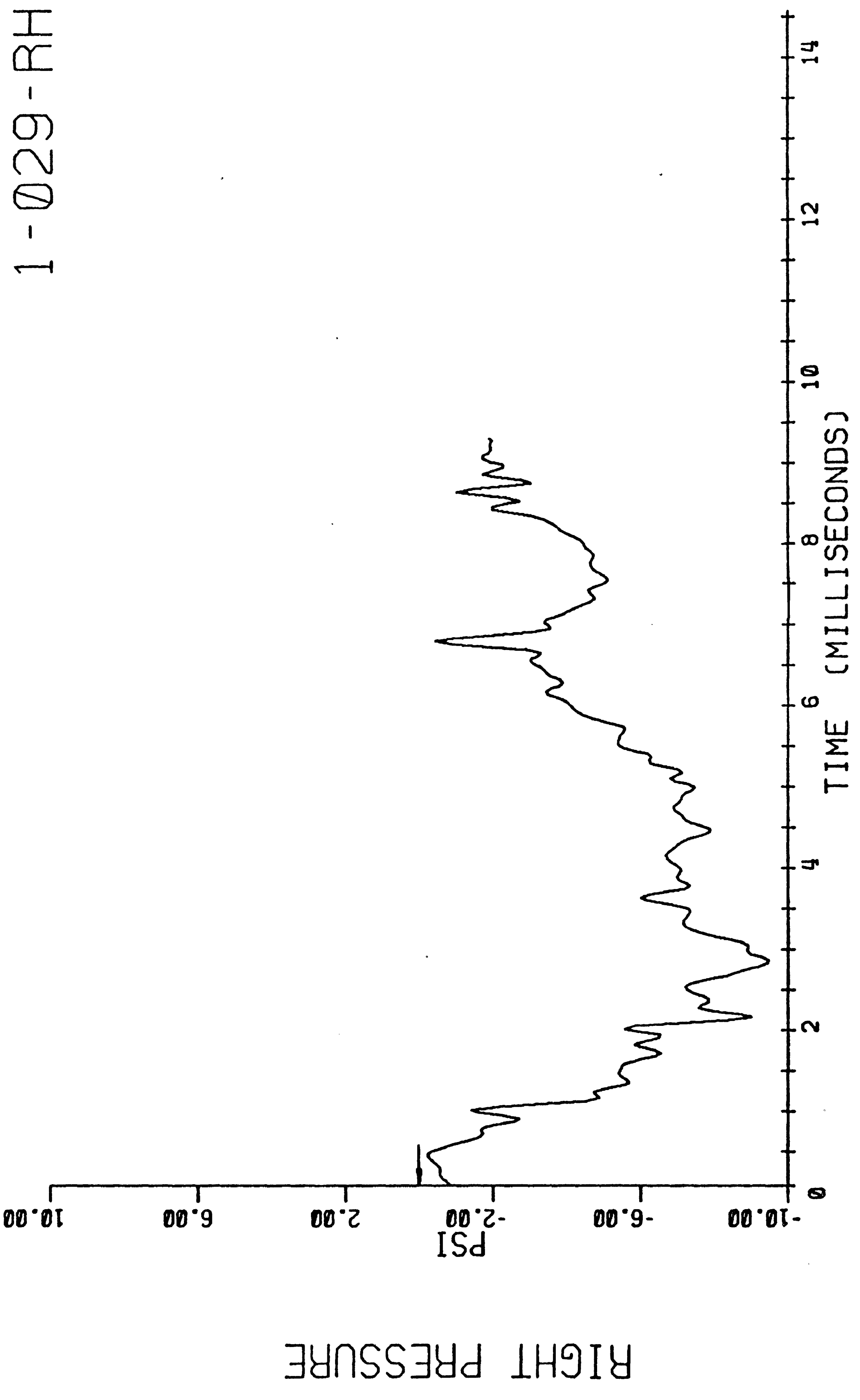
P = location of
Pressure transducer

Superior View

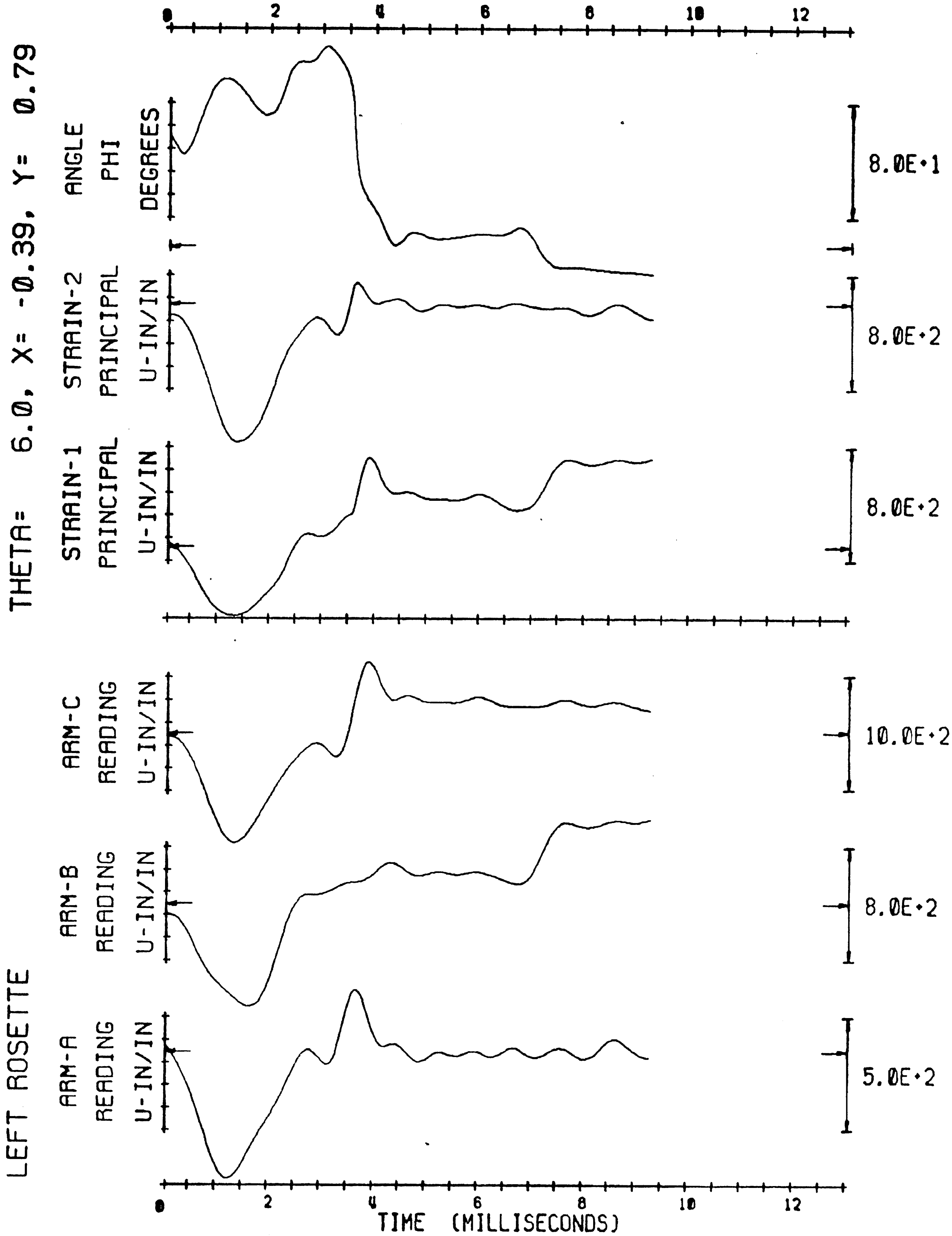


Inferior View

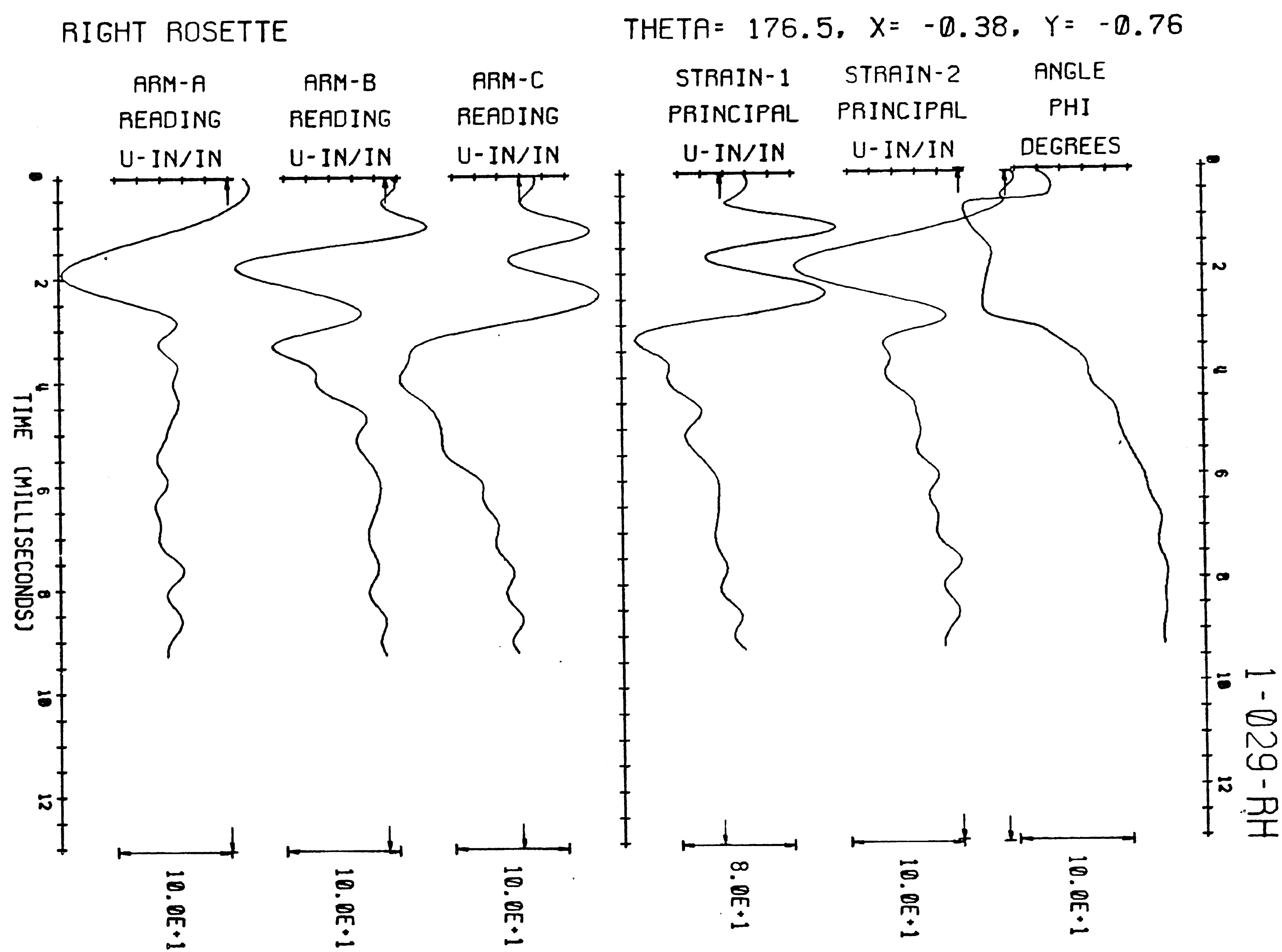

1-Ø29-RH
TIME (MILLISECONDS)
0
2
4
6
8
10
12
14
LBS (X10^1)
-10.00
30.00
70.00
110.00
150.00
190.00
FORCE


1-Ø29-RH
RIGHT PRESSURE
PSI
10.00
6.00
2.00
-2.00
-6.00
-10.00
TIME (MILLISECONDS)
0
2
4
6
8
10
12
14

1-029-RH



DELTA ROSETTE STRAIN GAGE



DELTA ROSETTE STRAIN GAGE

HEAD IMPACT TEST SUMMARY

TEST NO. 082

TEST DATE 8/4/75

TEST SUBJECT

SPECIES Cynomolgus

Body Weight 8.8 lb.

Sitting Height (Top of Head to bottom of Buttocks) 16.75 in.

Head Weight 0.89 lbs

Brain Weight 0.15 lbs

Brain Volume 4.27 in^3

Skull Inside Length A 2.43 in

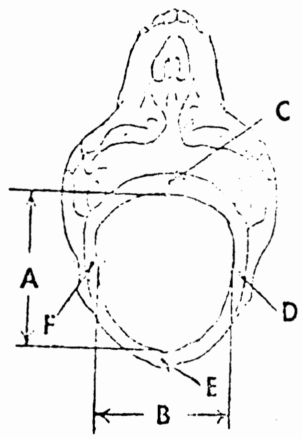
Skull Inside Width B 1.97 in

Skull Thickness at Pt. C 0.112 in

Skull Thickness at Pt. D 0.065 in

Skull Thickness at Pt. E 1.60 in

Skull Thickness at Pt. F 0.70 in



IMPACT CONDITIONS

Location of Impact Lt. side of head

Type of Impact One and one quarter inches diameter, 0.25 inch wall thickness, round cap

Impact Velocity 38.1 ft/sec

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site Good

Opposite to Impact Site ----

Epidural Pressures in Direction of Impact:

At Impact Site ----

Opposite to Impact Site Good

Strain Gage Rosettes:

Right Parietal Gage Good (Large Spike not data)

Left Parietal Gage Good

Frontal Gage ______

Force: Good

High Speed Motion Pictures:

Side Camera Good

Frame Rate 3000 fps

Type II

Accelerations in Direction of Impact:

At Impact Site ______

Opposite to Impact Site ______

Rigid Body Head Motion Analysis: ______

EEG DATA: Pre-Impact ______

Post Impact ______

- NOT ANALYZED -

Force: ______

High Speed Motion Pictures

Side Camera ______

Framing Rate ______

Front Camera ______

Framing Rate ______

INJURY:

Condition Prior to Impact Deep breathing, no muscle tone, little eye reflex

		Time After Impact	Condition
Consciousness	1.	0 min.	Unconscious
	2.	8 min.	Unconscious
	3.	9 min.	Regaining consciousness
	4.	15 min.	Conscious (full)
	5.		
	6.		
	7.		
	8.		
	9.		
	10.		

Autopsy Summary:

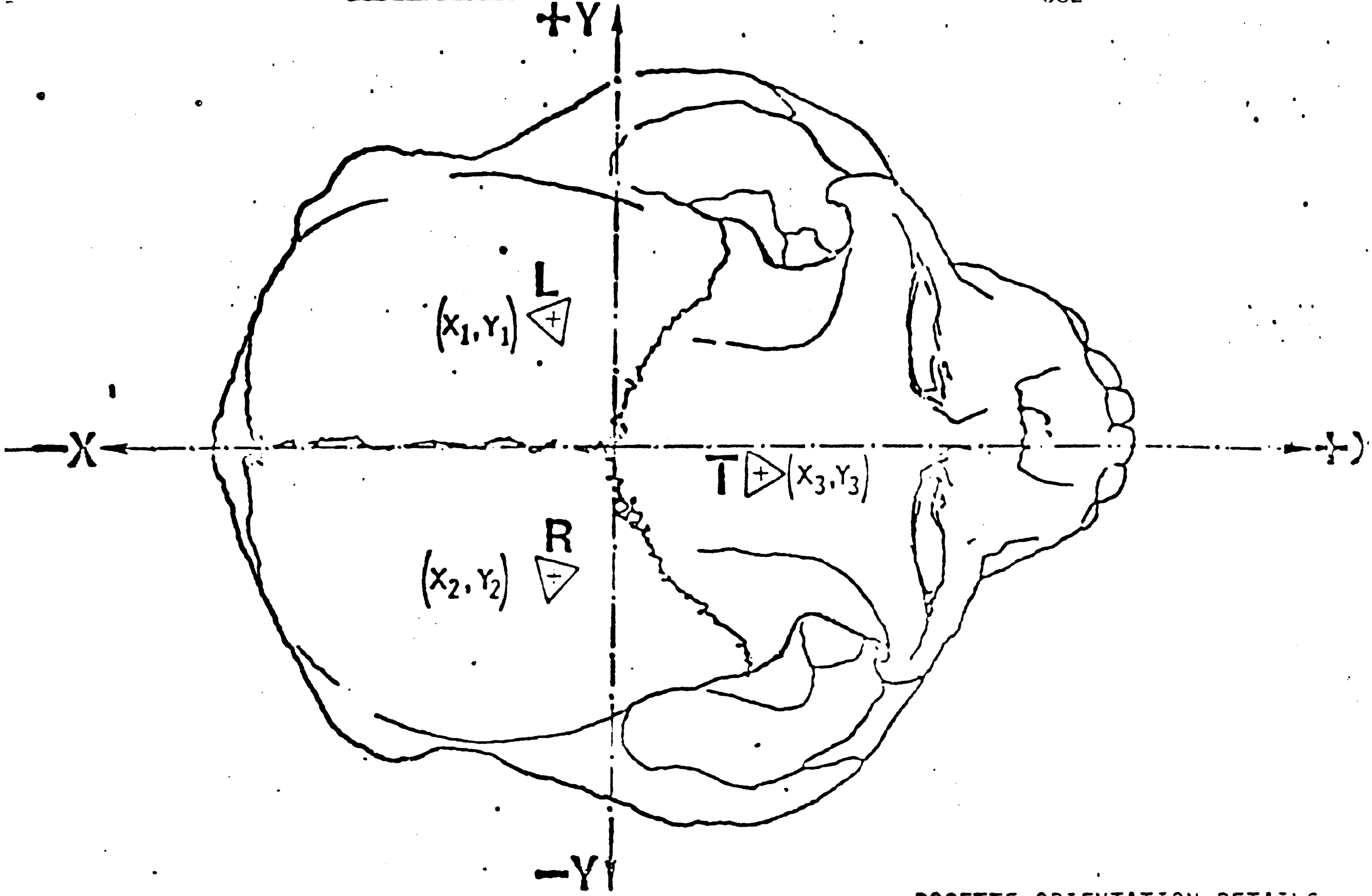
1. Hemorrhage in muscle over the Lt. zygomatic arch
2. Comminuted fracture of Lt. zygomatic arch
3. Depressed fracture of Lt. Temporal bone
4. Small laceration on Lt. Temboral lobe
5. Small bruise on Temporal lobe under accelerometer
6. Circular bruise under pressure transducer location
7.
8.
9.
10.
11.
12.
13.
14.
15.

Injuries Due to Impact only (not instrumentation)

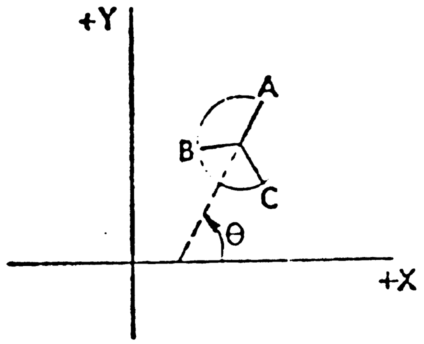
	Injury	AIS
1.	Muscle hemorrhage	1
2.	Fracture comminuted	3
3.	Unconscious less than 15 minutes	2
4.		
5.		
6.		
7.		
8.		
9.		
10.		

AIS OVERALL 3

HSRI STRAIN ROSETTE DATA SHEET   TEST 082



ROSETTE ORIENTATION DETAILS



a. △ -- Location of strain rosettes.

b. R -- Right   L -- Left   T -- Top

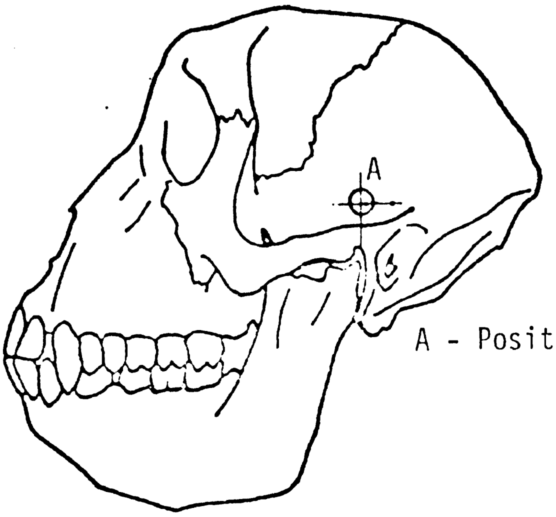
c. θ is the angle (measured anti-clockwise) arm 'A' of the rosette makes with the positive direction of the X-axis.

Note: Arm 'A' corresponds to arm '1' as printed on rosette.

d. All distances are measured along the surface of the skull.

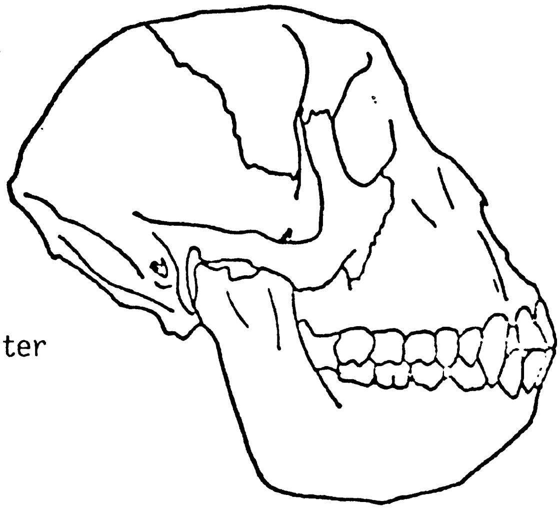
LEFT ROSETTE		RIGHT ROSETTE		TOP ROSETTE	
x_1 =	-0.131	x_2 =	-0.361	x_3 =	
y_1 =	0.454	y_2 =	-0.248	y_3 =	
θ_1 =	44°	θ_2 =	270°	θ_3 =	

Run Number 082

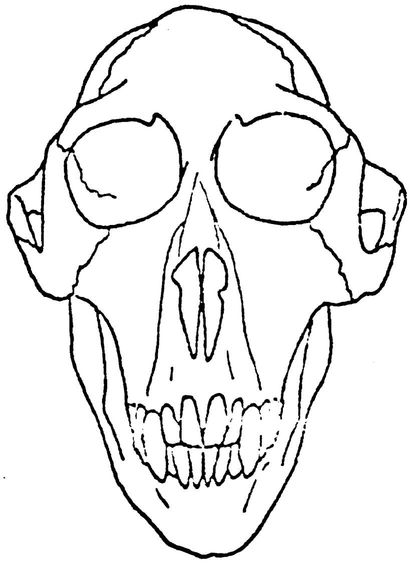


A - Position of accelerometer

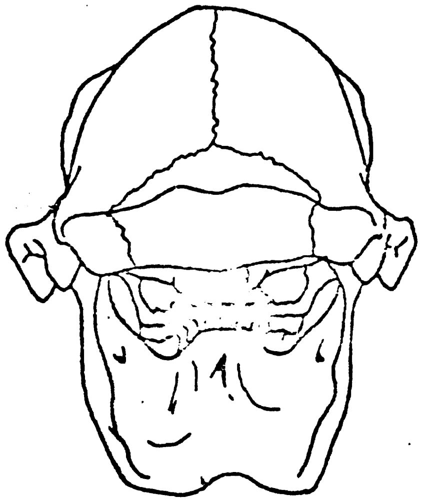
Left Lateral View



Right Lateral View

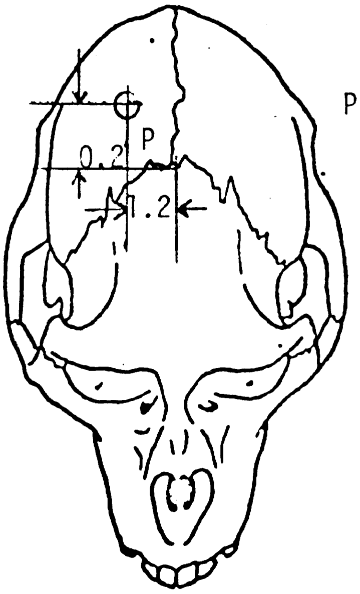


Anterior View



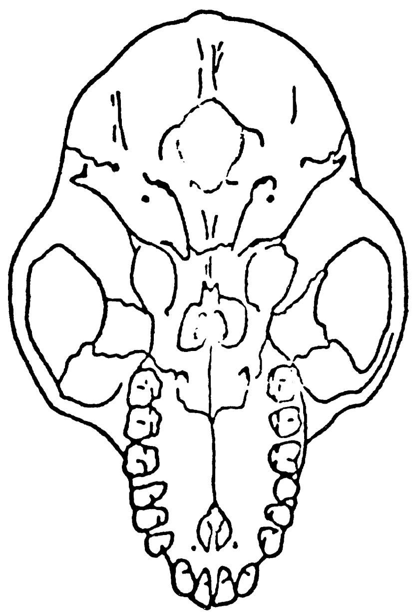
Posterior View

Distances measured along surface of skull



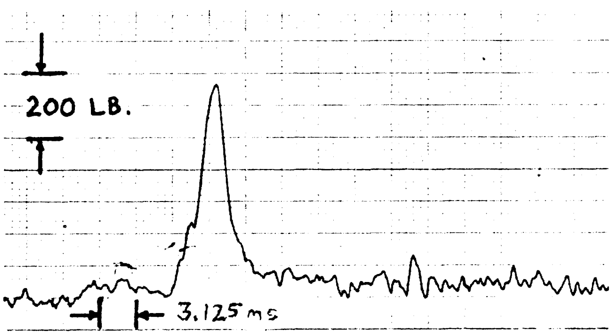
P - position of pressure transducer

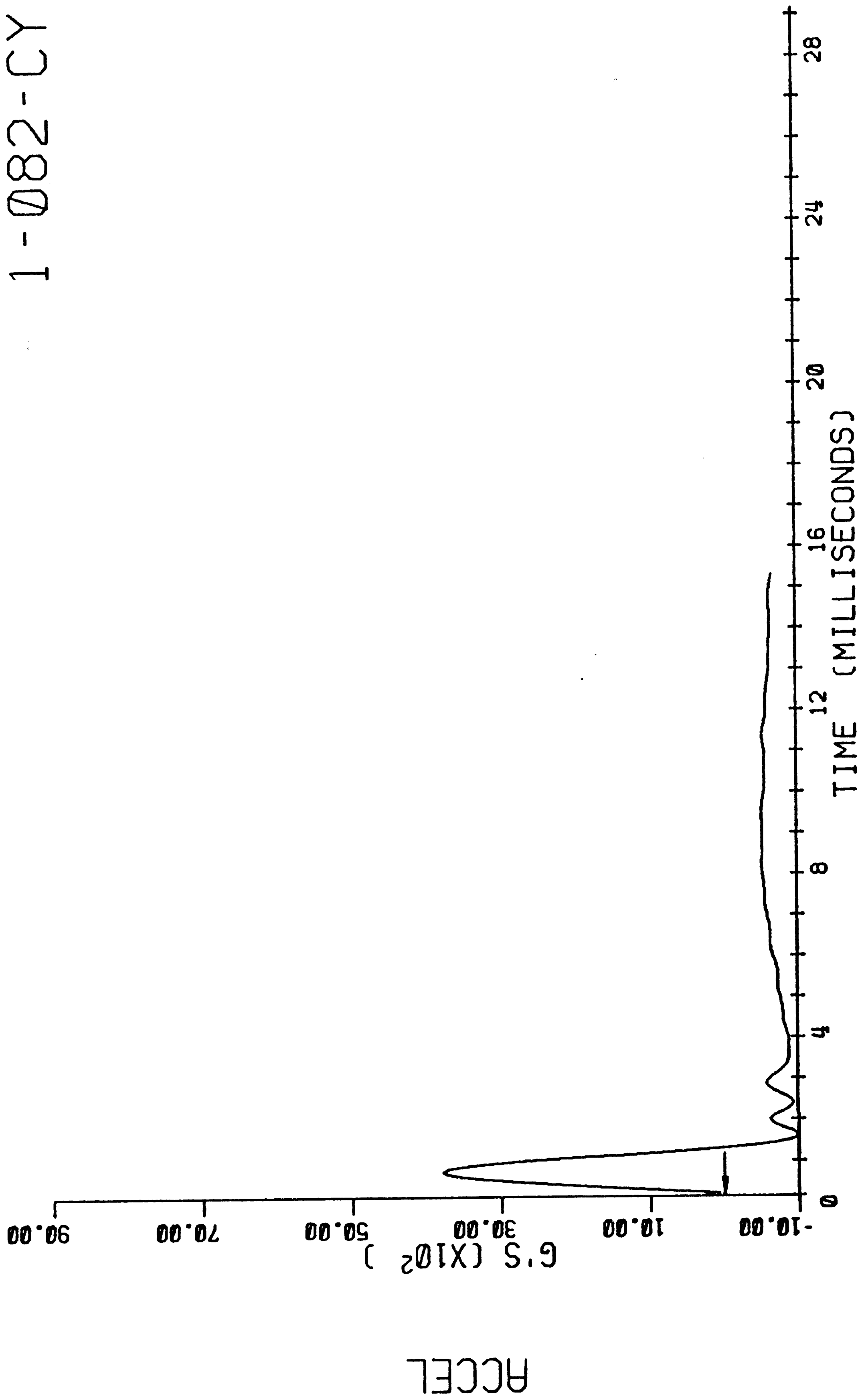
Superior View

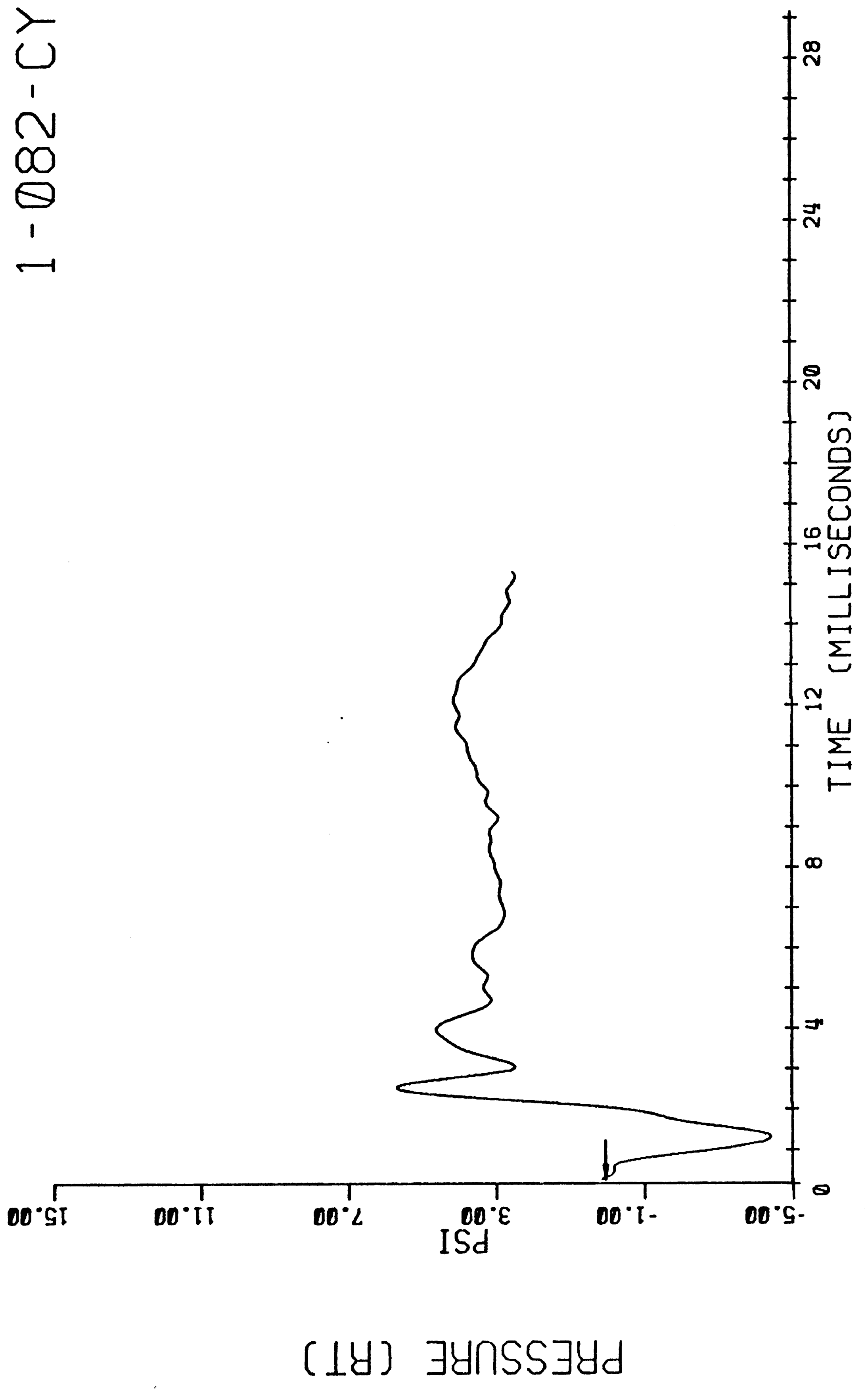


Inferior View

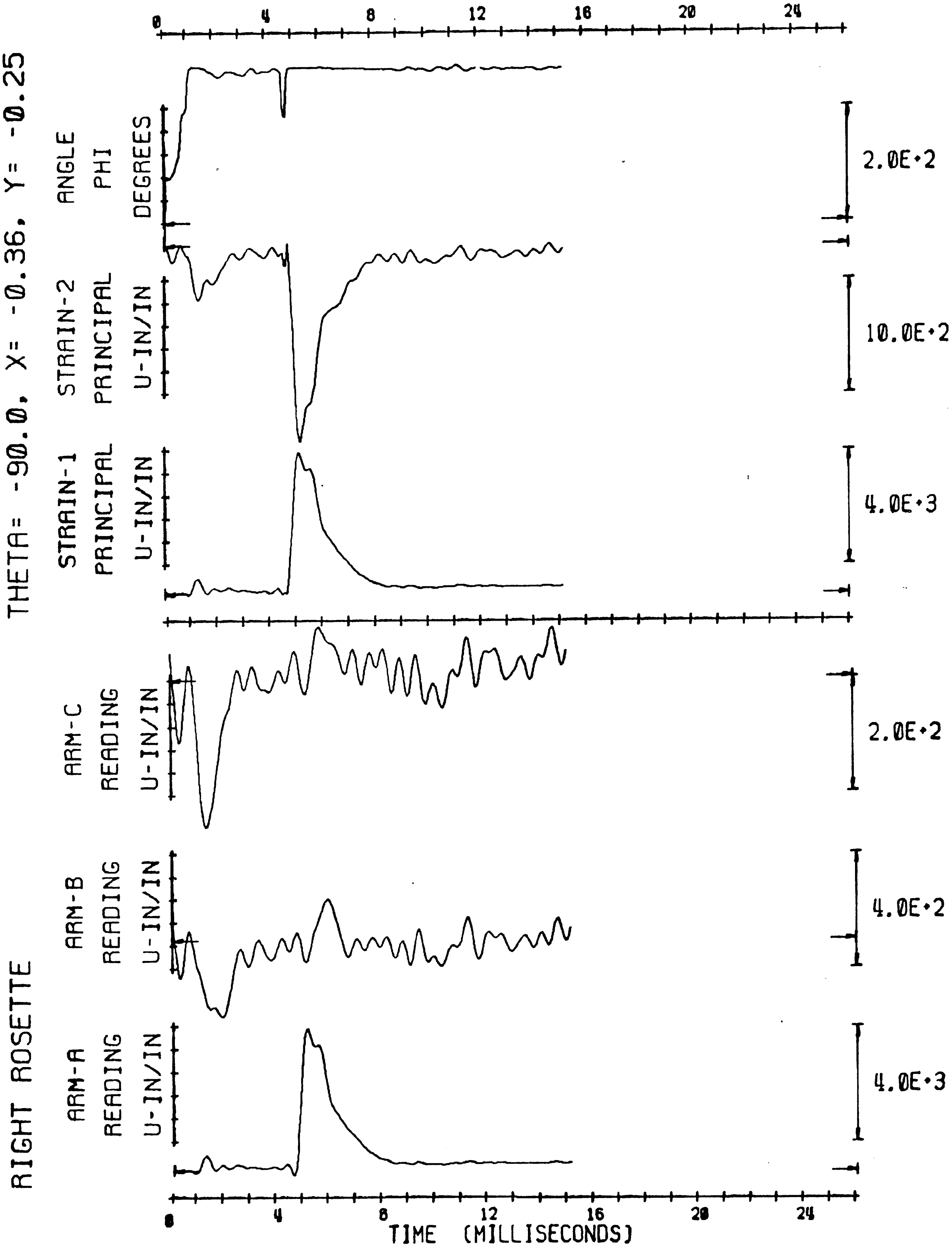
FORCE



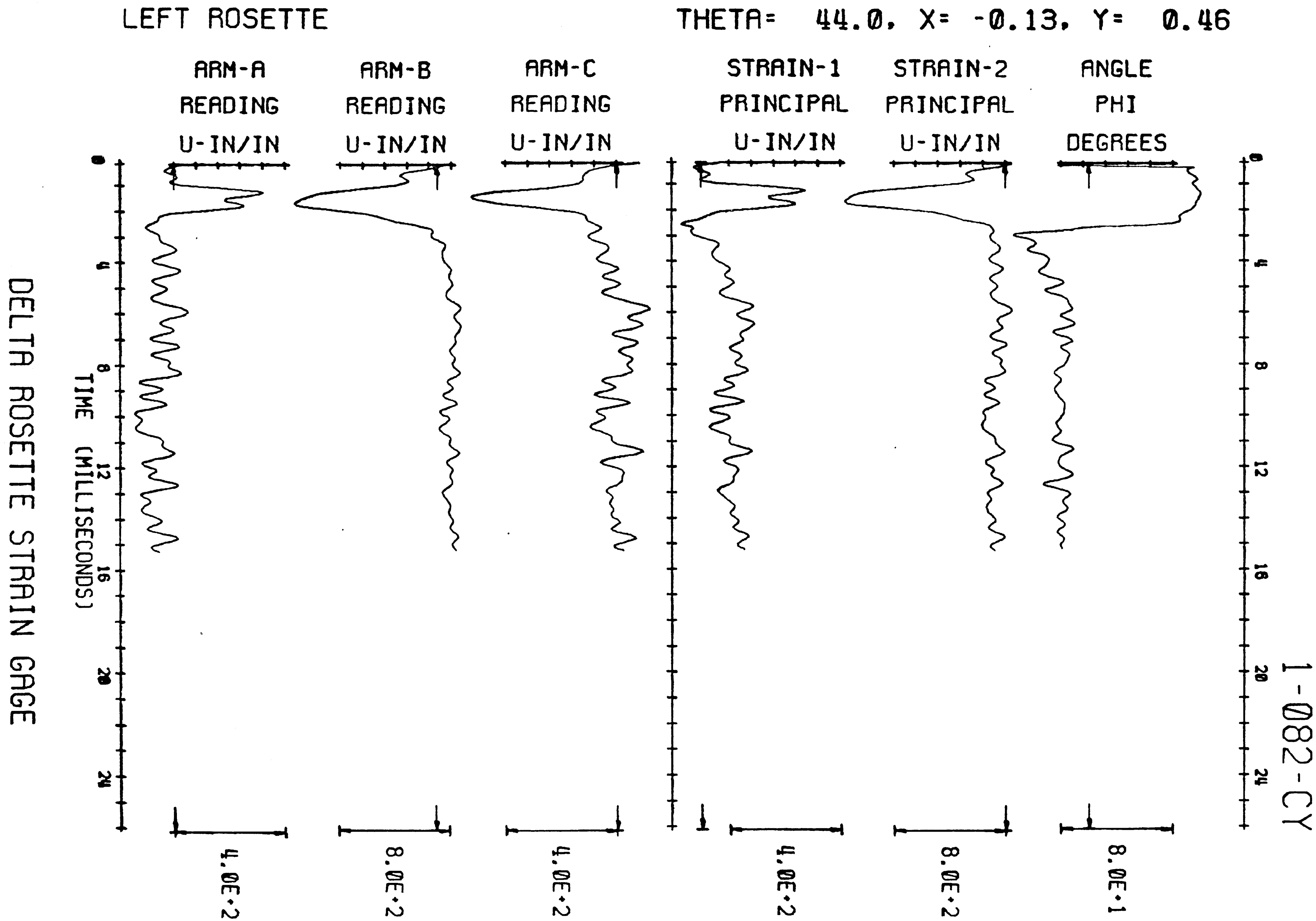

1-Ø82-CY
TIME (MILLISECONDS)
0
4
8
12
16
20
24
28
G'S (X1Ø2)
-10.00
10.00
30.00
50.00
70.00
90.00
ACCEL


1-Ø82-CY
PRESSURE (RT)
PSI
-5.00
-1.00
3.00
7.00
11.00
15.00
TIME (MILLISECONDS)
0
4
8
12
16
20
24
28

1-082-CY



DELTA ROSETTE STRAIN GAGE


LEFT ROSETTE
THETA= 44.0, X= -0.13, Y= 0.46
ARM-A READING U-IN/IN
ARM-B READING U-IN/IN
ARM-C READING U-IN/IN
STRAIN-1 PRINCIPAL U-IN/IN
STRAIN-2 PRINCIPAL U-IN/IN
ANGLE PHI DEGREES
TIME (MILLISECONDS)
0
4
8
12
16
20
24
4.0E+2
8.0E+2
4.0E+2
4.0E+2
8.0E+2
8.0E+1
DELTA ROSETTE STRAIN GAGE
1-082-CY

HEAD IMPACT TEST SUMMARY

TEST NO. 083 TEST DATE 8/5/75

TEST SUBJECT

SPECIES Cynomolgus

Body Weight 10.34 lb.

Sitting Height (Top of Head to bottom of Buttocks) 16.5 in.

Head Weight 1.18 lbs

Brain Weight 0.14 lbs

Brain Volume 3.05 in^3

Skull Inside Length A 2.49 in

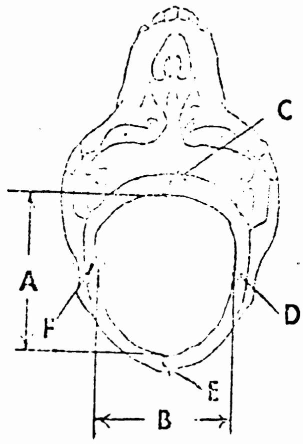
Skull Inside Width B 2.06 in

Skull Thickness at Pt. C 0.09 in

Skull Thickness at Pt. D 0.49 in

Skull Thickness at Pt. E .076 in

Skull Thickness at Pt. F .053 in



IMPACT CONDITIONS

Location of Impact Left side of head

Type of Impact Four inch diameter round impactor padded with .2 inches of Ensolite

Impact Velocity 40.53 ft/sec

TEST NO. 083

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site ---

Opposite to Impact Site Good

Epidural Pressures in Direction of Impact:

At Impact Site ---

Opposite to Impact Site Good

Strain Gage Rosettes:

Right Parietal Gage Lost

Left Parietal Gage Lost

Frontal Gage ---

Force: Good

High Speed Motion Pictures:

Side Camera Lost

Frame Rate 3000 fps

Type II

Accelerations in Direction of Impact:

At Impact Site ______

Opposite to Impact Site ______

Rigid Body Head Motion Analysis: ______

EEG DATA: Pre-Impact ______

Post Impact ______

- NOT ANALYZED -

TEST NO. 083

Hign Speed Motion Pictures:

Side Camera __________

Framing Rate __________

Front Camera __________

Framing Rate __________

INJURY:

Condition Prior to Impact Good arm muscle tone, good eye reflex

		Time After Impact	Condition
Consciousness	1.	0 min.	Conscious
	2.		
	3.		
	4.		
	5.		
	6.		
	7.		
	8.		
	9.		
	10.		

Autopsy Summary:

1. Bruise 1 cm under accelerometer mount
2. No unconscious
3. Focussed injury under pressure
4.
5.
6.
7.
8.
9.
10.
11.
12.
13.
14.
15.

Injuries Due to Impact only (not instrumentation)

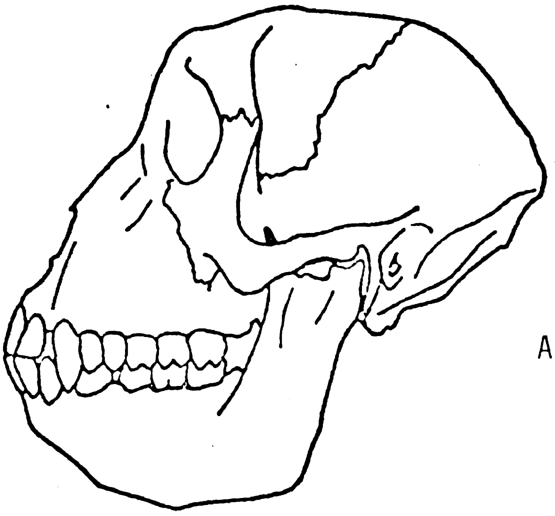
AIS

1.
2.
3.
4.
5.
6.
7.
8.
9.
10.

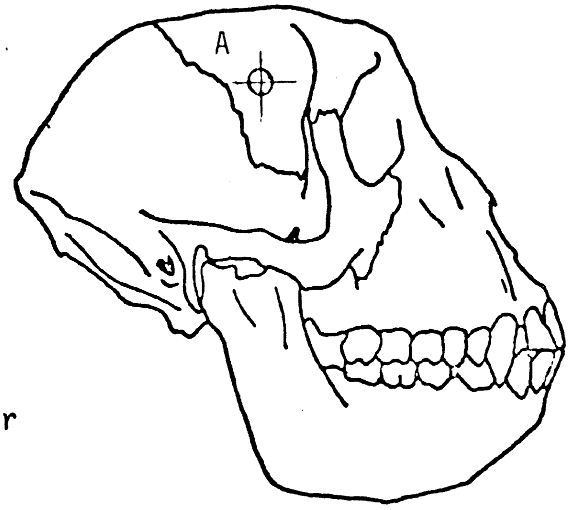
AIS Overall 0

Run Number 083

All distances along surface of skull

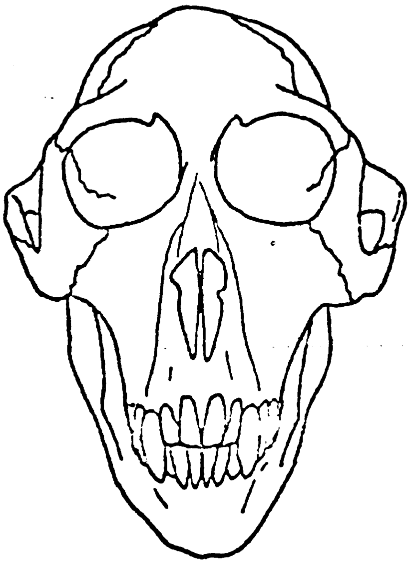


Left Lateral View

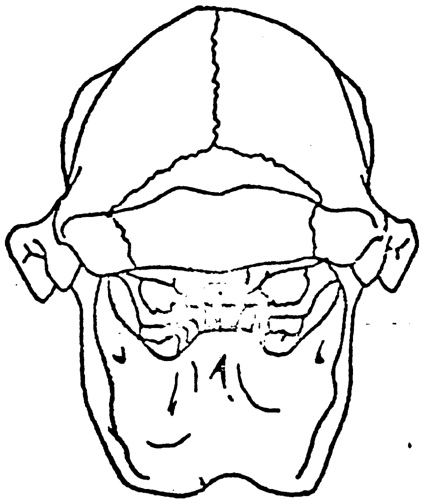


Right Lateral View

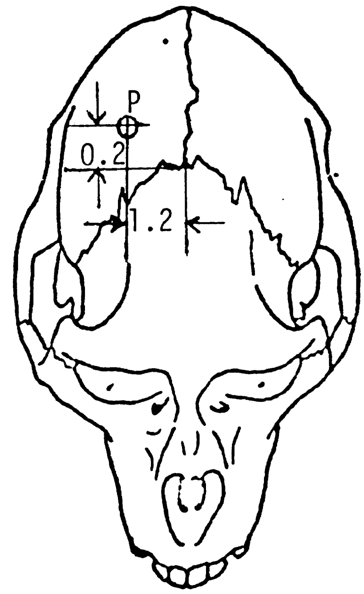
A - Position of Accelerometer



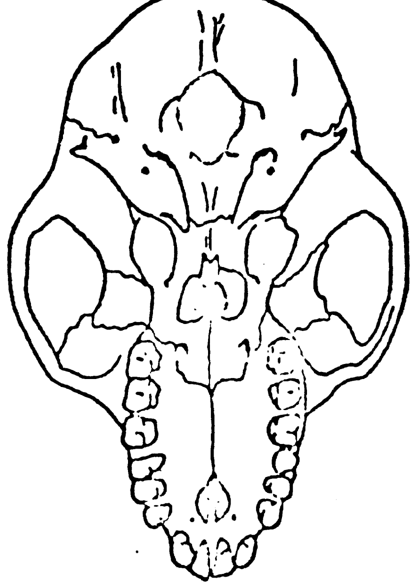
Anterior View



Posterior View

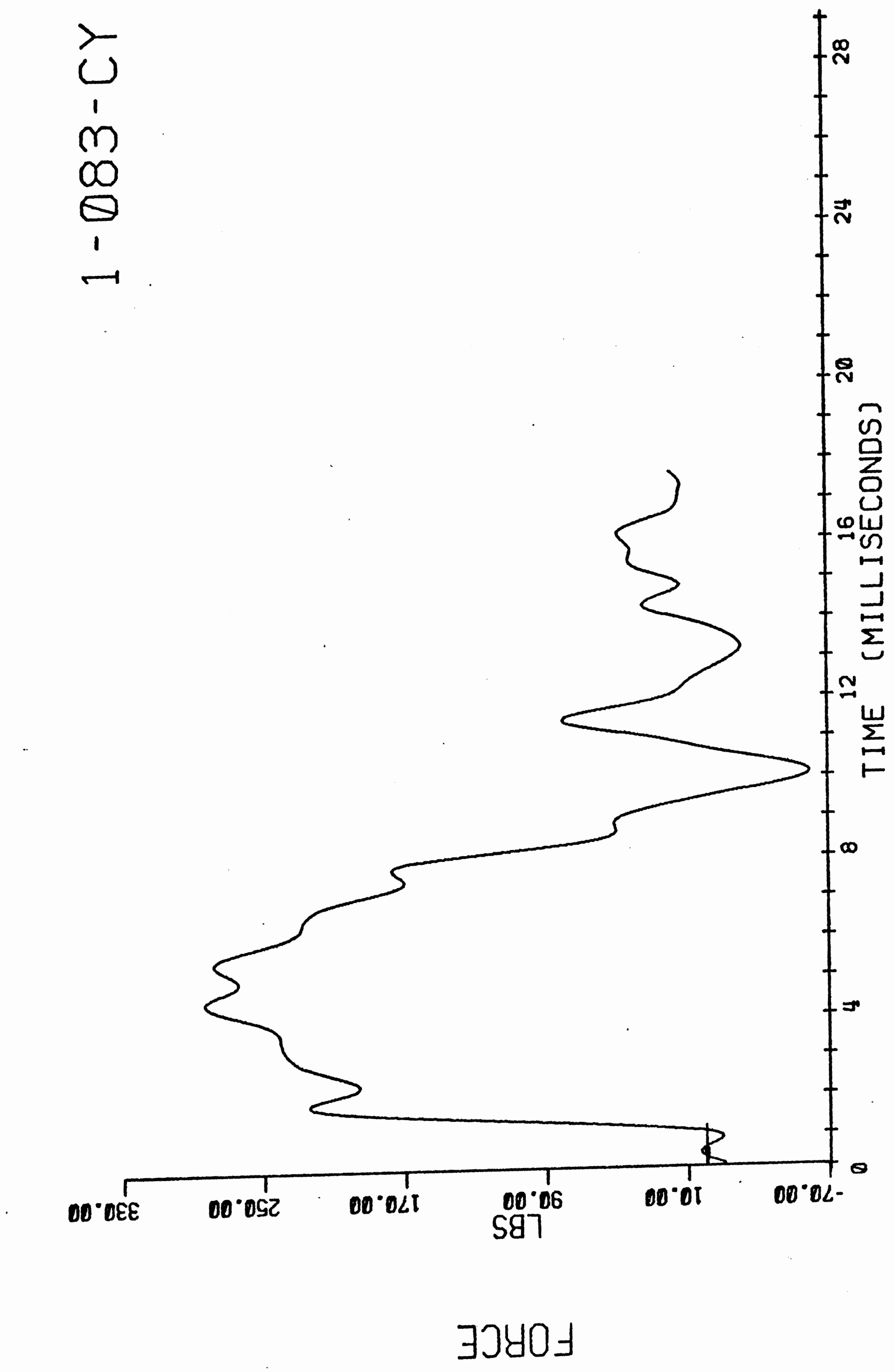


Superior View

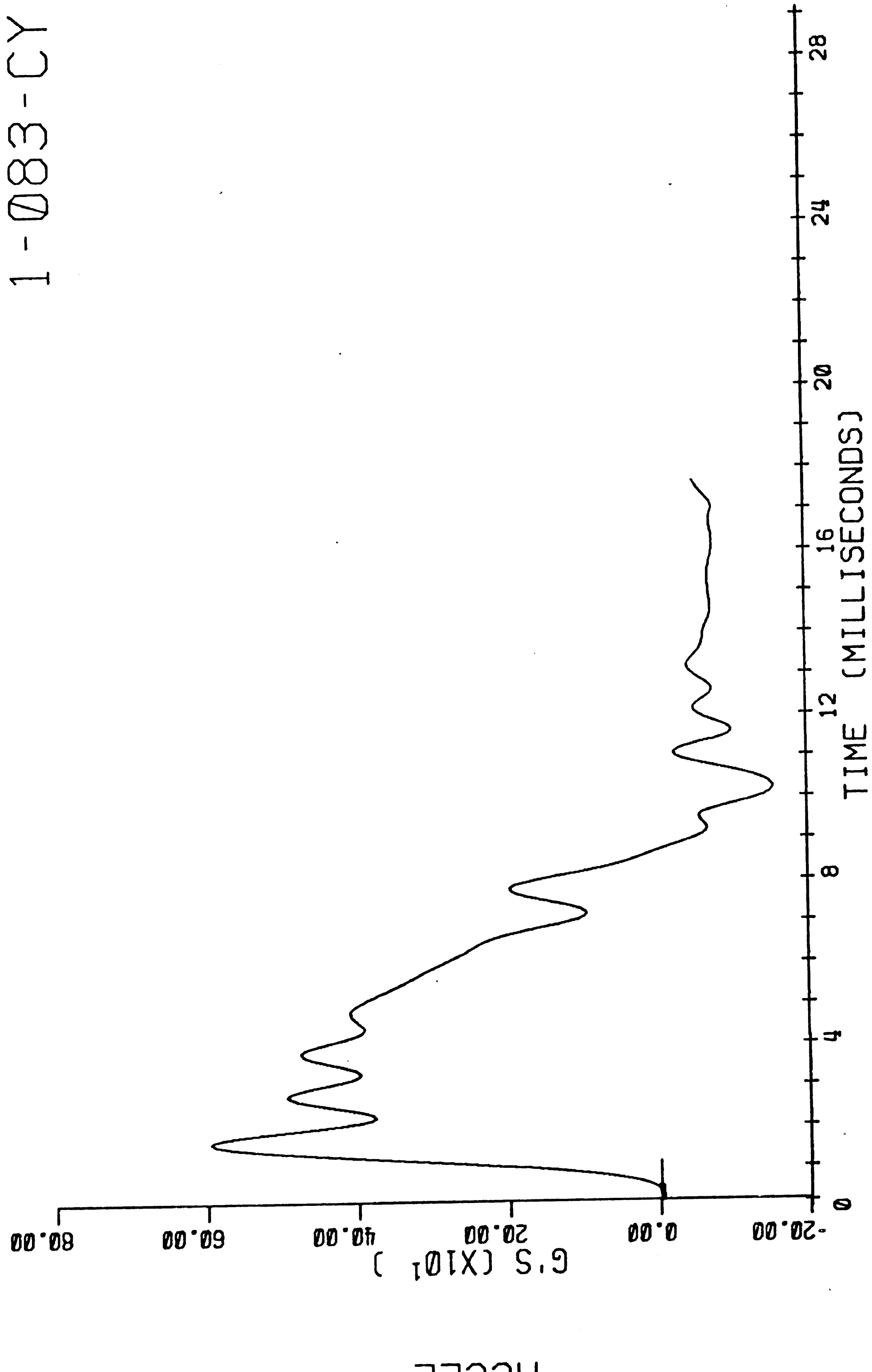


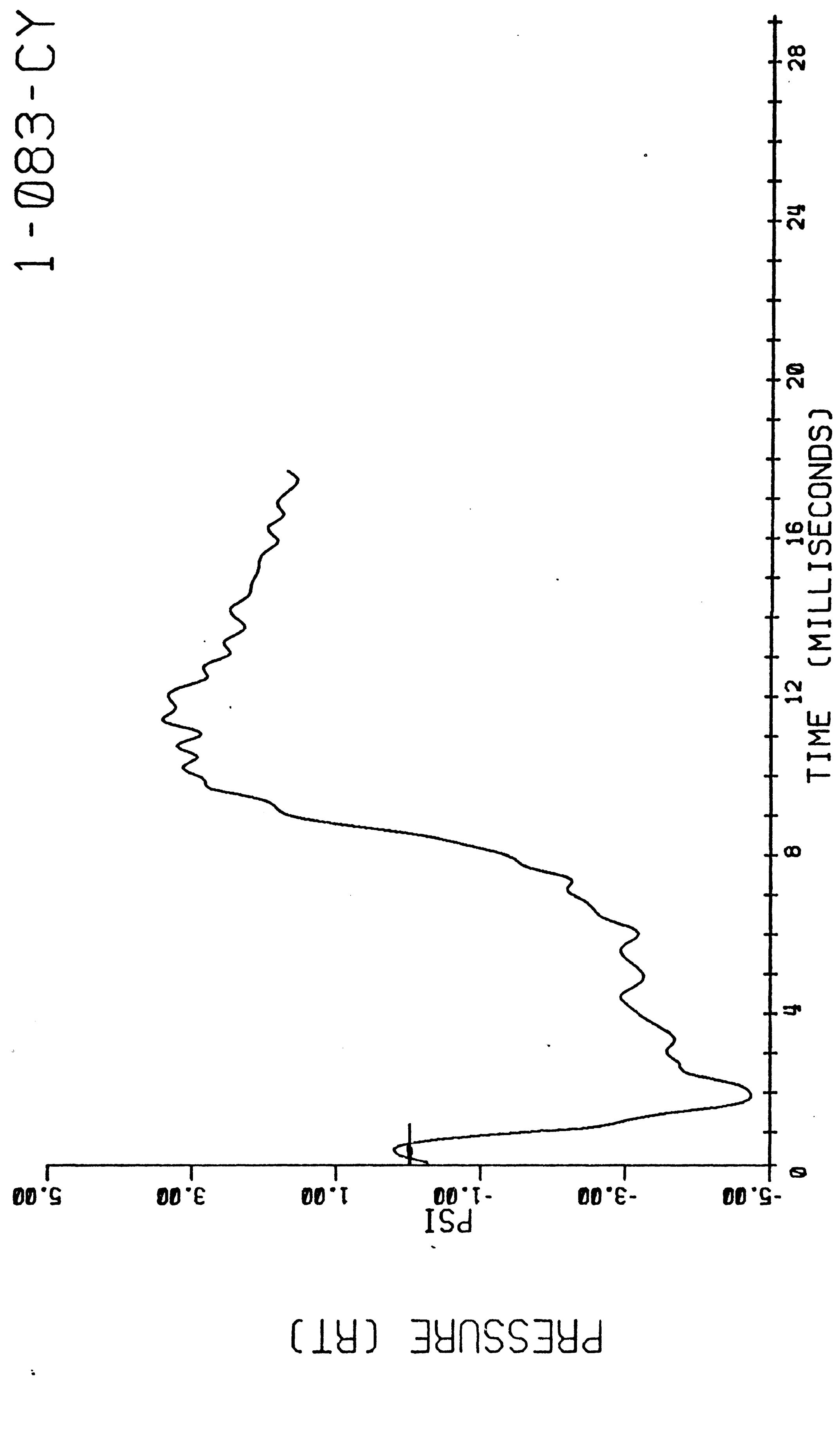
Inferior View

P - Position of Pressure Transducer



1-Ø83-CY
FORCE
LBS
330.00
250.00
170.00
90.00
10.00
-70.00
TIME (MILLISECONDS)
0
4
8
12
16
20
24
28


1-Ø83-CY
TIME (MILLISECONDS)
0
4
8
12
16
20
24
28
G'S (X1Ø1)
-20.00
0.00
20.00
40.00
60.00
80.00
ACCEL


1-Ø83-CY
TIME (MILLISECONDS)
0
4
8
12
16
20
24
28
PSI
-5.00
-3.00
-1.00
1.00
3.00
5.00
PRESSURE (RT)

HEAD IMPACT TEST SUMMARY

TEST NO. 084 TEST DATE 8/6/75

TEST SUBJECT

SPECIES Cynomolgus

Body Weight 7.04 lb.

Sitting Height (Top of Head to bottom of Buttocks) 15.00 in.

Head Weight 0.68 lbs

Brain Weight 0.13 lbs

Brain Volume 3.05 in^3

Skull Inside Length A 2.28 in

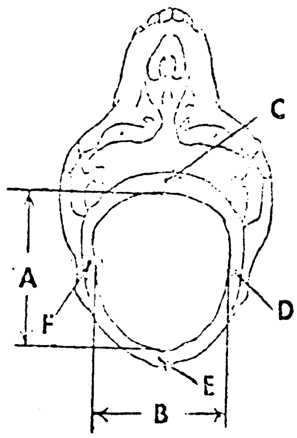
Skull Inside Width B 1.92 in

Skull Thickness at Pt. C 0.10 in

Skull Thickness at Pt. D 0.041 in

Skull Thickness at Pt. E 0.111 in

Skull Thickness at Pt. F 0.550 in



IMPACT CONDITIONS

Location of Impact Back of head

Type of Impact Four inch diameter round impactor padded with 2 inches of Ensolite

Impact Velocity 43.54 ft/sec

TEST NO. 084

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site ----

Opposite to Impact Site Good

Epidural Pressures in Direction of Impact:

At Impact Site Good

Opposite to Impact Site Good

Strain Gage Rosettes:

Right Parietal Gage ----

Left Parietal Gage ----

Frontal Gage ----

Force: Good

High Speed Motion Pictures:

Side Camera Good

Frame Rate 3000 fps

Type II

Accelerations in Direction of Impact:

At Impact Site __________

Opposite to Impact Site __________

Rigid Body Head Motion Analysis: __________

EEG DATA: Pre-Impact __________

Post Impact __________

- NOT ANALYZED -

Force: __________

TEST NO. 084

High Speed Motion Pictures

Side Camera ____________________

Framing Rate ____________________

Front Camera ____________________

Framing Rate ____________________

INJURY:

Condition Prior to Impact Good arm muscle tone, no eye reflex

		Time After Impact	Condition
Consciousness	1.	0 min.	Unconscious
	2.	1.5 min	Conscious
	3.	30 min	Fully awake
	4.		
	5.		
	6.		
	7.		
	8.		
	9.		
	10.		

TEST NO. 084

Autopsy Summary

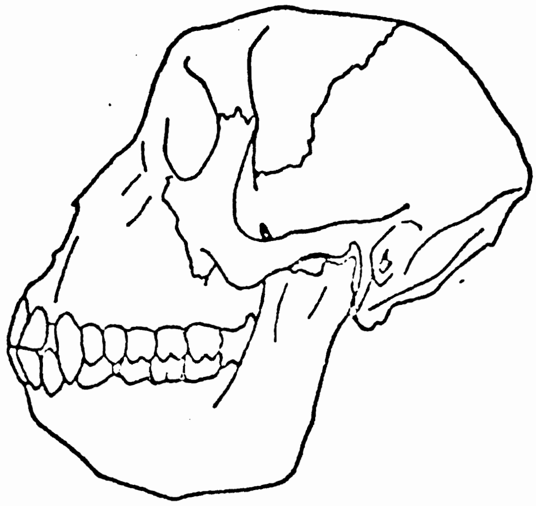
1. Circular bruise under front pressure transducer
2. Circular bruise under rear pressure transducer
3.
4.
5.
6.
7.
8.
9.
10.
11.
12.
13.
14.
15.

Injuries Due to Impact only (not instrumentation)

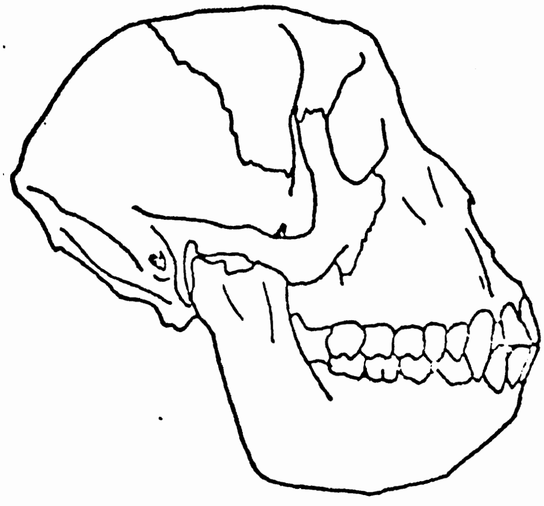
		AIS
1.	Unconscious less than 15 minutes	2
2.		
3.		
4.		
5.		
6.		
7.		
8.		
9.		
10.		

AIS Overall 2

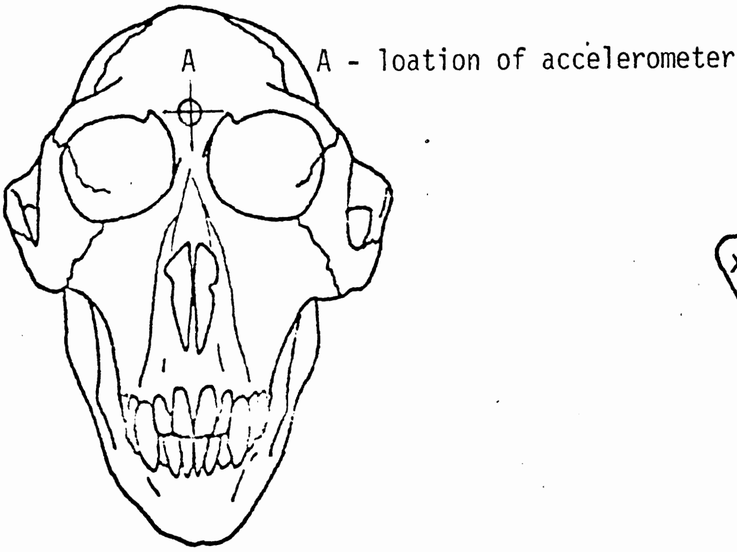
Run Number 084



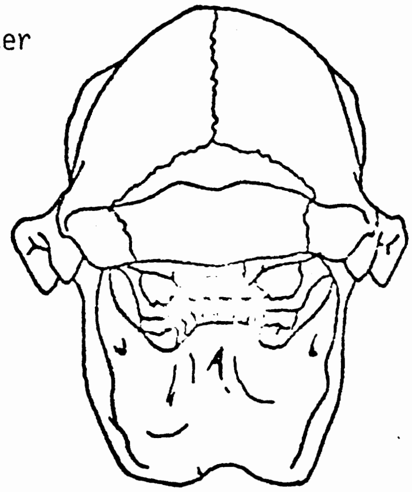
Left Lateral View



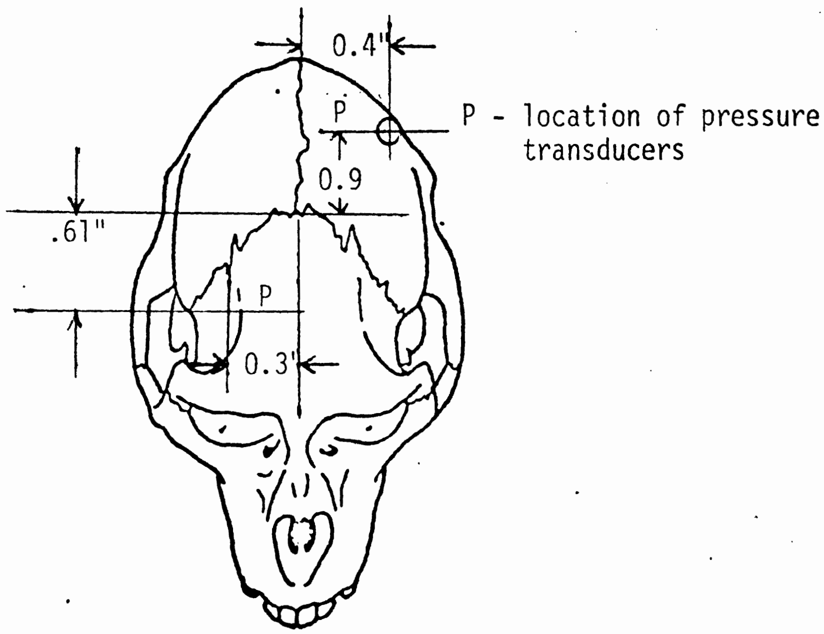
Right Lateral View



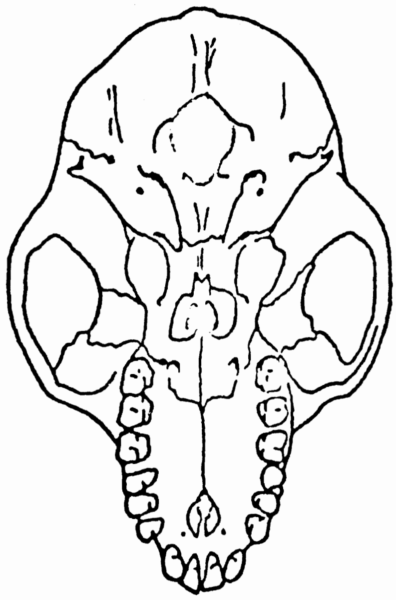
Anterior View



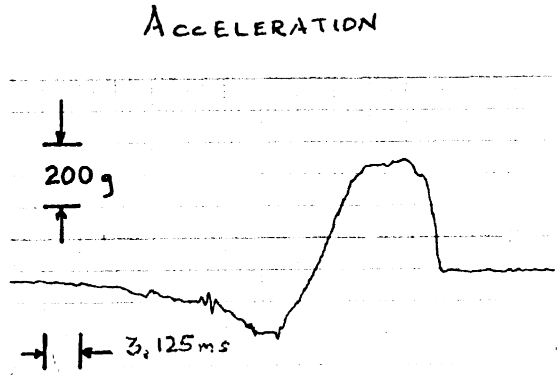
Posterior View

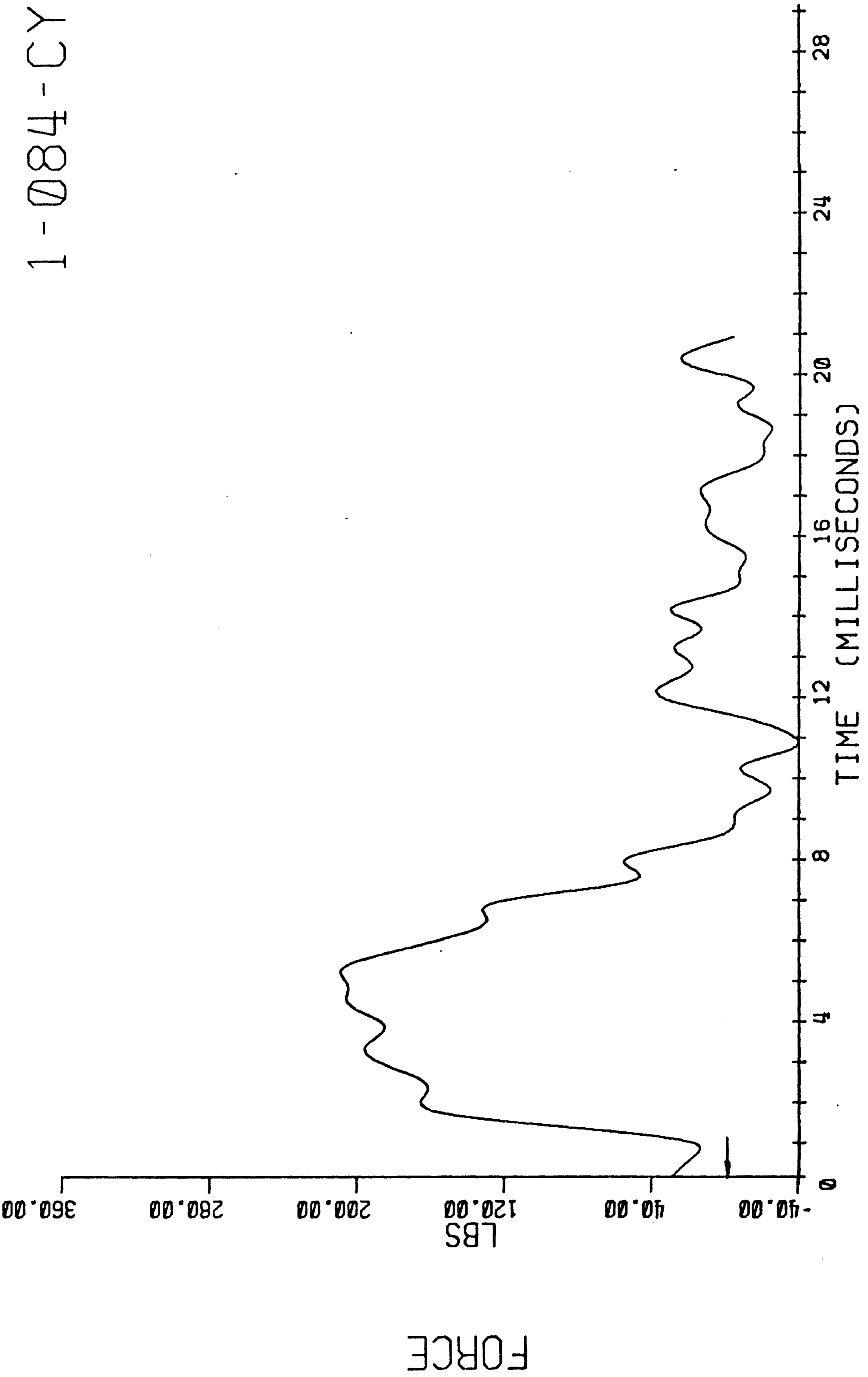


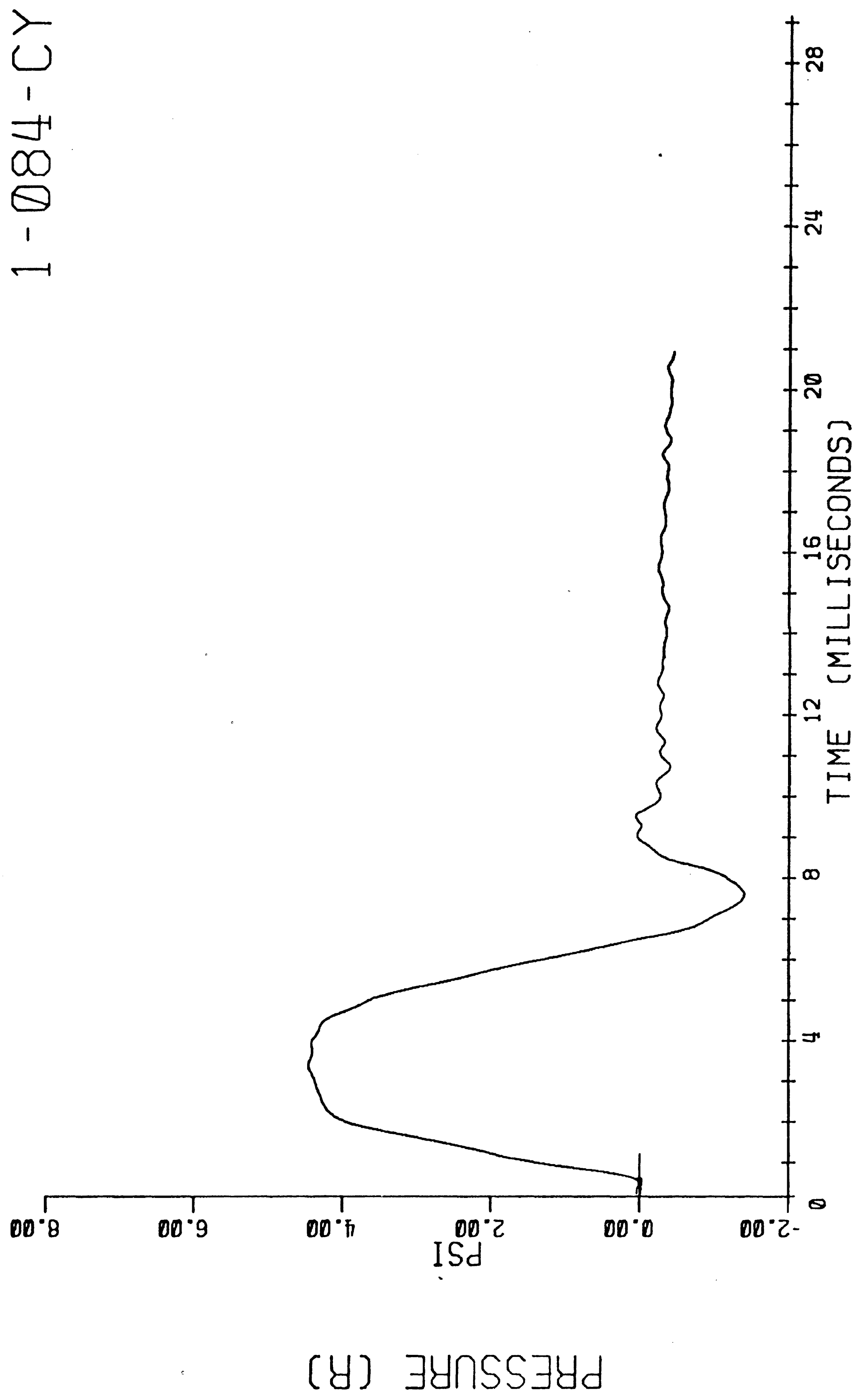
Superior View



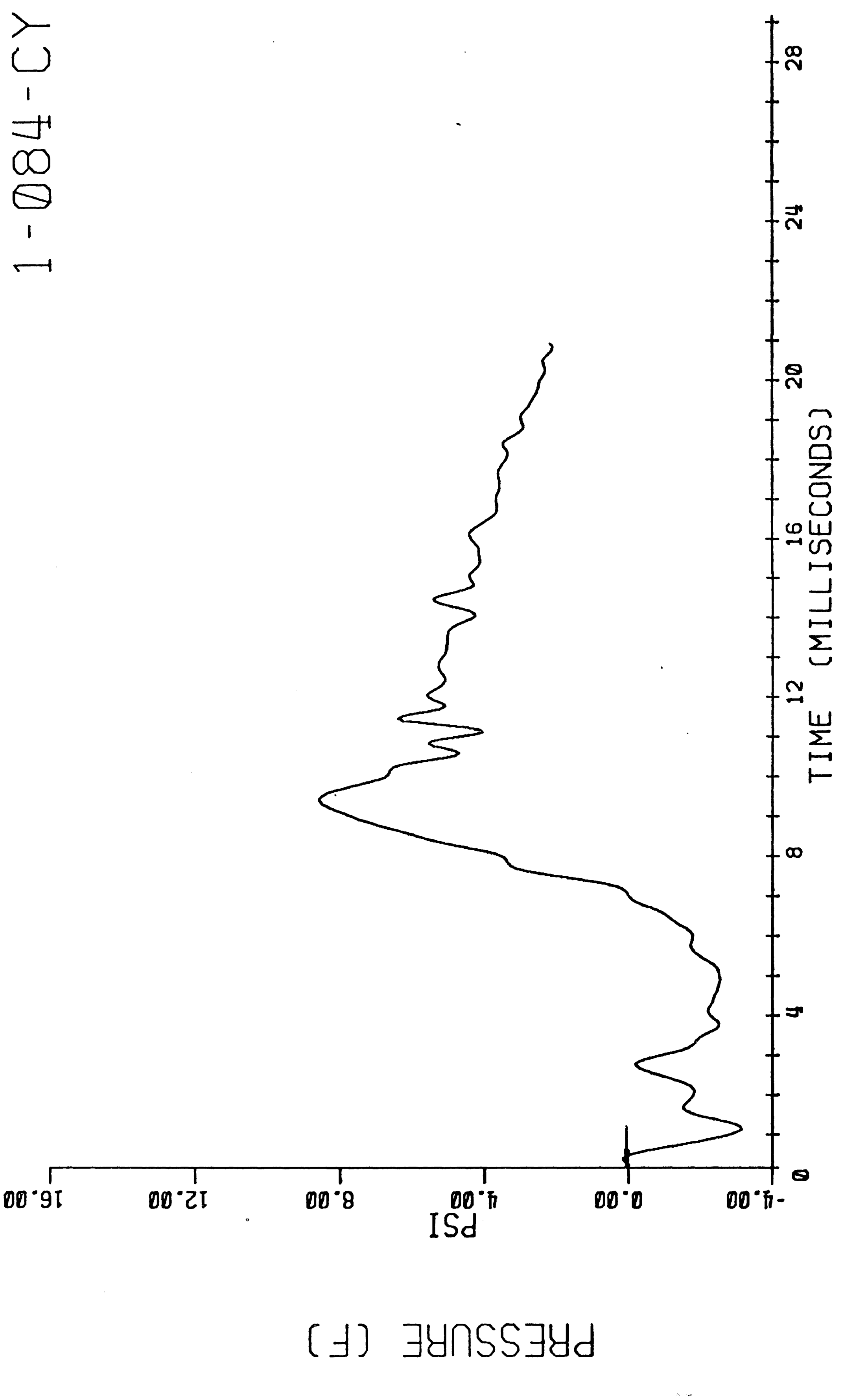
Inferior View


ACCELERATION
200 g
3.125 ms


1-084-CY
FORCE
LBS
-40.00
40.00
120.00
200.00
280.00
360.00
TIME (MILLISECONDS)
0
4
8
12
16
20
24
28



1-084-CY
TIME (MILLISECONDS)
0
4
8
12
16
20
24
28
PSI
-2.00
0.00
2.00
4.00
6.00
8.00
PRESSURE (R)


1-Ø84-CY
TIME (MILLISECONDS)
0
4
8
12
16
20
24
28
PSI
-4.00
0.00
4.00
8.00
12.00
16.00
PRESSURE (F)

HEAD IMPACT TEST SUMMARY

TEST NO. 085

TEST DATE 8/6/75

TEST SUBJECT

SPECIES Cynomolgus

Body Weight 9.24 lb.

Sitting Height (Top of Head to bottom of Buttocks) 17.25 in.

Head Weight 1.06 lbs

Brain Weight 0.131 lbs

Brain Volume 2.75 in^3

Skull Inside Length A 2.31 in

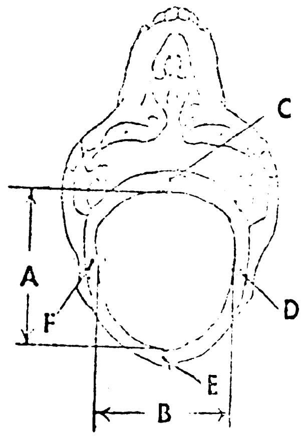
Skull Inside Width B 1.97 in

Skull Thickness at Pt. C 0.108 in

Skull Thickness at Pt. D 0.066 in

Skull Thickness at Pt. E 0.202 in

Skull Thickness at Pt. F 0.064 in



IMPACT CONDITIONS

Location of Impact Back of head

Type of Impact Four inch diameter rigid impactor

Impact Velocity 35.17 ft/sec

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site ----

Opposite to Impact Site Good

Epidural Pressures in Direction of Impact:

At Impact Site Good

Opposite to Impact Site Good

Strain Gage Rosettes:

Right Parietal Gage ----

Left Parietal Gage Good

Frontal Gage ----

Force: Good

High Speed Motion Pictures:

Side Camera Good

Frame Rate 3000 fps

Type II

Accelerations in Direction of Impact:

At Impact Site ______

Opposite to Impact Site ______

Rigid Body Head Motion Analysis: ______

EEG DATA: Pre-Impact ______

Post Impact ______

\- NOT ANALYZED -

Force: ______

High Speed Motion Pictures:

Side Camera __________

Framing Rate __________

Front Camera __________

Framing Rate __________

INJURY:

Condition Prior to Impact Deep breathing, no muscle tone, no eye reflex

		Time After Impact	Condition
Consciousness	1.	0 min.	Unconscious (No respiration)
	2.	2 min.	Unconscious (respiration)
	3.	8 min.	Unconscious
	4.	16 min.	Regaining consciousness
	5.	25 min.	Conscious
	6.		
	7.		
	8.		
	9.		
	10.		

Autopsy Summary

1. Deep laceration on back of head
2. Muscle tear of neck
3. Simple fracture of occipital bone
4. Highly localized contre-coup injury right frontal lobe
5. Subdural hemorrhage right side of frontal and parietal lobe
6. Circular bruise under front pressure transducer
7. Circular bruise under rear pressure transducer
8.
9.
10.
11.
12.
13.
14.
15.

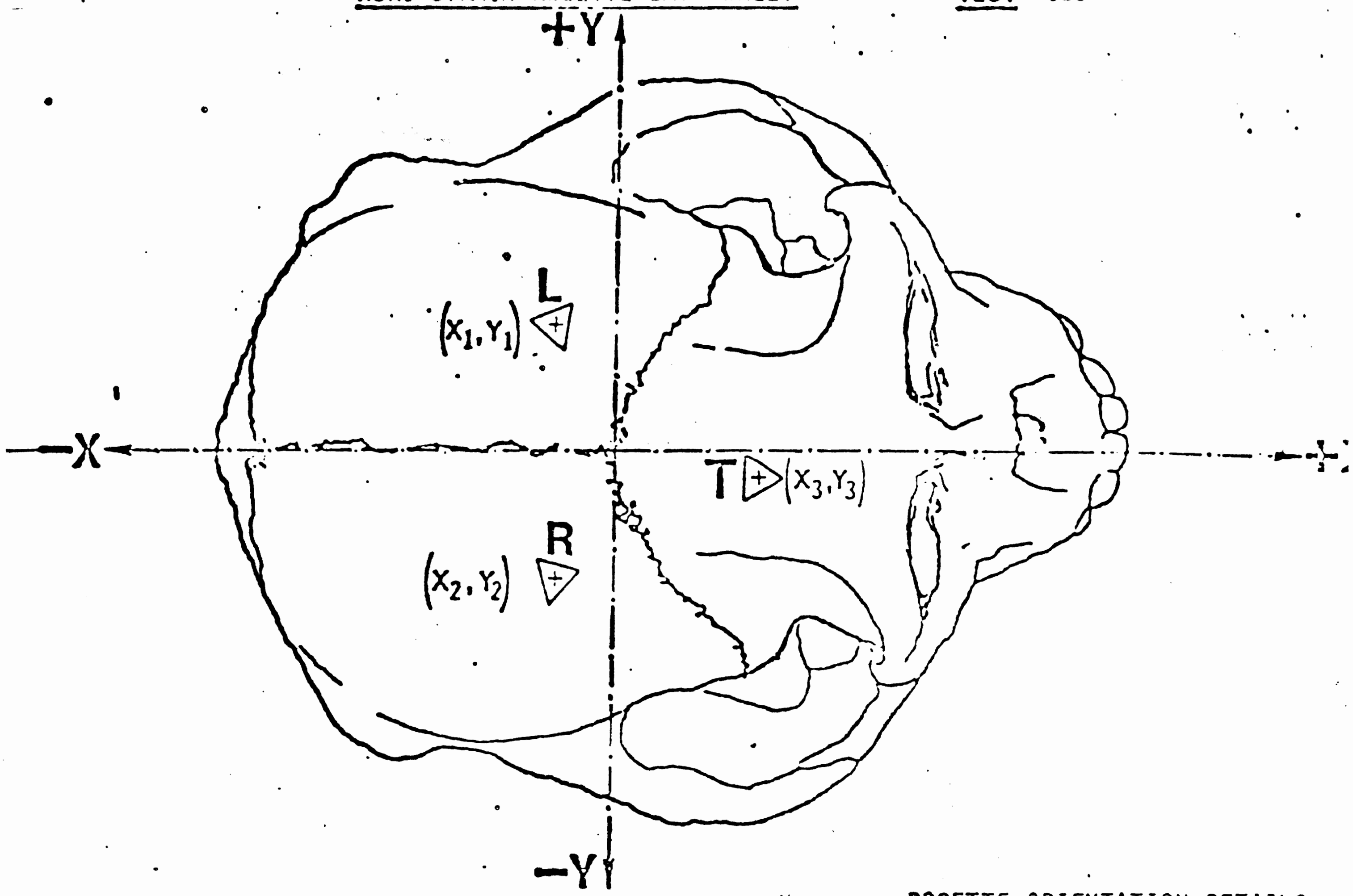
Injuries Due to Impact only (not instrumentation)

	Injury	AIS
1.	Deep laceration on back of head	2
2.	Muscle tear of neck	2
3.	Simple fracture of occipital bone	3
4.	Contre-coup Rt. frontal lobe	3
5.	Subdural hemorrhage Rt. frontal & parietal lobe	4
6.	Unconscious for more than 15 minutes	4
7.		
8.		
9.		
10.		

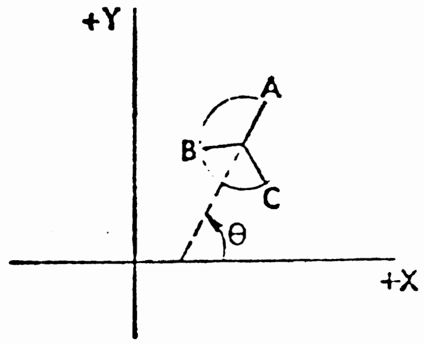
AIS Overall 6

HSRI STRAIN ROSETTE DATA SHEET

TEST 085



ROSETTE ORIENTATION DETAILS



a. △ -- Location of strain rosettes.

b. R -- Right L -- Left T -- Top

c. θ is the angle (measured anti-clockwise) arm 'A' of the rosette makes with the positive direction of the X-axis.

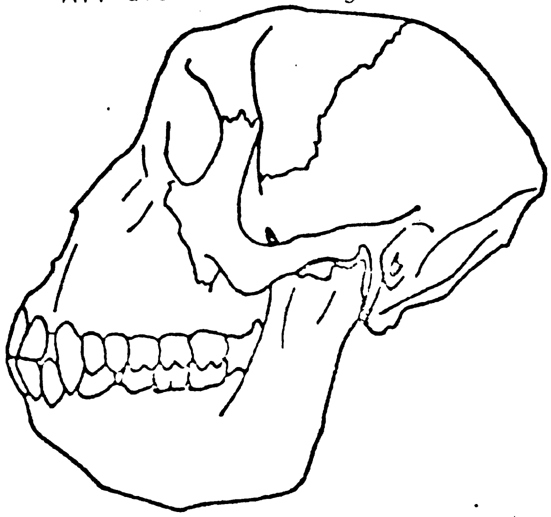
Note: Arm 'A' corresponds to arm '1' as printed on rosette.

d. All distances are measured along the surface of the skull.

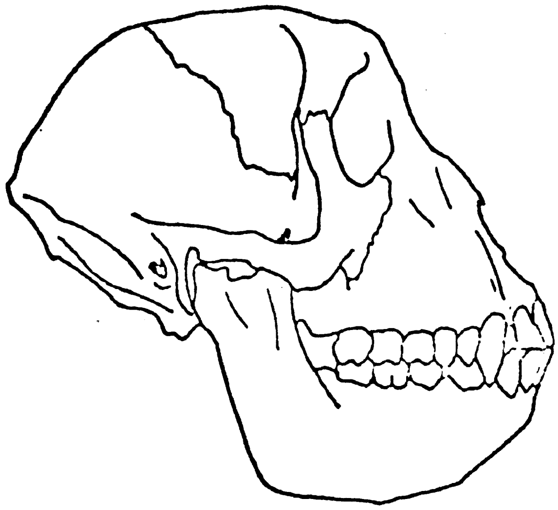
LEFT ROSETTE		RIGHT ROSETTE	TOP ROSETTE
x_1 =	-0.067"	x_2 =	x_3 =
y_1 =	0.439"	y_2 =	y_3 =
θ_1 =	250°	θ_2 =	θ_3 =

Run Number 085

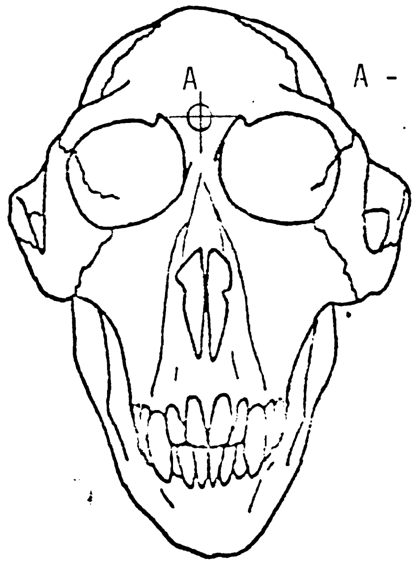
All distances along surface of skull



Left Lateral View

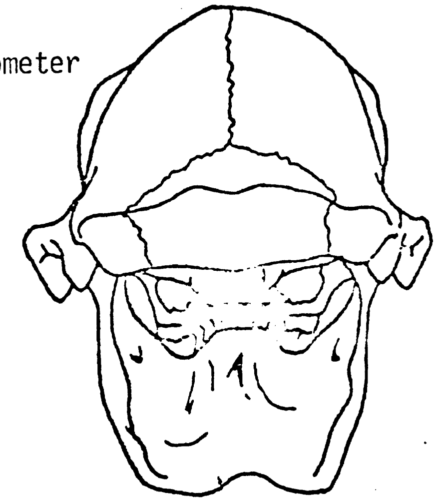


Right Lateral View

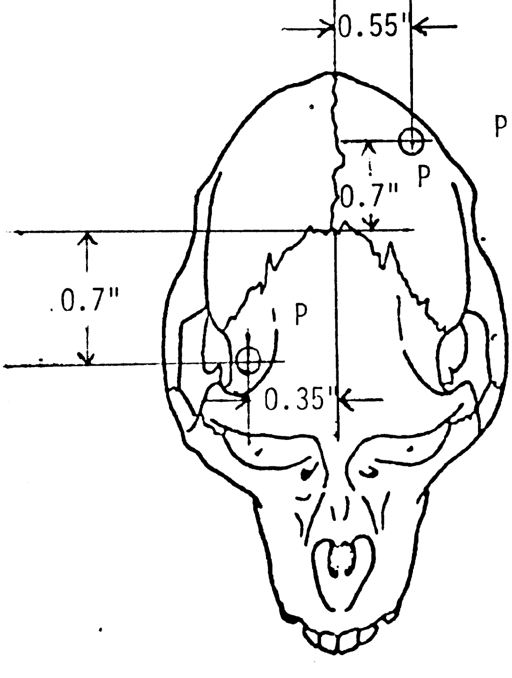


Anterior View

A - location of accelerometer

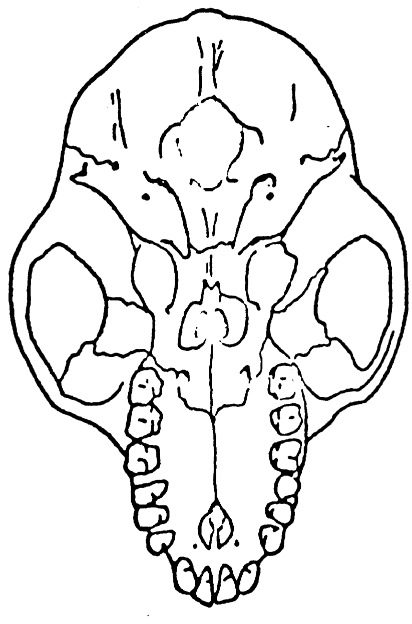


Posterior View

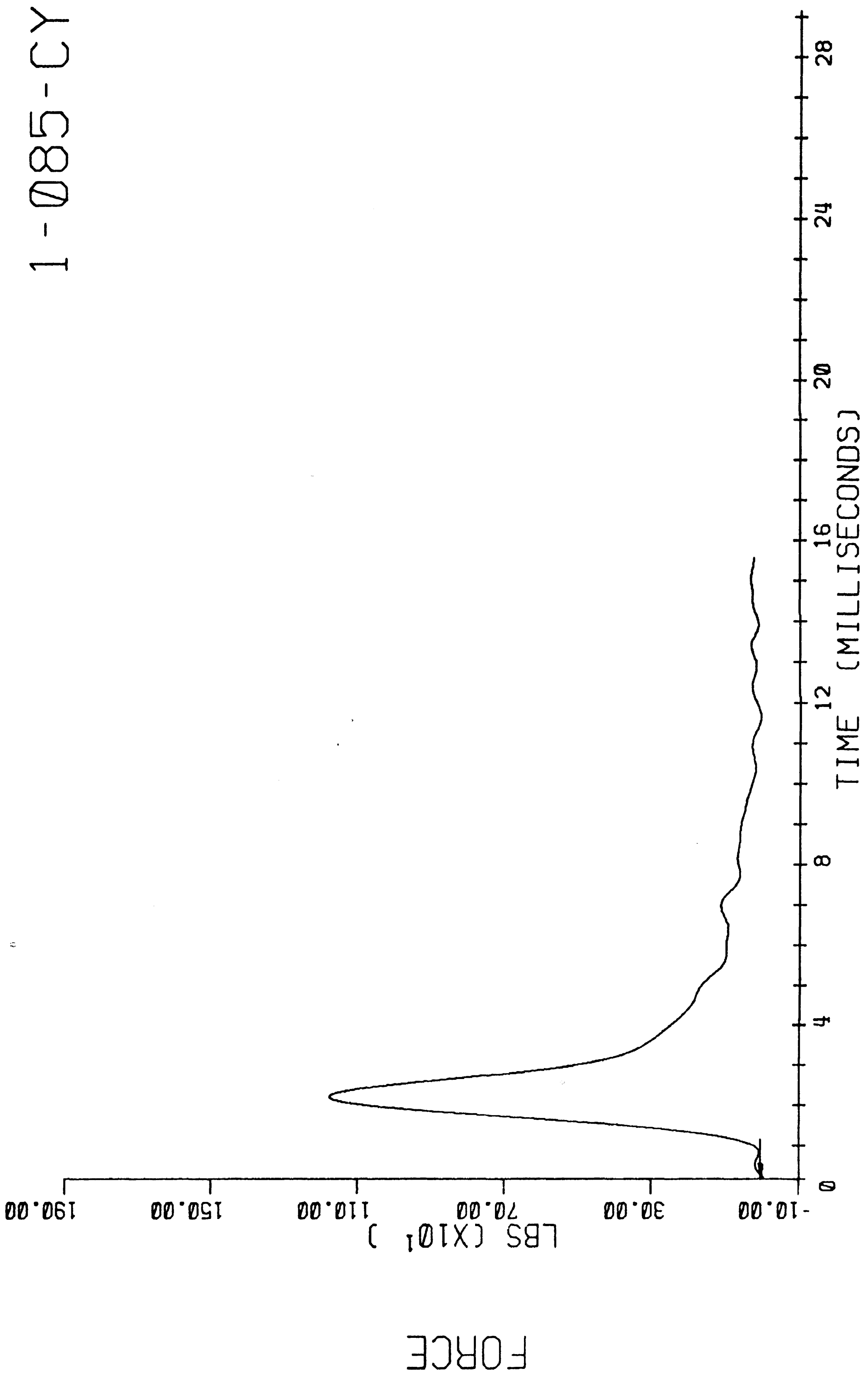


Superior View

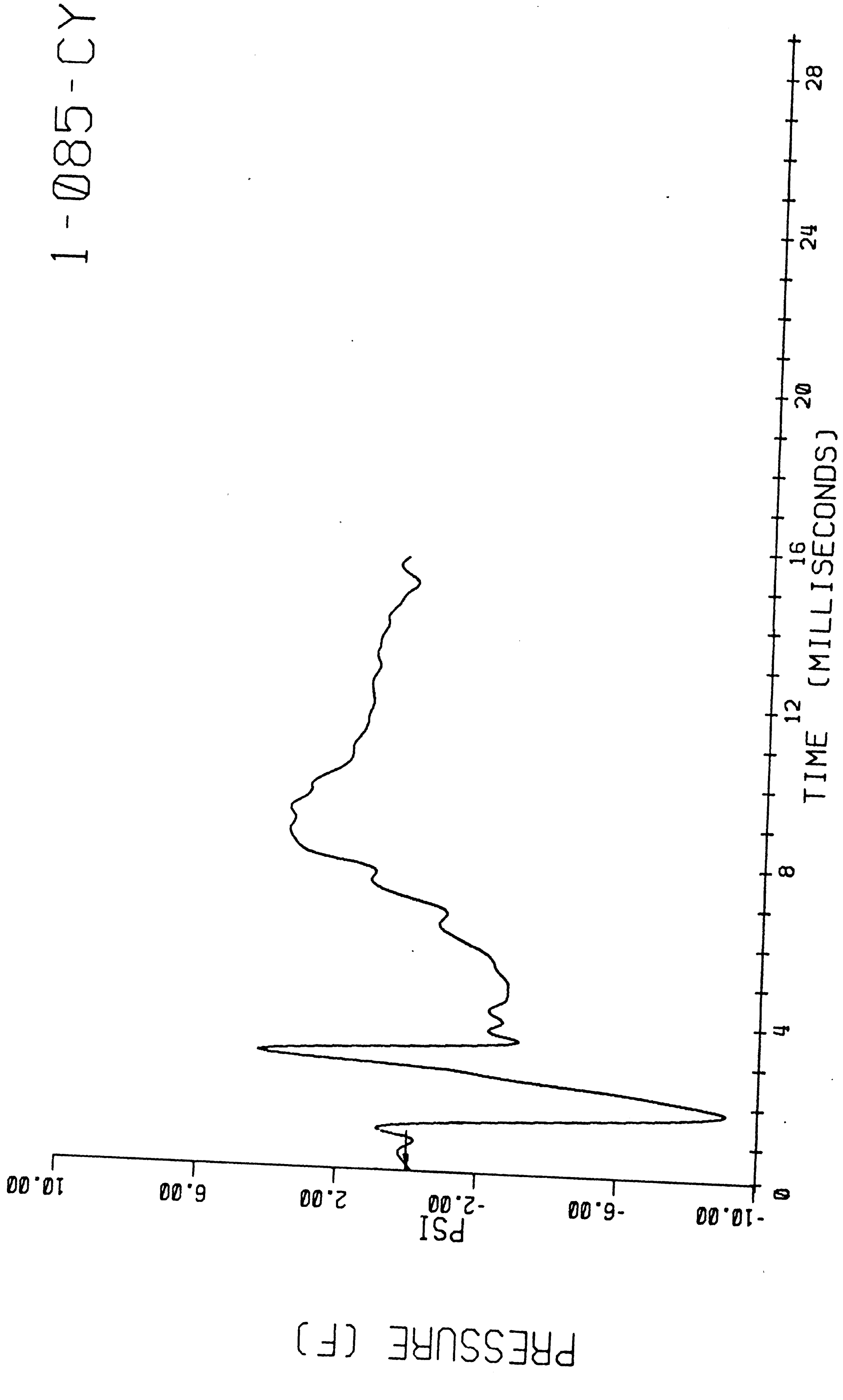
P - location of pressure transducers

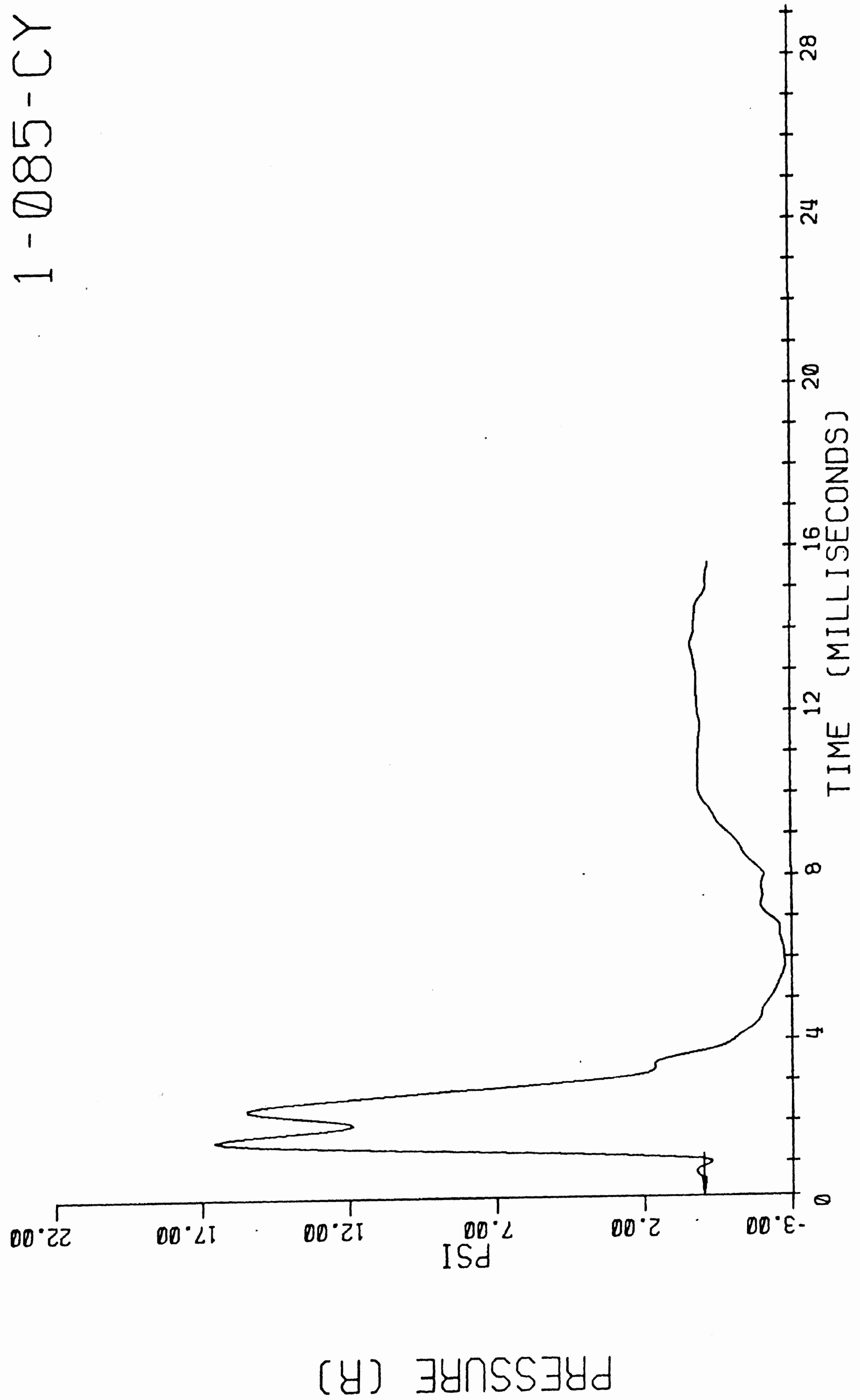


Inferior View

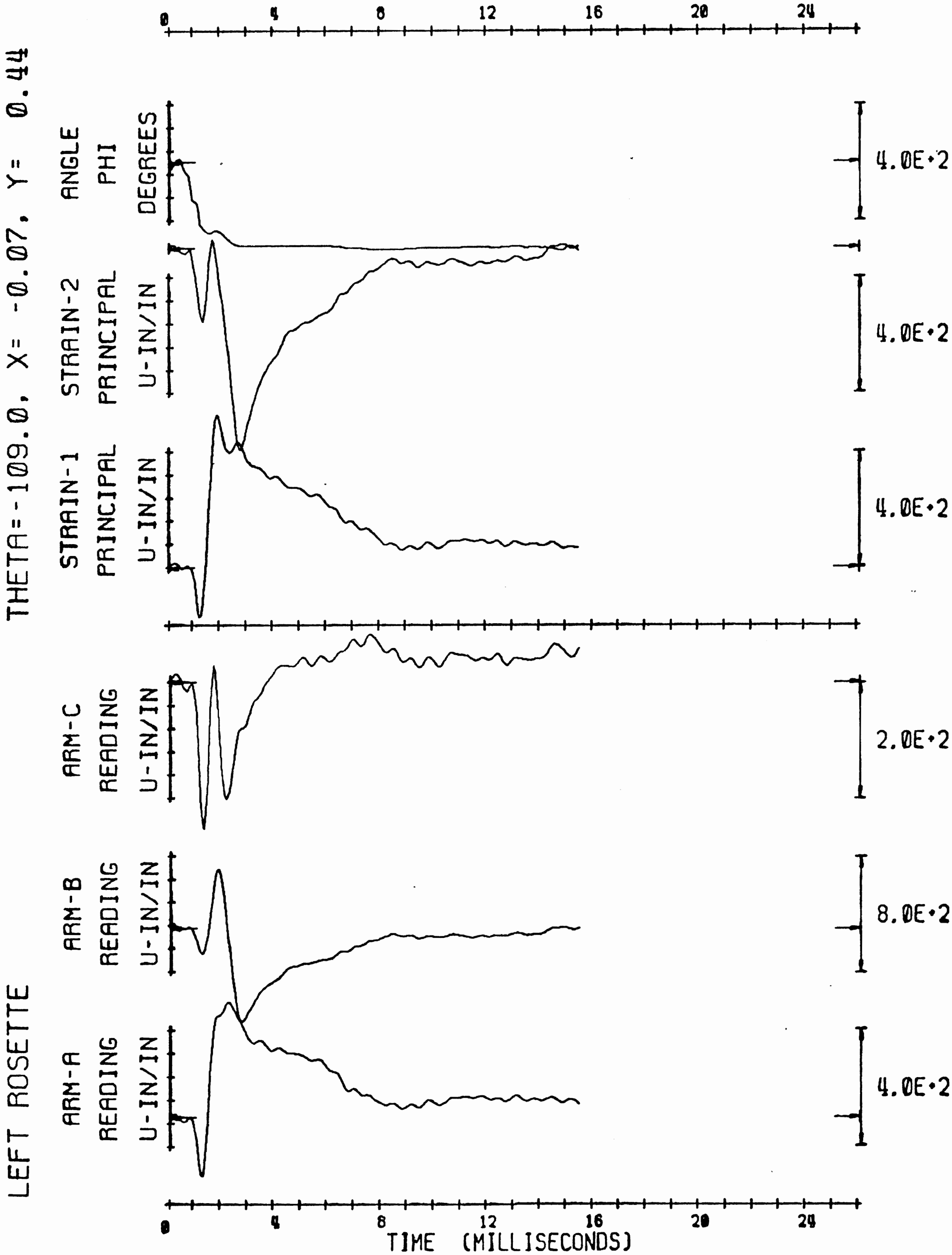


1-Ø85-CY
FORCE
LBS (X1Ø¹)
-10.ØØ
30.ØØ
70.ØØ
110.ØØ
150.ØØ
190.ØØ
TIME (MILLISECONDS)
Ø
4
8
12
16
2Ø
24
28

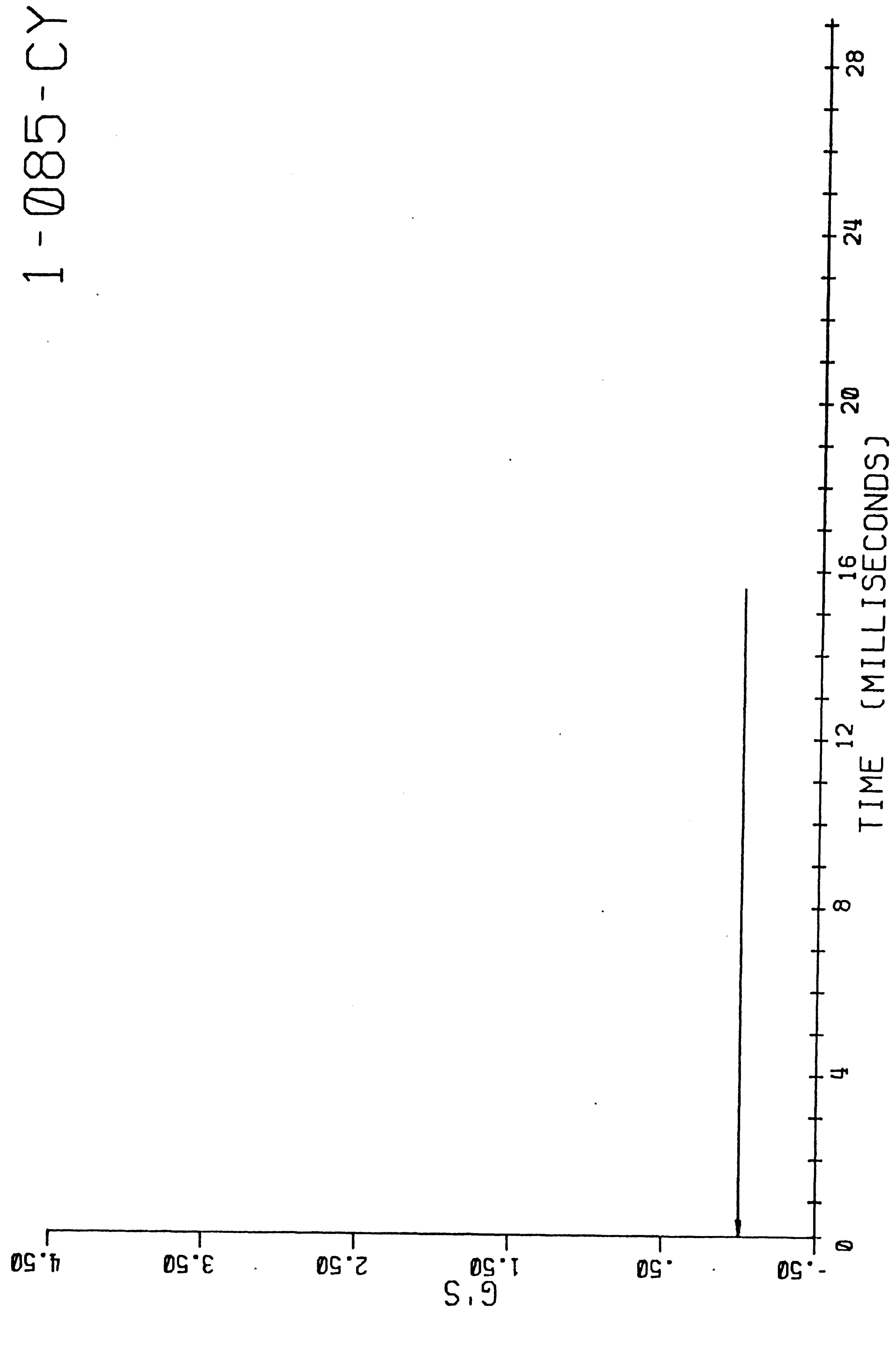

1-Ø85-CY
PRESSURE (F)
PSI
10.00
6.00
2.00
-2.00
-6.00
-10.00
TIME (MILLISECONDS)
0
4
8
12
16
20
24
28


1-085-CY
PRESSURE (R)
PSI
22.00
17.00
12.00
7.00
2.00
-3.00
TIME (MILLISECONDS)
0
4
8
12
16
20
24
28

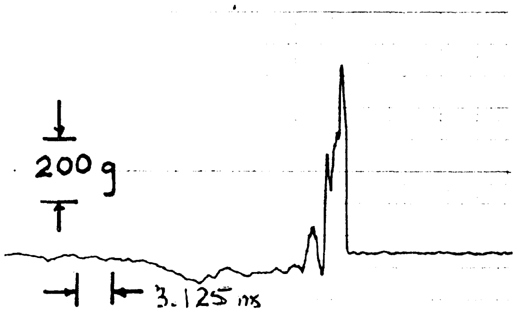
1-085-CY



DELTA ROSETTE STRAIN GAGE


1-Ø85-CY
TIME (MILLISECONDS)
Ø
4
8
12
16
20
24
28
ACCEL
G'S
-.50
.50
1.50
2.50
3.50
4.50

ACCELERATION



APPENDIX B-3

MONKEY TYPE II

TEST NO. 004

HEAD IMPACT TEST SUMMARY

TEST NO. 004 TEST DATE 1/7/75

TEST SUBJECT

SPECIES Rhesus

Body Weight 11.88 lb.

Sitting Height (Top of Head to bottom of Buttocks) 19.00 in.

Head Weight 1.18 lbs

Brain Weight 0.195 lbs

Brain Volume 6.32 in^3

Skull Inside Length A 2.90 in

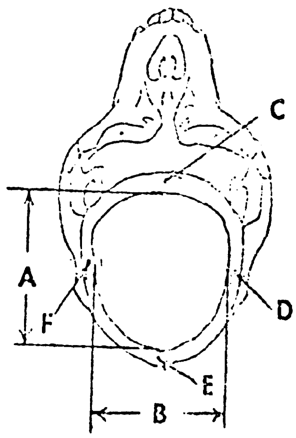
Skull Inside Width B 2.32 in

Skull Thickness at Pt. C 0.110 in

Skull Thickness at Pt. D 0.070 in

Skull Thickness at Pt. E 0.150 in

Skull Thickness at Pt. F 0.070 in



IMPACT CONDITIONS

Location of Impact Back of head

Type of Impact One and one quarter inches diameter, 0.25 inch wall thickness, round cap

Impact Velocity 29.86 ft/sec

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site ____________

Opposite to Impact Site ____________

Epidural Pressures in Direction of Impact:

At Impact Site ____________

Opposite to Impact Site ____________

Strain Gage Rosettes:

Right Parietal Gage ____________

Left Parietal Gage ____________

Frontal Gage ____________

Force: ____________

High Speed Motion Pictures:

Side Camera ____________

Frame Rate ____________

Type II

Accelerations in Direction of Impact:

At Impact Site OK

Opposite to Impact Site OK

Rigid Body Head Motion Analysis: OK

EEG DATA: Pre-Impact Yes

Post Impact Yes

- NOT ANALYZED -

Force: Good

TEST NO. 004

High Speed Motion Pictures:

Side Camera Good

Framing Rate 3000 fps

Front Camera Good

Framing Rate 1000 fps

INJURY:

Condition Prior to Impact Slight muscle tone, slight eye reflex, and some shivering

		Time After Impact	Condition
Consciousness	1.	0 min.	Conscious
	2.		
	3.		
	4.		
	5.		
	6.		
	7.		
	8.		
	9.		
	10.		

Autopsy Summary:

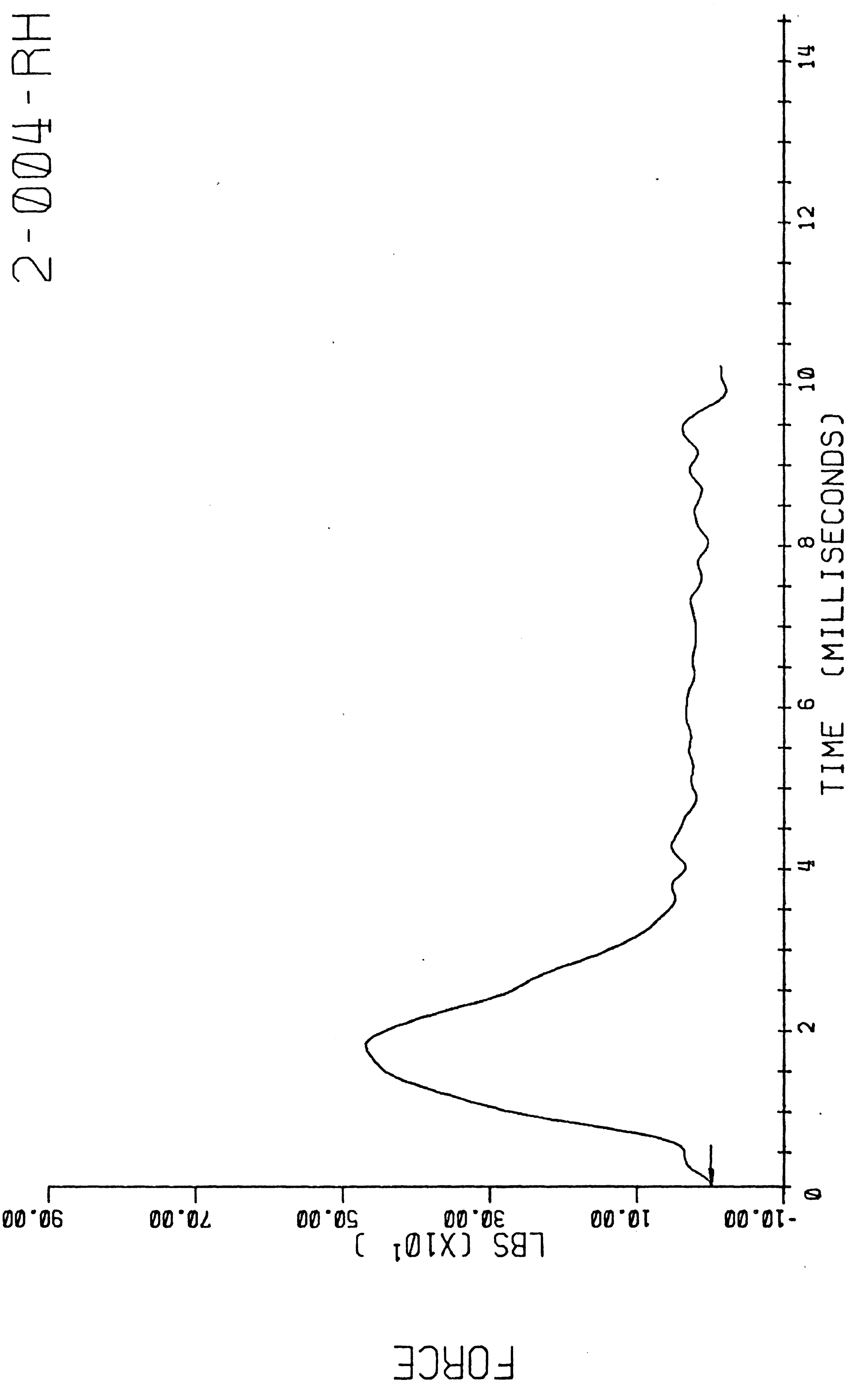
1. Minor epidural hemorrhage under right mid. accelerometer mount
2.
3.
4.
5.
6.
7.
8.
9.
10.
11.
12.
13.
14.
15.

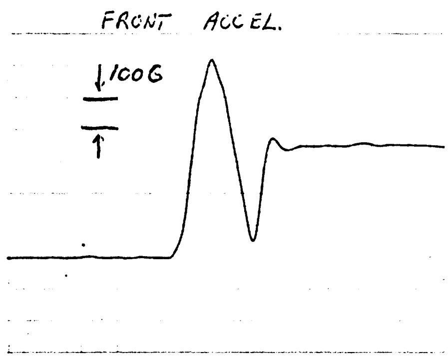
Injuries Due to Impact only (not instrumentation)

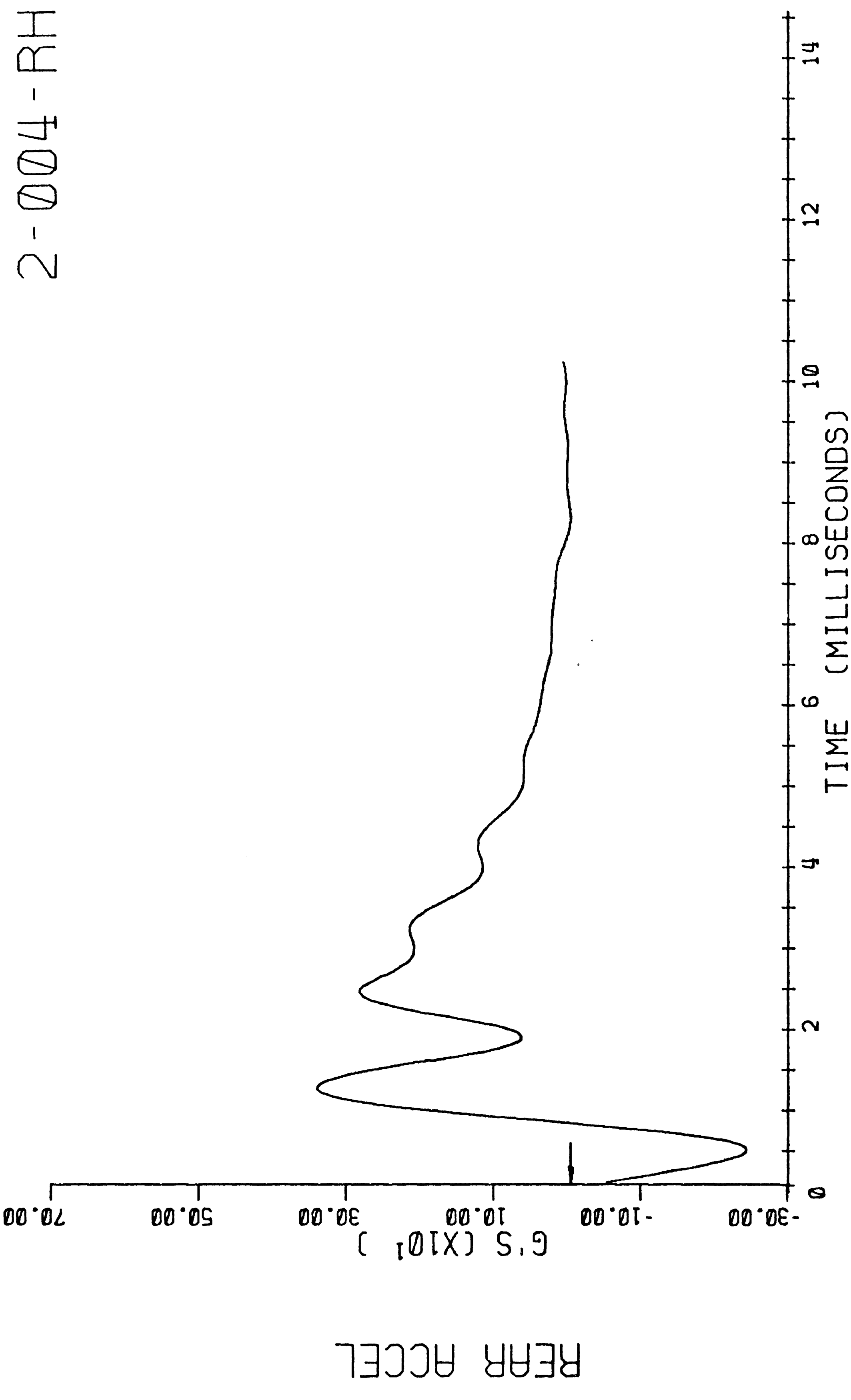
AIS

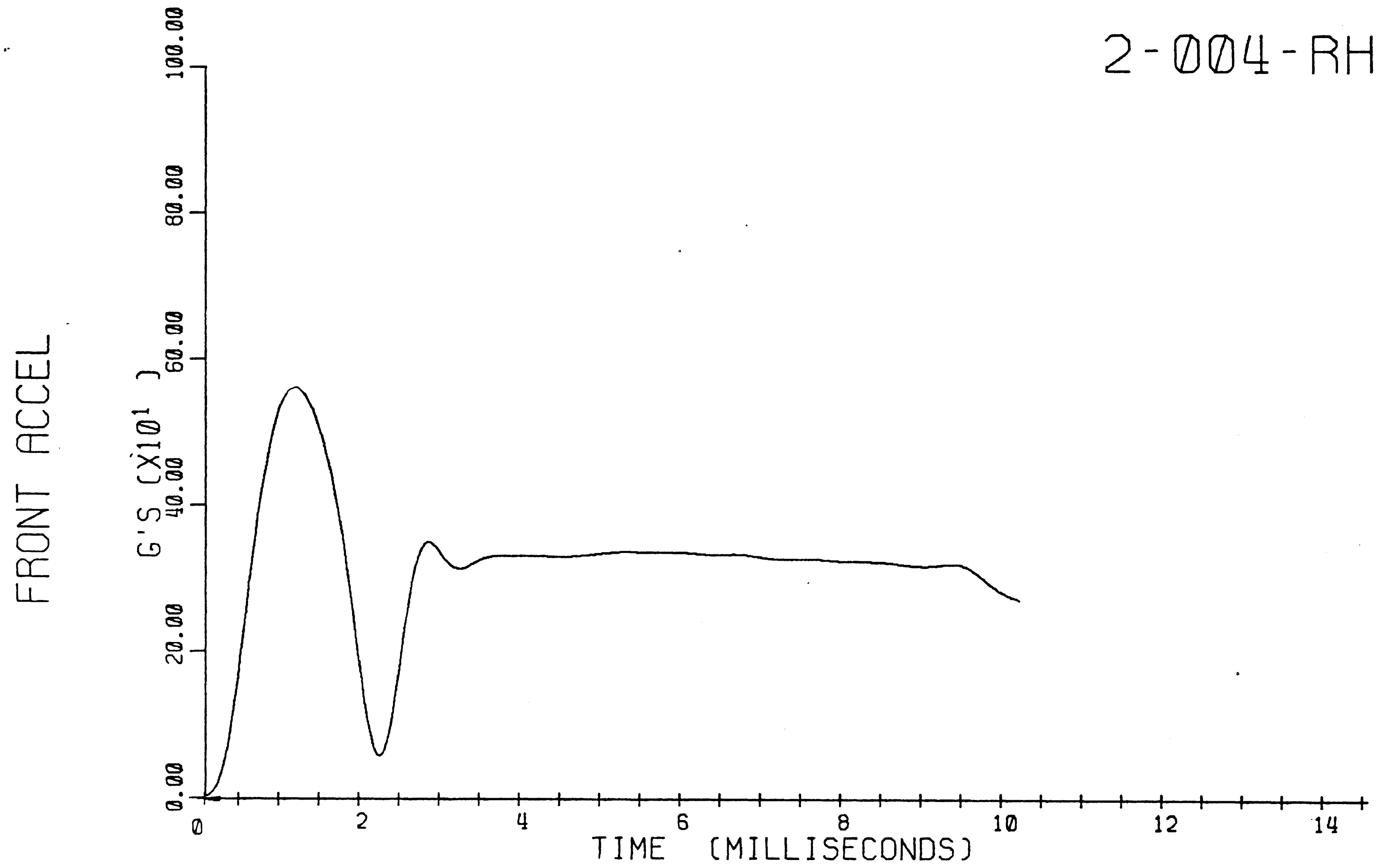
1.
2.
3.
4.
5.
6.
7.
8.
9.
10.

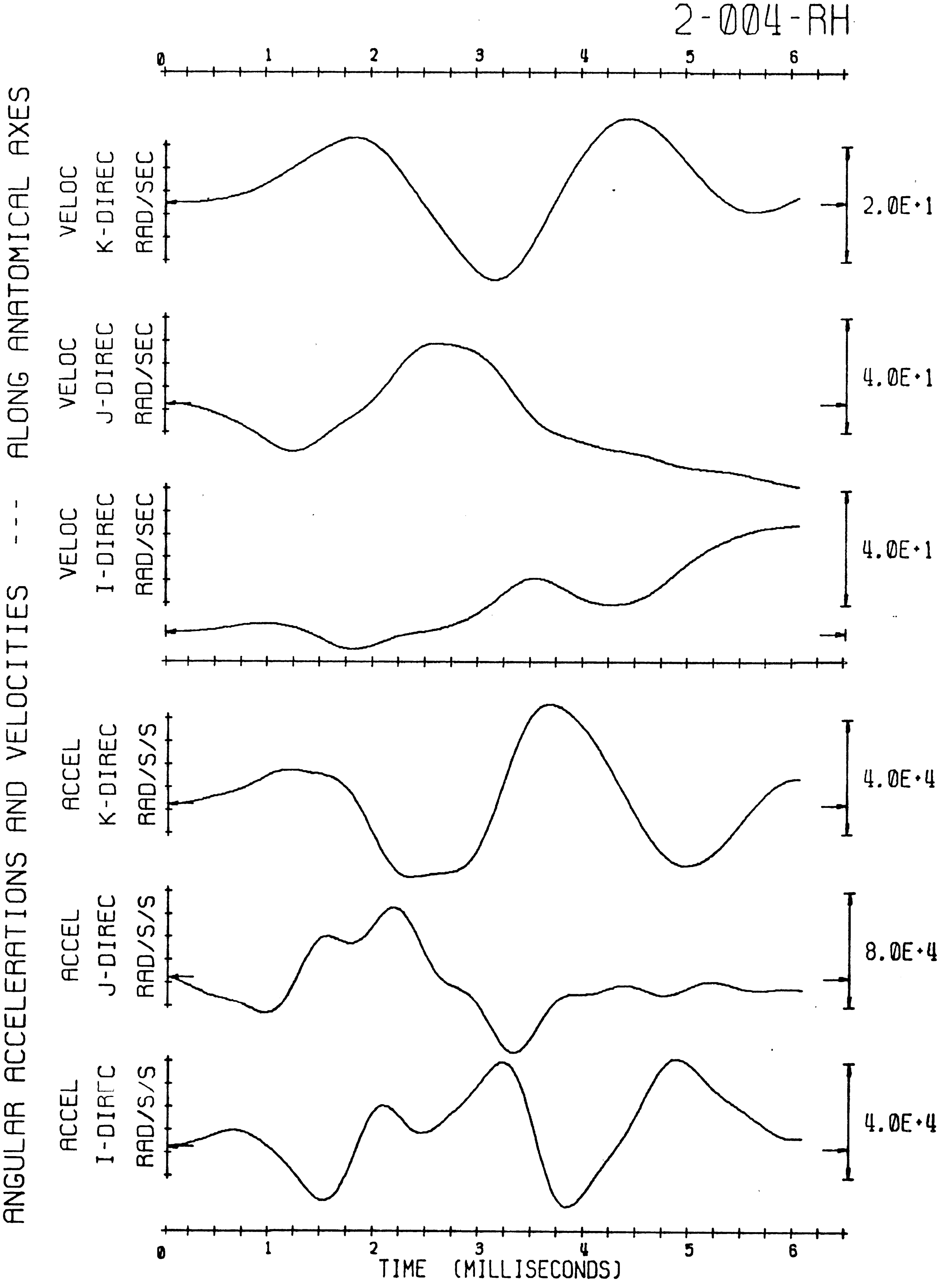
AIS Overall 0


2-004-RH
TIME (MILLISECONDS)
0
2
4
6
8
10
12
14
FORCE
LBS (X10¹)
-10.00
10.00
30.00
50.00
70.00
90.00

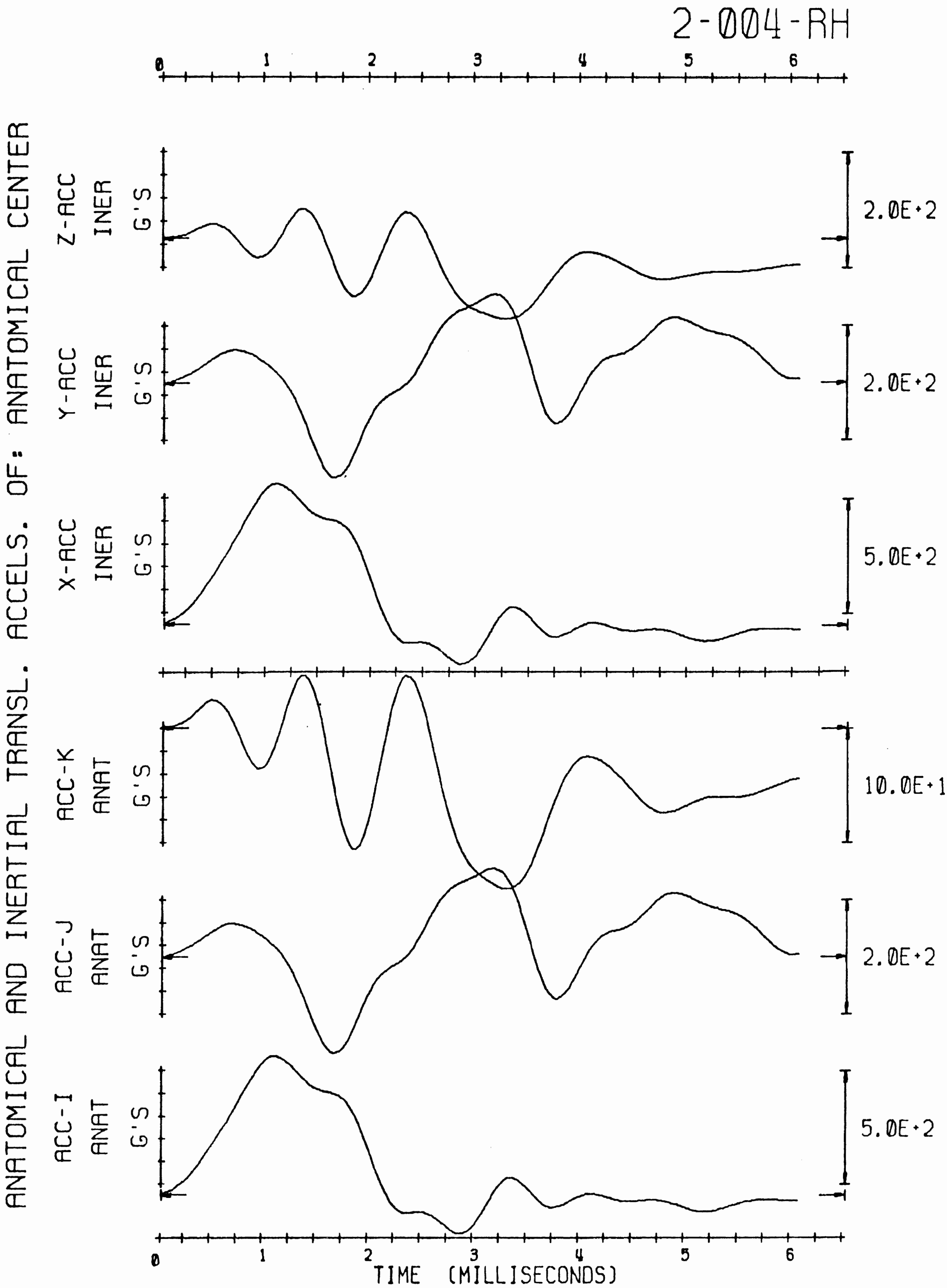

FRONT ACCEL.
100G


2-004-RH
REAR ACCEL
TIME (MILLISECONDS)
0
2
4
6
8
10
12
14
G'S (X10¹)
-30.00
-10.00
10.00
30.00
50.00
70.00


2-004-RH
FRONT ACCEL
G'S (X10¹)
0.00
20.00
40.00
60.00
80.00
100.00
0
2
4
6
8
10
12
14
TIME (MILLISECONDS)



3-D RIGID BODY MOTION ANALYSIS



3-D RIGID BODY MOTION ANALYSIS

HEAD IMPACT TEST SUMMARY

TEST NO. 012

TEST DATE 1/22/75

TEST SUBJECT

SPECIES Rhesus

Body Weight 8.80 lb.

Sitting Height (Top of Head to bottom of Buttocks) 21.00 in.

Head Weight 0.92 lbs

Brain Weight 0.178 lbs

Brain Volume 6.00 in^3

Skull Inside Length A 2.77 in

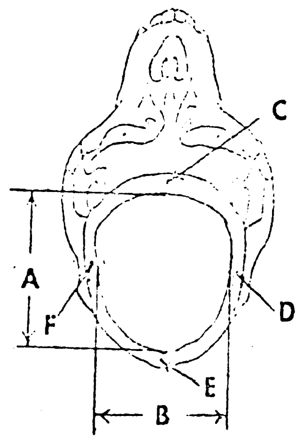
Skull Inside Width B 2.30 in

Skull Thickness at Pt. C 0.100 in

Skull Thickness at Pt. D 0.067 in

Skull Thickness at Pt. E 0.135 in

Skull Thickness at Pt. F 0.070 in



IMPACT CONDITIONS

Location of Impact Back of head

Type of Impact One and one quarter inches diameter, 0.25 inch wall thickness, round cap

Impact Velocity 23.52 ft/sec

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site ______

Opposite to Impact Site ______

Epidural Pressures in Direction of Impact:

At Impact Site ______

Opposite to Impact Site ______

Strain Gage Rosettes:

Right Parietal Gage ______

Left Parietal Gage ______

Frontal Gage ______

Force: ______

High Speed Motion Pictures:

Side Camera ______

Frame Rate ______

Type II

Accelerations in Direction of Impact:

At Impact Site No

Opposite to Impact Site Good

Rigid Body Head Motion Analysis: OK

EEG DATA: Pre-Impact Yes

Post Impact Yes

- NOT ANALYZED -

Force: Good

High Speed Motion Pictures:

Side Camera Good

Framing Rate 3000 fps

Front Camera Good

Framing Rate 1000 fps

INJURY:

Condition Prior to Impact Slight muscle tone, slight eye reflex, and some Shivering

		Time After Impact	Condition
Consciousness	1.	0 min	Unconscious
	2.	11 min	Conscious
	3.	20 min	Full consciousness
	4.		
	5.		
	6.		
	7.		
	8.		
	9.		
	10.		

TEST NO. 012

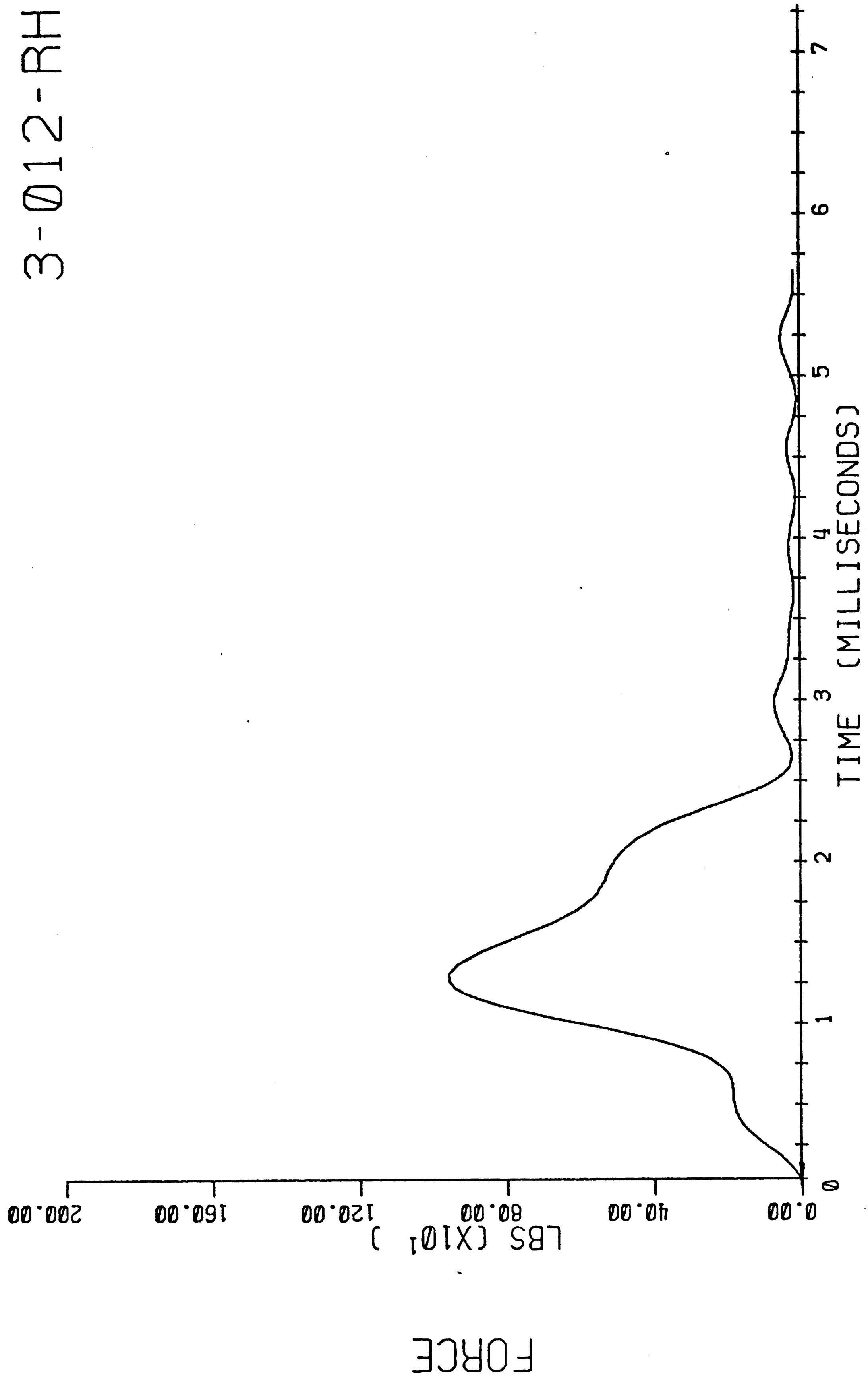
Autopsy Summary

1. Slight brain congestion
2. Congested around accelerometer mounts
3. Small hole in brain from EEG electrode
4. Unconscious for less than 15 minutes
5.
6.
7.
8.
9.
10.
11.
12.
13.
14.
15.

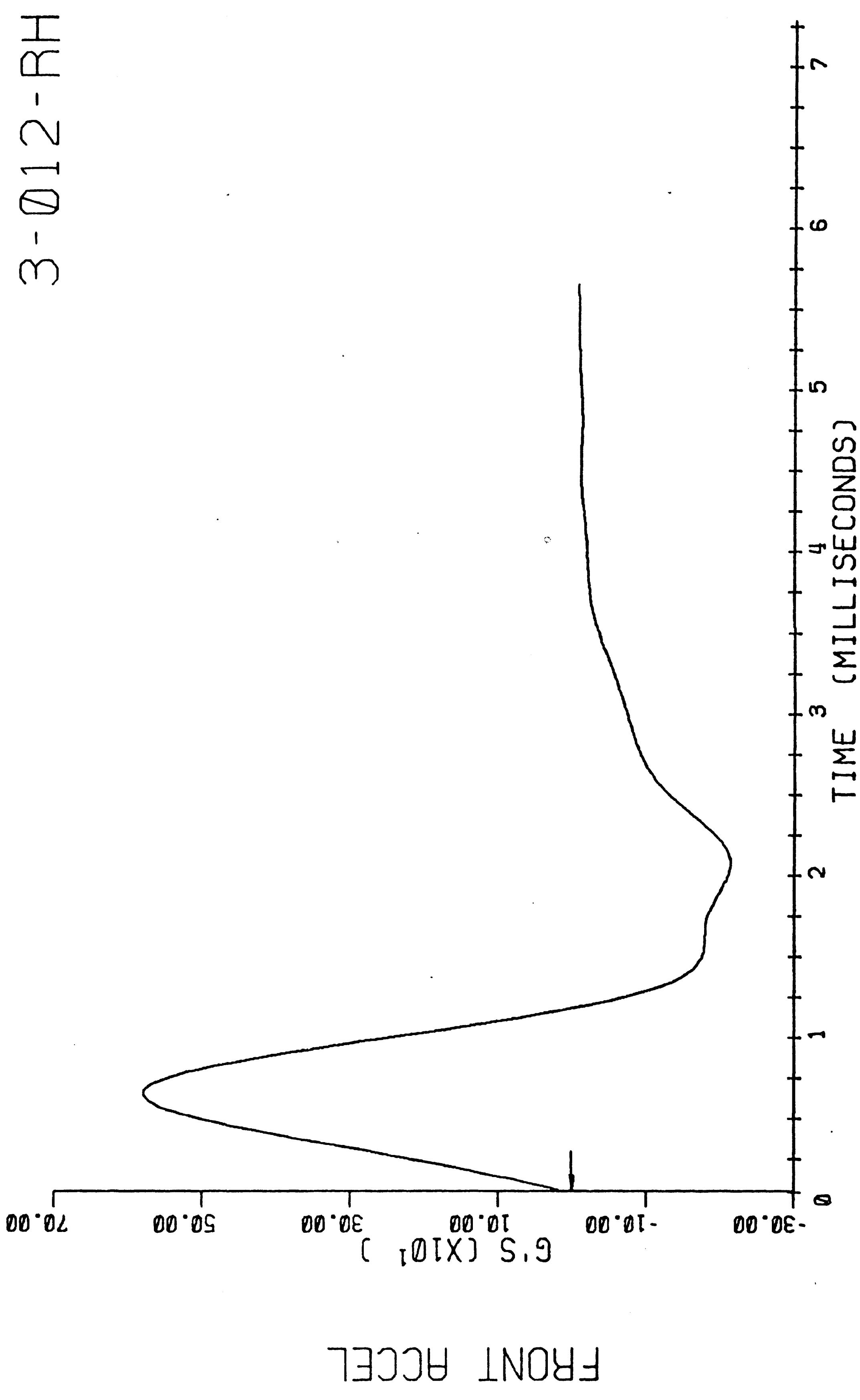
Injuries Due to Impact only (not instrumentation)

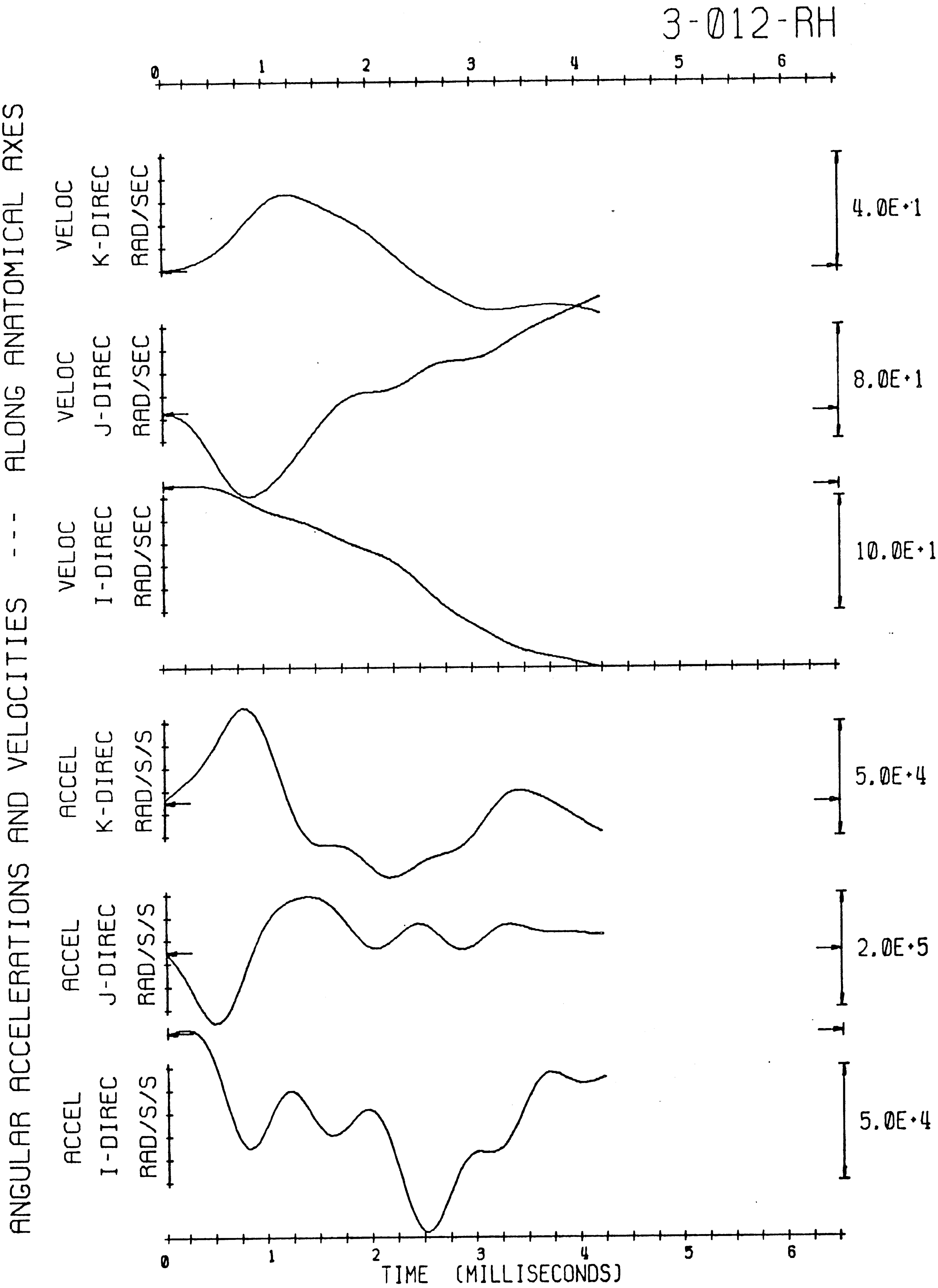
	Injury	AIS
1.	Unconscious for less than 15 minutes	2
2.	Slight brain congestion	1
3.		
4.		
5.		
6.		
7.		
8.		
9.		
10.		

AIS Overall 2



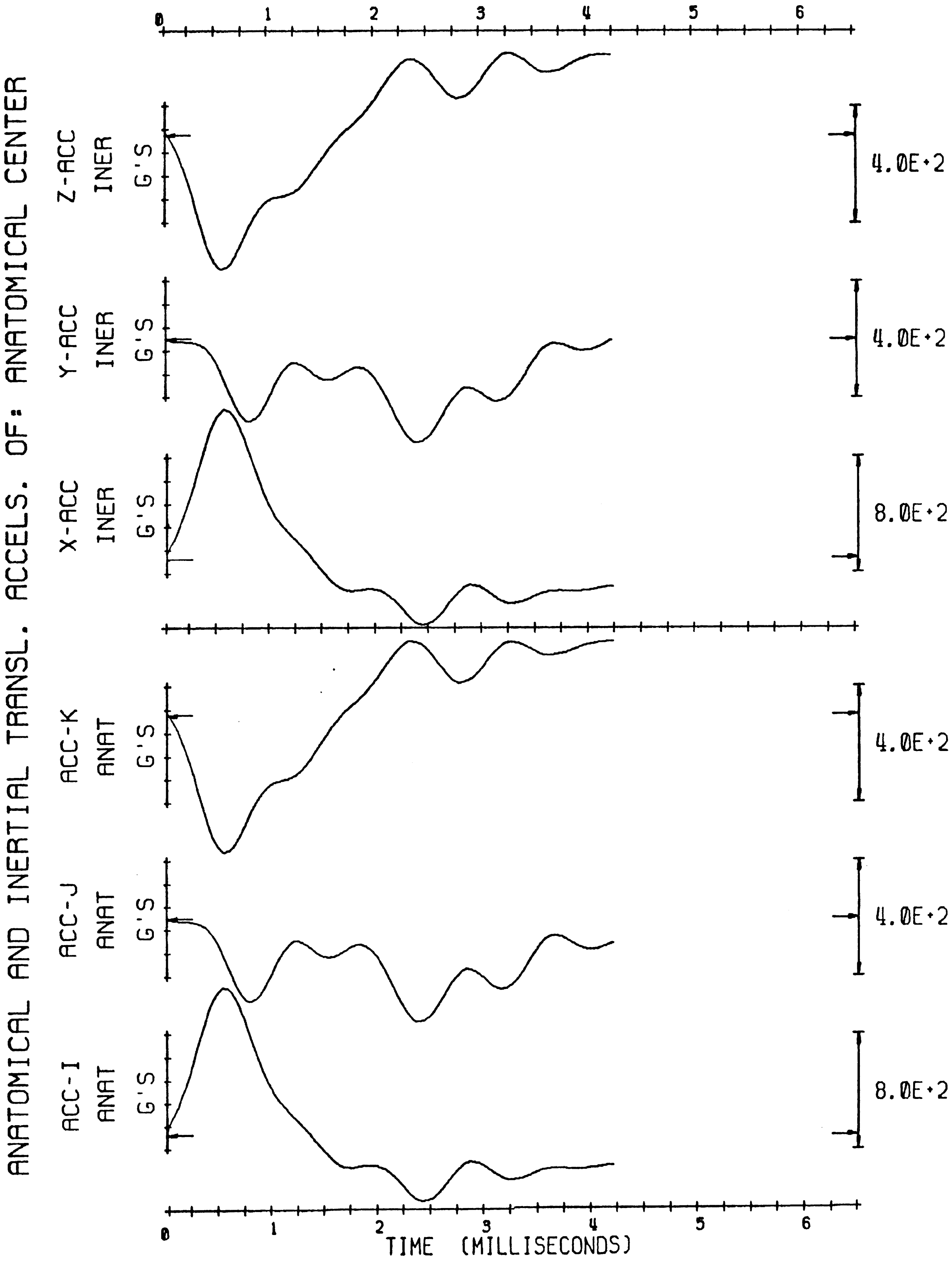
3-Ø12-RH
FORCE
LBS (X10¹)
0.00
40.00
80.00
120.00
160.00
200.00
TIME (MILLISECONDS)
0
1
2
3
4
5
6
7


3-Ø12-RH
FRONT ACCEL
G'S (X10¹)
TIME (MILLISECONDS)
-30.00
-10.00
10.00
30.00
50.00
70.00
Ø
1
2
3
4
5
6
7



3-D RIGID BODY MOTION ANALYSIS

3-Ø12-RH



3-D RIGID BODY MOTION ANALYSIS

HEAD IMPACT TEST SUMMARY

TEST NO. 013

TEST DATE 1/22/75

TEST SUBJECT

SPECIES Rhesus

Body Weight 11.66 lb.

Sitting Height (Top of Head to bottom of Buttocks) 20.50 in.

Head Weight 1.15 lbs

Brain Weight 0.193 lbs

Brain Volume 6.28 in^3

Skull Inside Length A 2.90 in

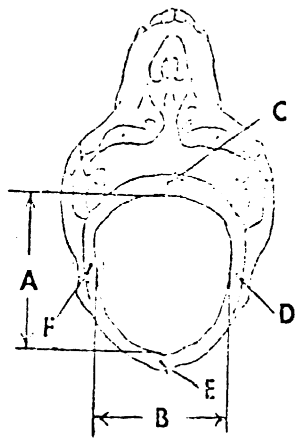
Skull Inside Width B 2.56 in

Skull Thickness at Pt. C 0.108 in

Skull Thickness at Pt. D 0.073 in

Skull Thickness at Pt. E 0.145 in

Skull Thickness at Pt. F 0.068 in



IMPACT CONDITIONS

Location of Impact Back of head

Type of Impact One and one quarter inches diameter, 0.25 inch wall thickness, round cap

Impact Velocity 24.40 ft/sec

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site ______________

Opposite to Impact Site ______________

Epidural Pressures in Direction of Impact:

At Impact Site ______________

Opposite to Impact Site ______________

Strain Gage Rosettes:

Right Parietal Gage ______________

Left Parietal Gage ______________

Frontal Gage ______________

Force: ______________

High Speed Motion Pictures:

Side Camera ______________

Frame Rate ______________

Type II

Accelerations in Direction of Impact:

At Impact Site No

Opposite to Impact Site Good

Rigid Body Head Motion Analysis: OK

EEG DATA: Pre-Impact Yes

Post Impact Yes

- NOT ANALYZED -

Force: Good

TEST NO. 013

High Speed Motion Pictures

Side Camera: Good

Framing Rate: 3000 fps

Front Camera: Good

Framing Rate: 1000 fps

INJURY:

Condition Prior to Impact: Slight muscle tone, slight eye reflex, and some shivering

		Time After Impact	Condition
Consciousness	1.	0 min	Dazed
	2.	1 min	Conscious
	3.		
	4.		
	5.		
	6.		
	7.		
	8.		
	9.		
	10.		

TEST NO. 013

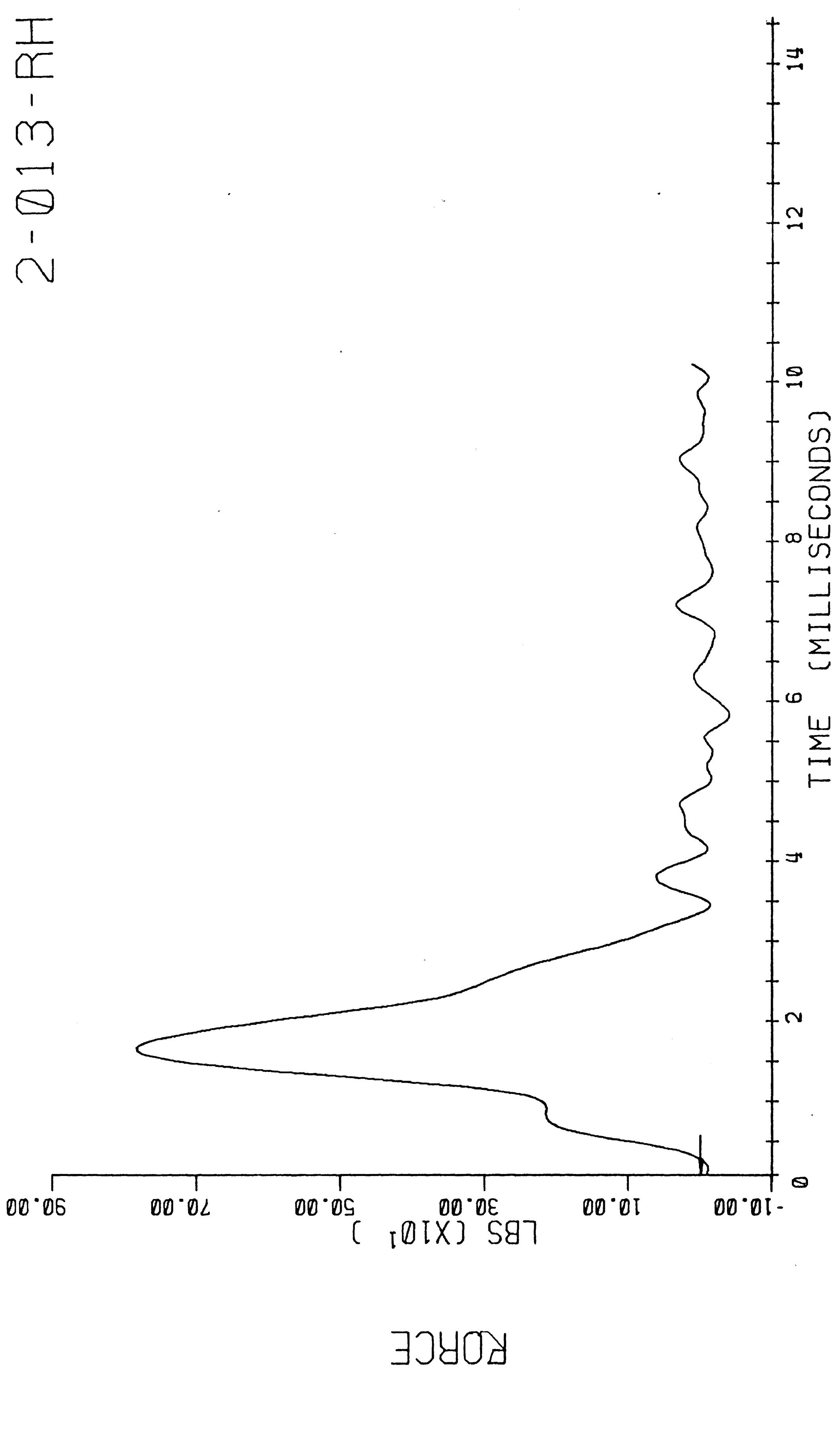
Autopsy Summary

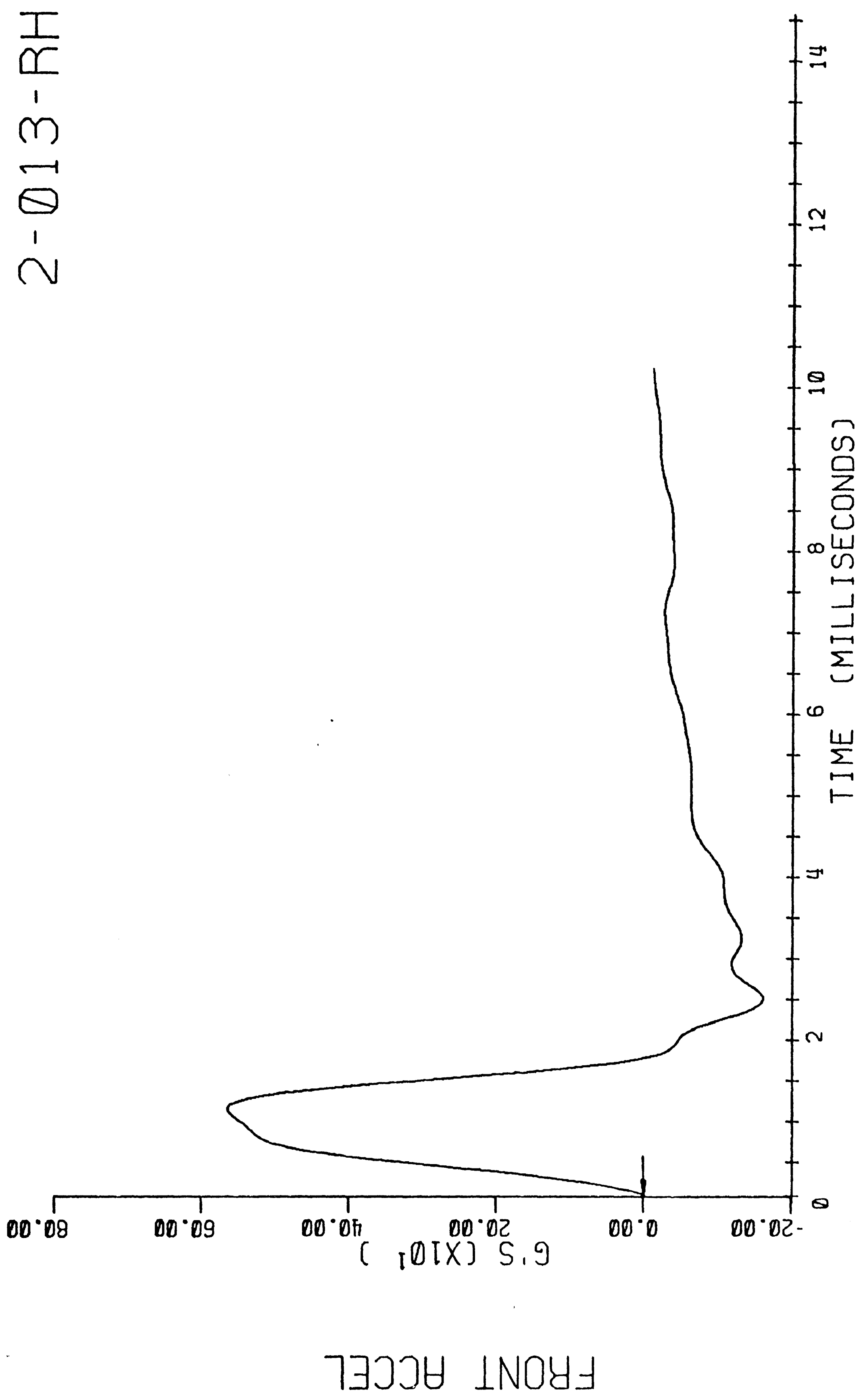
1. Congested brain around accelerometer mounts
2. Slight brain congestion
3. Dazed
4.
5.
6.
7.
8.
9.
10.
11.
12.
13.
14.
15.

Injuries Due to Impact only (not instrumentation)

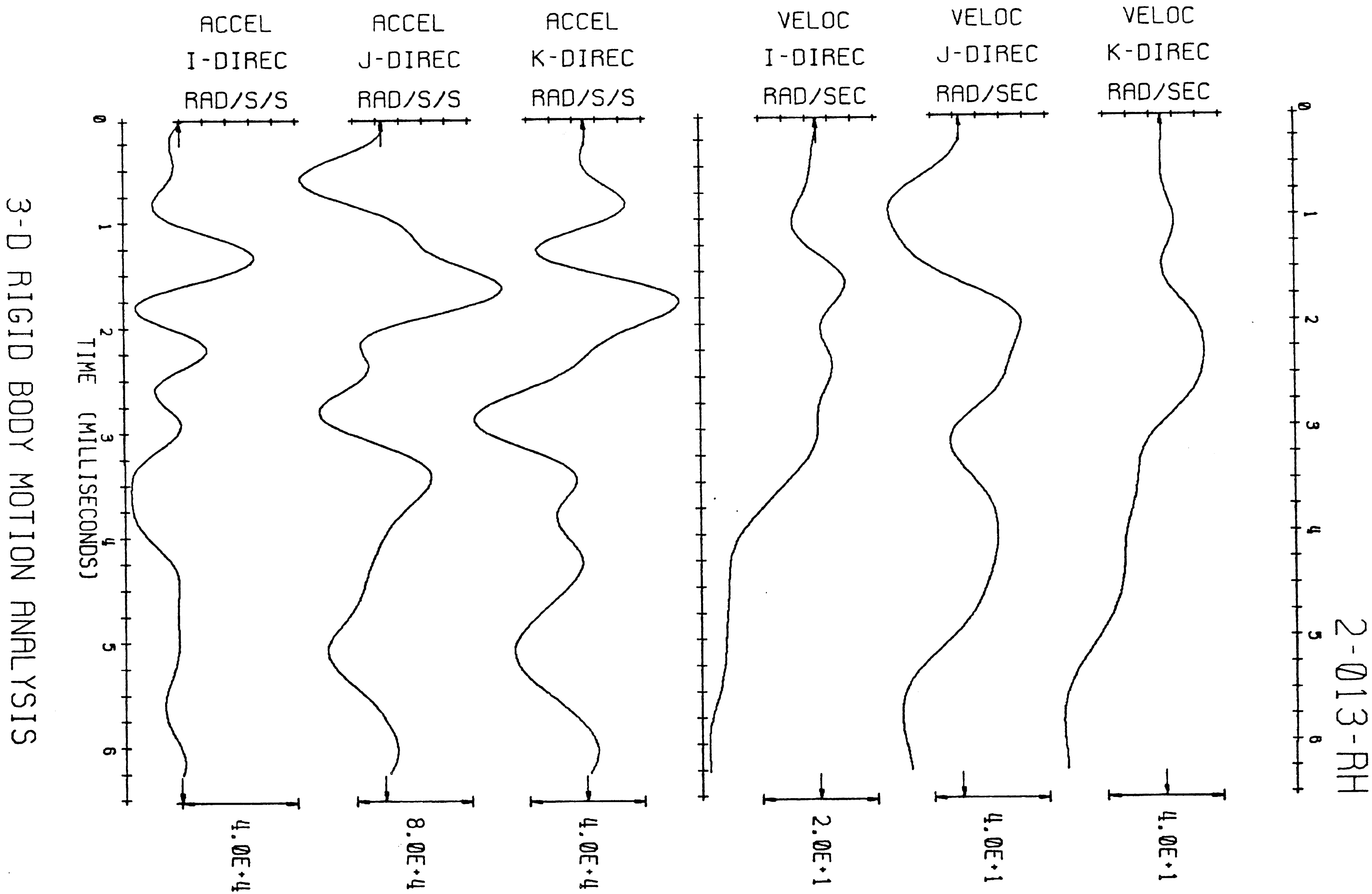
		AIS
1.	Slight brain congestion	1
2.	Dazed	1
3.		
4.		
5.		
6.		
7.		
8.		
9.		
10.		

AIS Overall 1

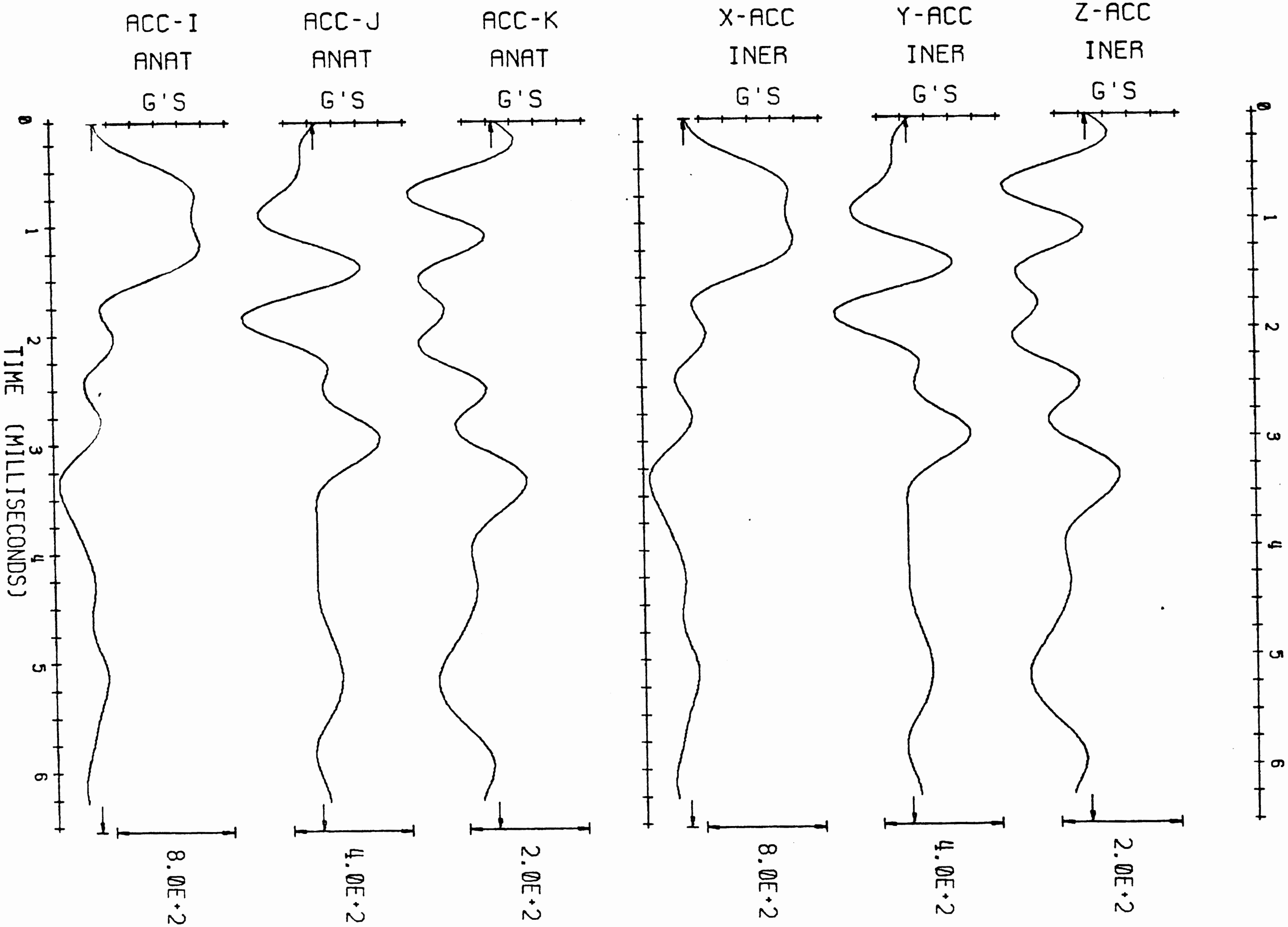

2-Ø13-RH
FORCE
LBS (X1Ø1)
-10.00
10.00
30.00
50.00
70.00
90.00
TIME (MILLISECONDS)
Ø
2
4
6
8
10
12
14


2-Ø13-RH
TIME (MILLISECONDS)
0
2
4
6
8
10
12
14
G'S (X10¹)
-20.00
0.00
20.00
40.00
60.00
80.00
FRONT ACCEL

ANGULAR ACCELERATIONS AND VELOCITIES --- ALONG ANATOMICAL AXES



ANATOMICAL AND INERTIAL TRANSL. ACCELS. OF: ANATOMICAL CENTER



2-013-RH

3-D RIGID BODY MOTION ANALYSIS

HEAD IMPACT TEST SUMMARY

TEST NO. 014 TEST DATE 1/22/75

TEST SUBJECT

SPECIES Rhesus

Body Weight 11.44 lb.

Sitting Height (Top of Head to bottom of Buttocks) 19.50 in.

Head Weight 1.13 lbs

Brain Weight 0.189 lbs

Brain Volume 6.15 in^3

Skull Inside Length A 2.91 in

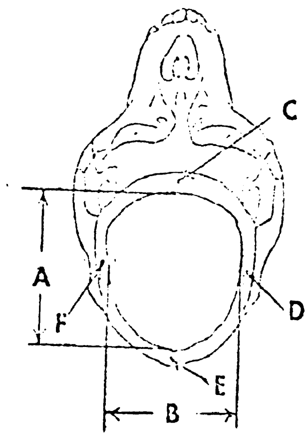
Skull Inside Width B 2.45 in

Skull Thickness at Pt. C 0.100 in

Skull Thickness at Pt. D 0.068 in

Skull Thickness at Pt. E 0.125 in

Skull Thickness at Pt. F 0.071 in



IMPACT CONDITIONS

Location of Impact Back of head

Type of Impact One and one quarter inches diameter 0.25 inch wall thickness, round cap

Impact Velocity 31.73 ft/sec

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site ______________

Opposite to Impact Site ______________

Epidural Pressures in Direction of Impact:

At Impact Site ______________

Opposite to Impact Site ______________

Strain Gage Rosettes:

Right Parietal Gage ______________

Left Parietal Gage ______________

Frontal Gage ______________

Force: ______________

High Speed Motion Pictures:

Side Camera ______________

Frame Rate ______________

Type II

Accelerations in Direction of Impact:

At Impact Site No

Opposite to Impact Site Knocked out by impact

Rigid Body Head Motion Analysis: Fair

EEG DATA: Pre-Impact Yes

Post Impact No (dead)

- NOT ANALYZED -

Force: Good

TEST NO. 014

High Speed Motion Pictures:

Side Camera: Good

Framing Rate: 3000 fps

Front Camera: Good

Framing Rate: 1000 fps

INJURY:

Condition Prior to Impact: Slight muscle tone, slight eye reflex, and some shivering

		Time After Impact	Condition
Consciousness	1.	0 min	dead
	2.		
	3.		
	4.		
	5.		
	6.		
	7.		
	8.		
	9.		
	10.		

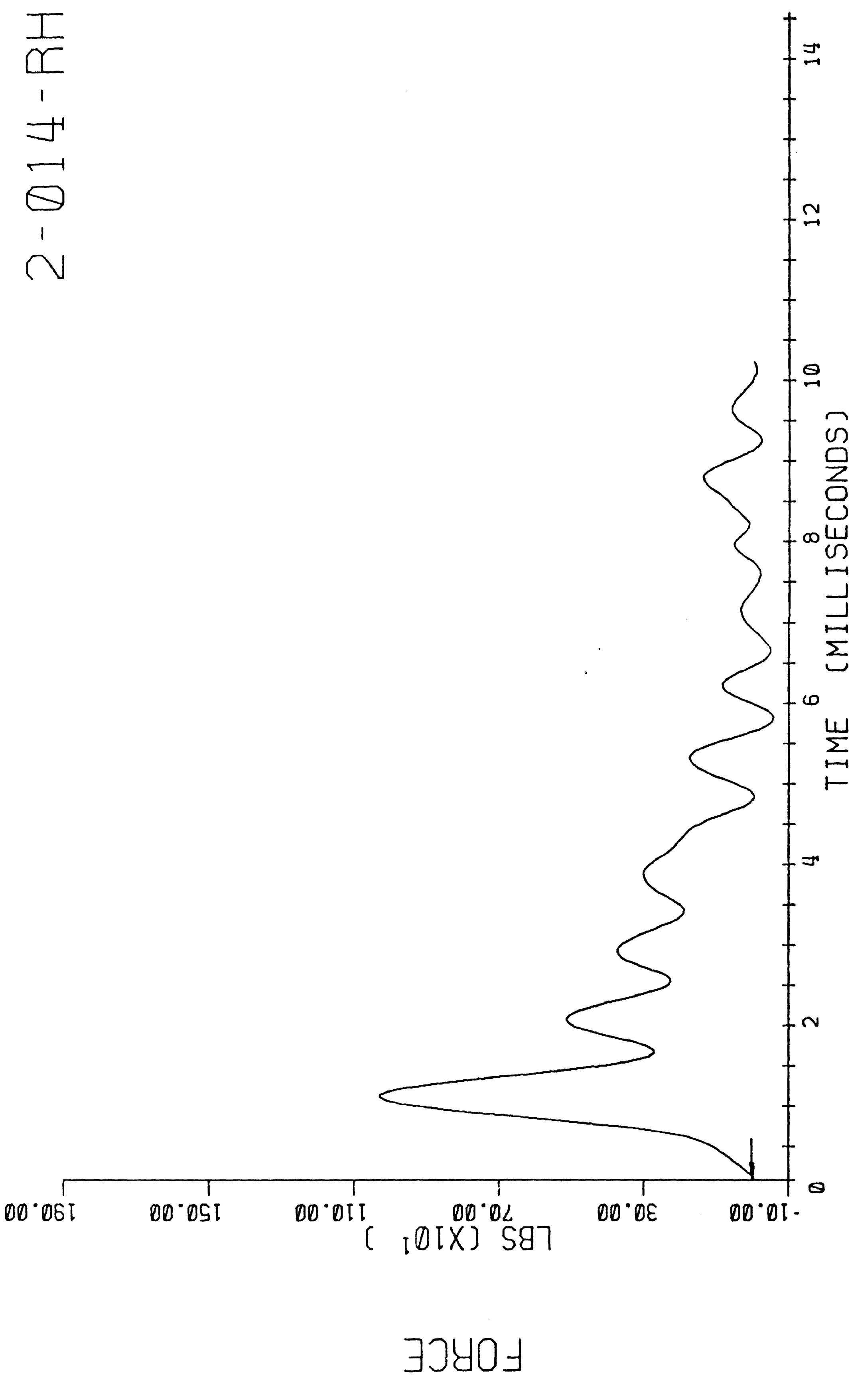
Autopsy Summary:

1. Hemorrhage and tear of neck musculature
2. Simple fracture of Rt. Temporal bone
3. Simple fracture of Lt. Temporal bone
4. Simple fracture of Rt. Parietal bone
5. Simple fracture of Lt. Parietal bone
6. Subdural hemorrhage Rt. side of brain
7. Five simple fractures of basilar bone
8. Dura tears
9. Hematoma and laceration of cerebellum
10. Hematoma and laceration of medula pons
11. Laceration of brain under accelerometer mounts
12.
13.
14.
15.

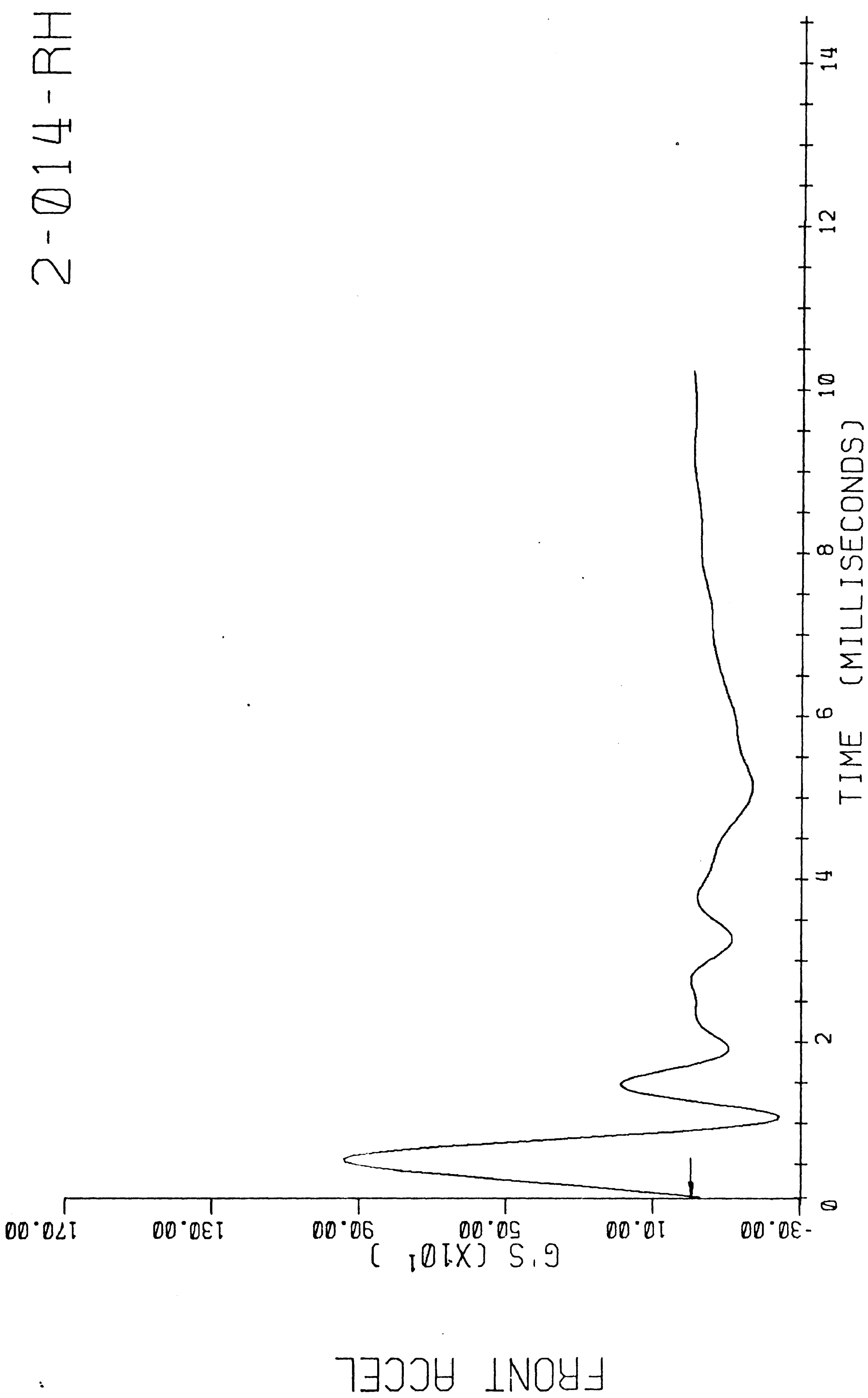
Injuries Due to Impact only (not instrumentation)

	Injury	AIS
1.	Hemorrhage and tear of neck musculature	3
2.	Simple fracture of Rt. Temporal bone	2
3.	Simple fracture of Lt. Temporal bone	2
4.	Simple fracture of Rt. Parietal bone	2
5.	Simple fracture of Lt. Parietal bone	2
6.	Subdural hemorrhage Rt. side of brain	4
7.	Five simple fractures of basilar bone	5
8.	Dura tears	3
9.	Hematoma and laceration of cerebellum	5
10.	Hematoma and laceration of medulla pons	5

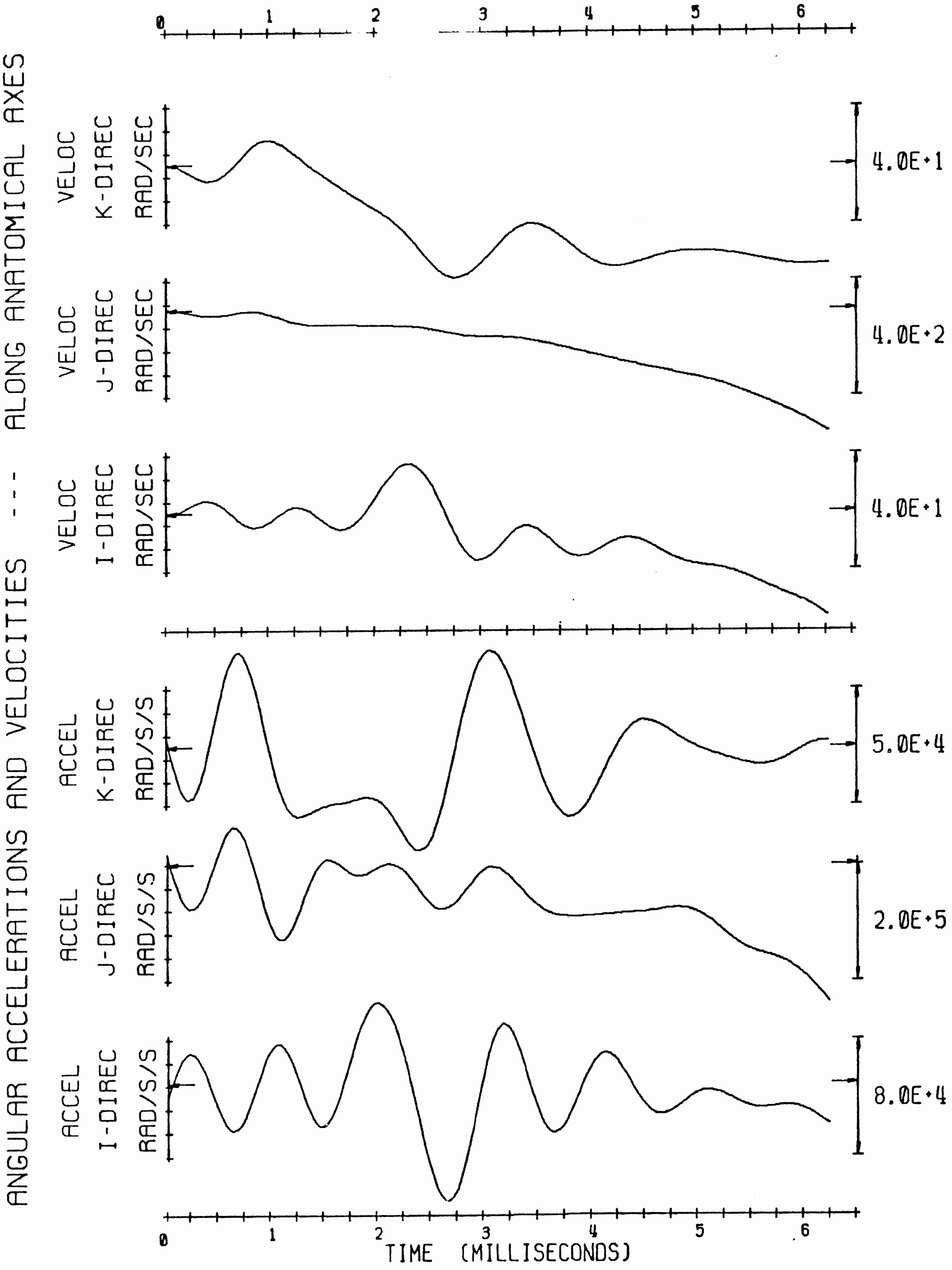
AIS Overall 6



2-014-RH
FORCE
LBS (X10[1])
-10.00
30.00
70.00
110.00
150.00
190.00
TIME (MILLISECONDS)
0
2
4
6
8
10
12
14

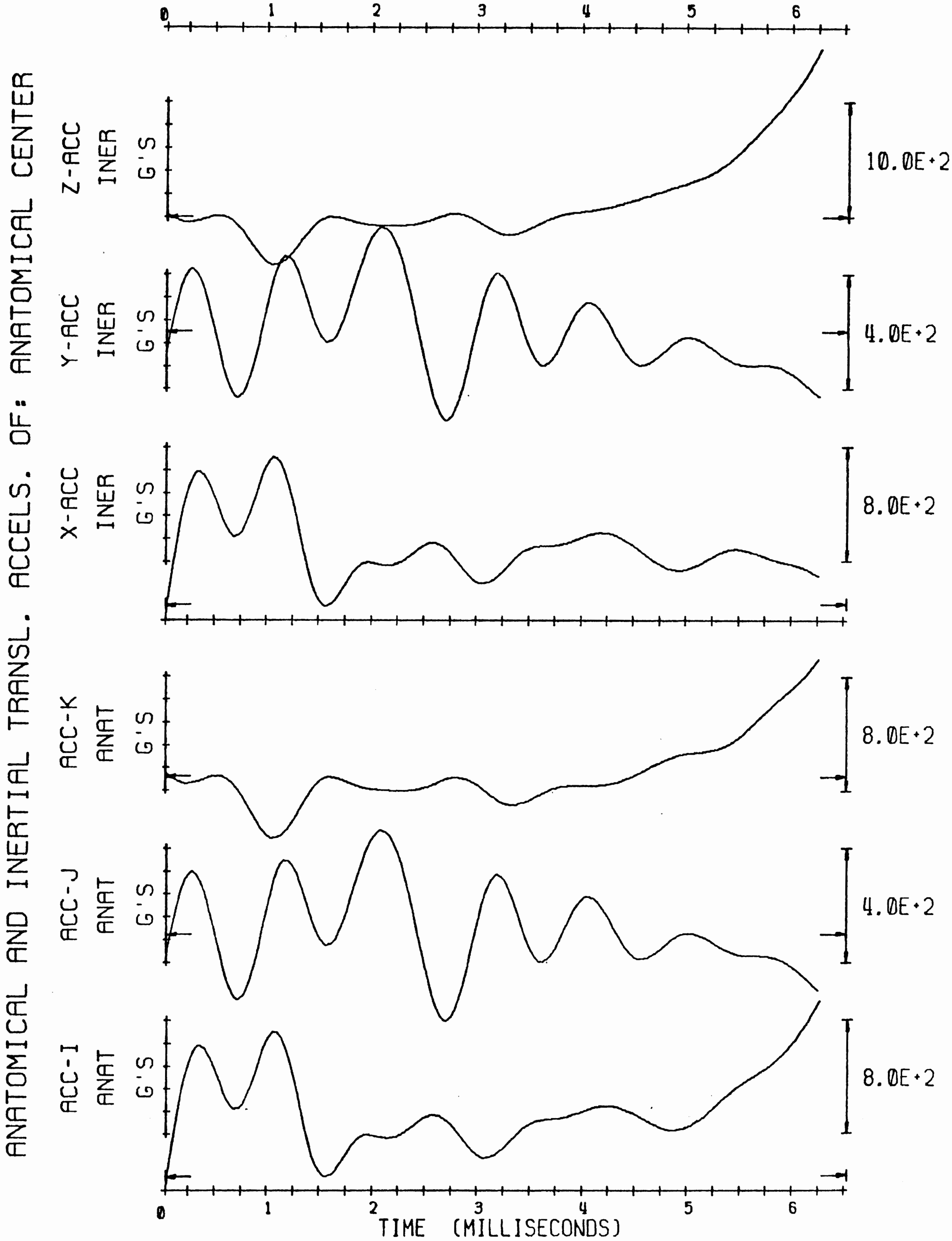

2-Ø14-RH
TIME (MILLISECONDS)
0
2
4
6
8
10
12
14
G'S (X10¹)
-30.00
10.00
50.00
90.00
130.00
170.00
FRONT ACCEL

2-014-RH



3-D RIGID BODY MOTION ANALYSIS

2-014-RH



3-D RIGID BODY MOTION ANALYSIS

HEAD IMPACT TEST SUMMARY

TEST NO. 015 TEST DATE 1/23/75

TEST SUBJECT

SPECIES Rhesus

Body Weight 12.10 lb.

Sitting Height (Top of Head to bottom of Buttocks) 20.5 in.

Head Weight 1.06 lbs

Brain Weight 0.195 lbs

Brain Volume 6.25 in^3

Skull Inside Length A 2.73 in

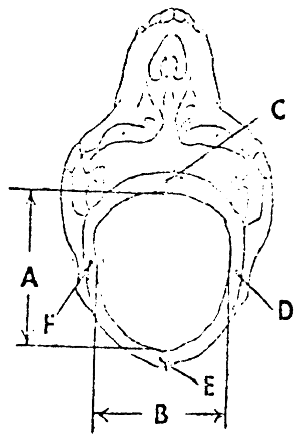
Skull Inside Width B 2.34 in

Skull Thickness at Pt. C 0.120 in

Skull Thickness at Pt. D 0.057 in

Skull Thickness at Pt. E 0.145 in

Skull Thickness at Pt. F 0.071 in



IMPACT CONDITIONS

Location of Impact Back of head

Type of Impact One and one quarter inches diameter, 0.25 inch wall thickness, round cap plus 2 inches of Insulite

Impact Velocity 30.21 ft/sec

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site __________

Opposite to Impact Site __________

Epidural Pressures in Direction of Impact:

At Impact Site __________

Opposite to Impact Site __________

Strain Gage Rosettes:

Right Parietal Gage __________

Left Parietal Gage __________

Frontal Gage __________

Force: __________

High Speed Motion Pictures:

Side Camera __________

Frame Rate __________

Type II

Accelerations in Direction of Impact:

At Impact Site No

Opposite to Impact Site Loose after impact

Rigid Body Head Motion Analysis: Analysis blew up after 6 msecs.

EEG DATA: Pre-Impact Yes

Post Impact Yes

- NOT ANALYZED -

Force: OK

TEST NO. 015

High Speed Motion Pictures:

Side Camera Good

Framing Rate 3000 fps

Front Camera Good

Framing Rate 1000 fps

INJURY:

Condition Prior to Impact Slight muscle tone, slight eye reflex, and some shivering

		Time After Impact	Condition
Consciousness	1.	0 min	Conscious (good)
	2.		
	3.		
	4.		
	5.		
	6.		
	7.		
	8.		
	9.		
	10.		

Autopsy Summary:

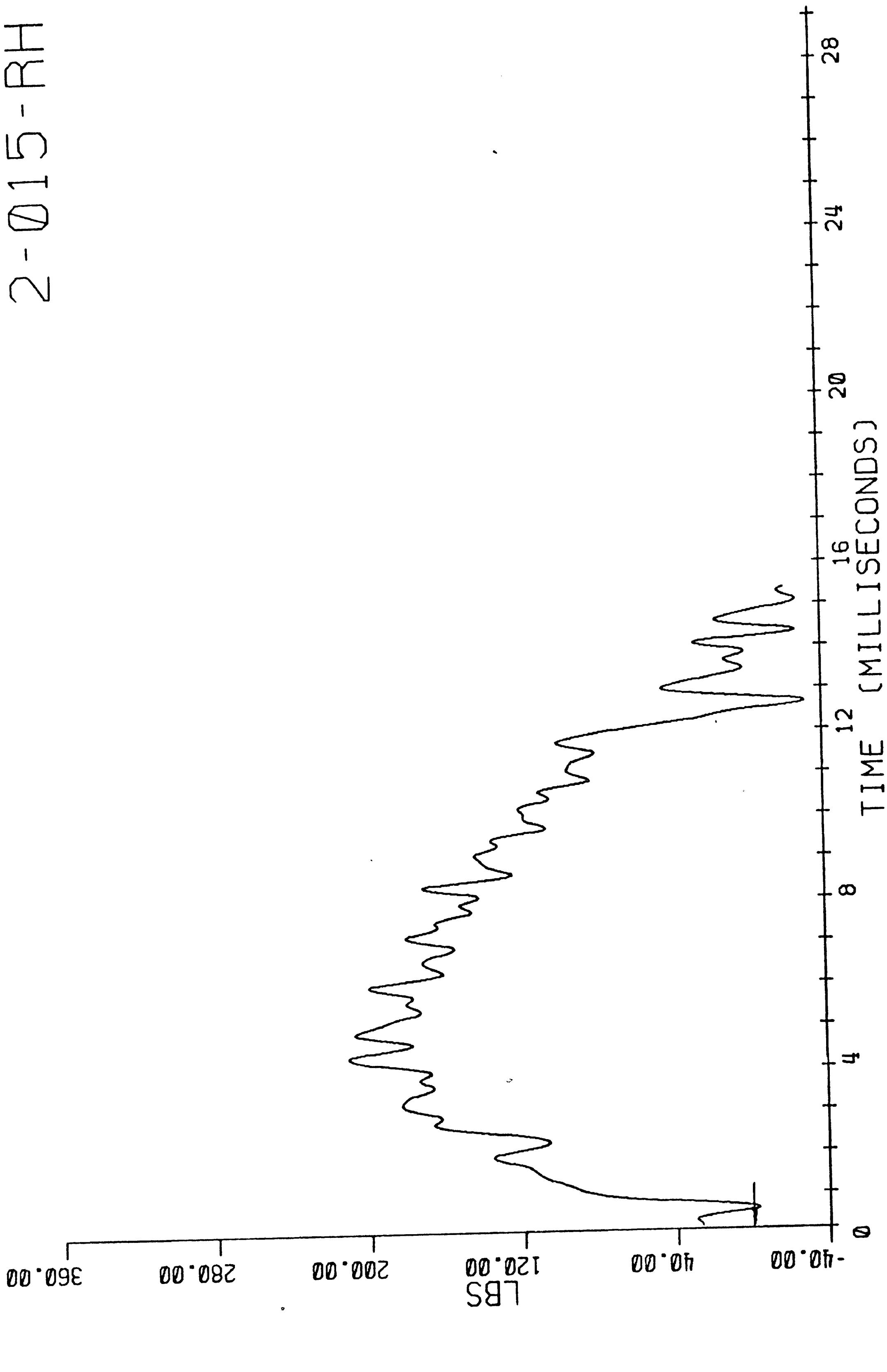
1. No injury
2.
3.
4.
5.
6.
7.
8.
9.
10.
11.
12.
13.
14.
15.

Injuries Due to Impact only (not instrumentation)

AIS

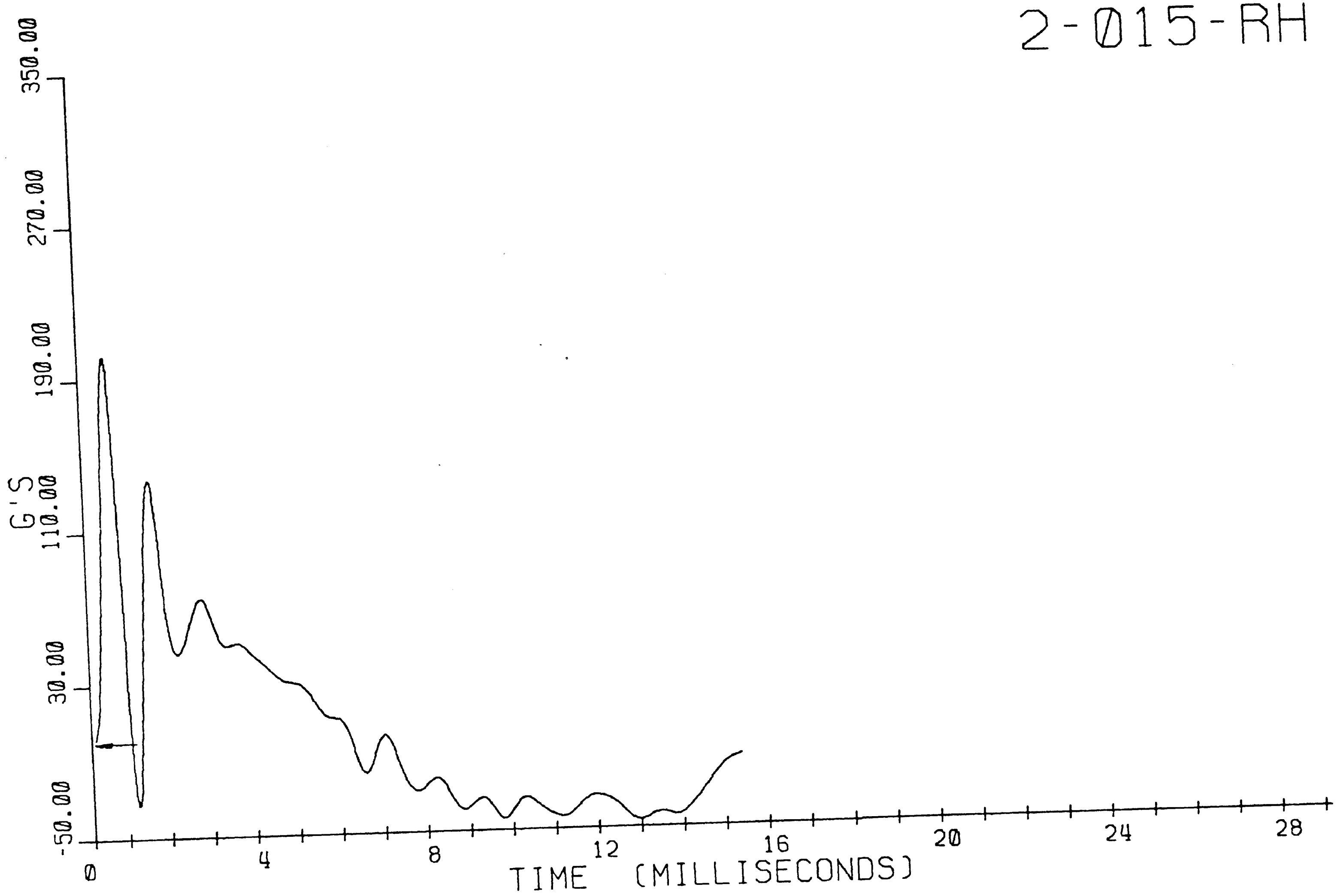
1.
2.
3.
4.
5.
6.
7.
8.
9.
10.

AIS Overall 0

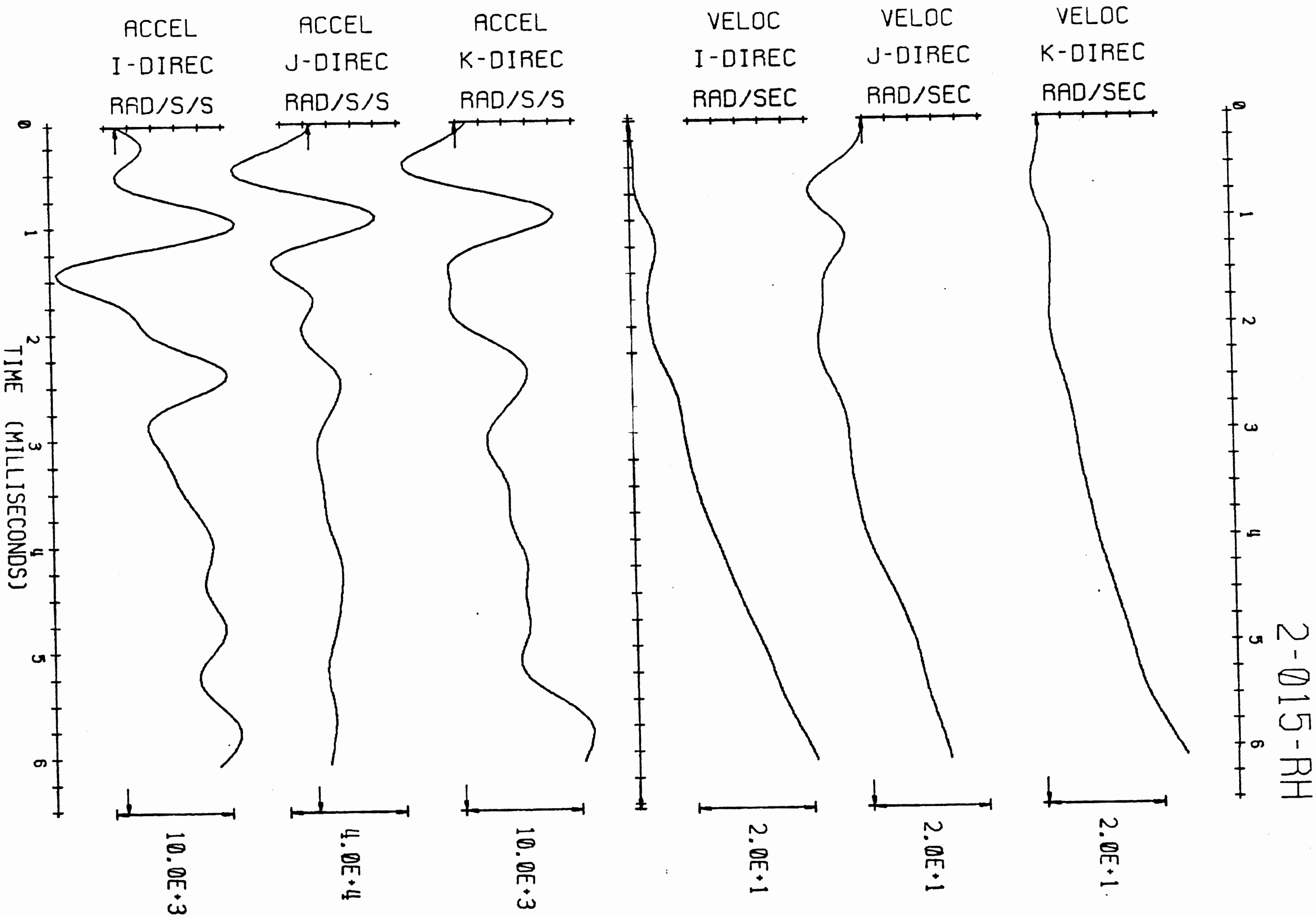

2-Ø15-RH
FORCE
LBS
-40.00
40.00
120.00
200.00
280.00
360.00
TIME (MILLISECONDS)
Ø
4
8
12
16
20
24
28

FRONT ACCEL

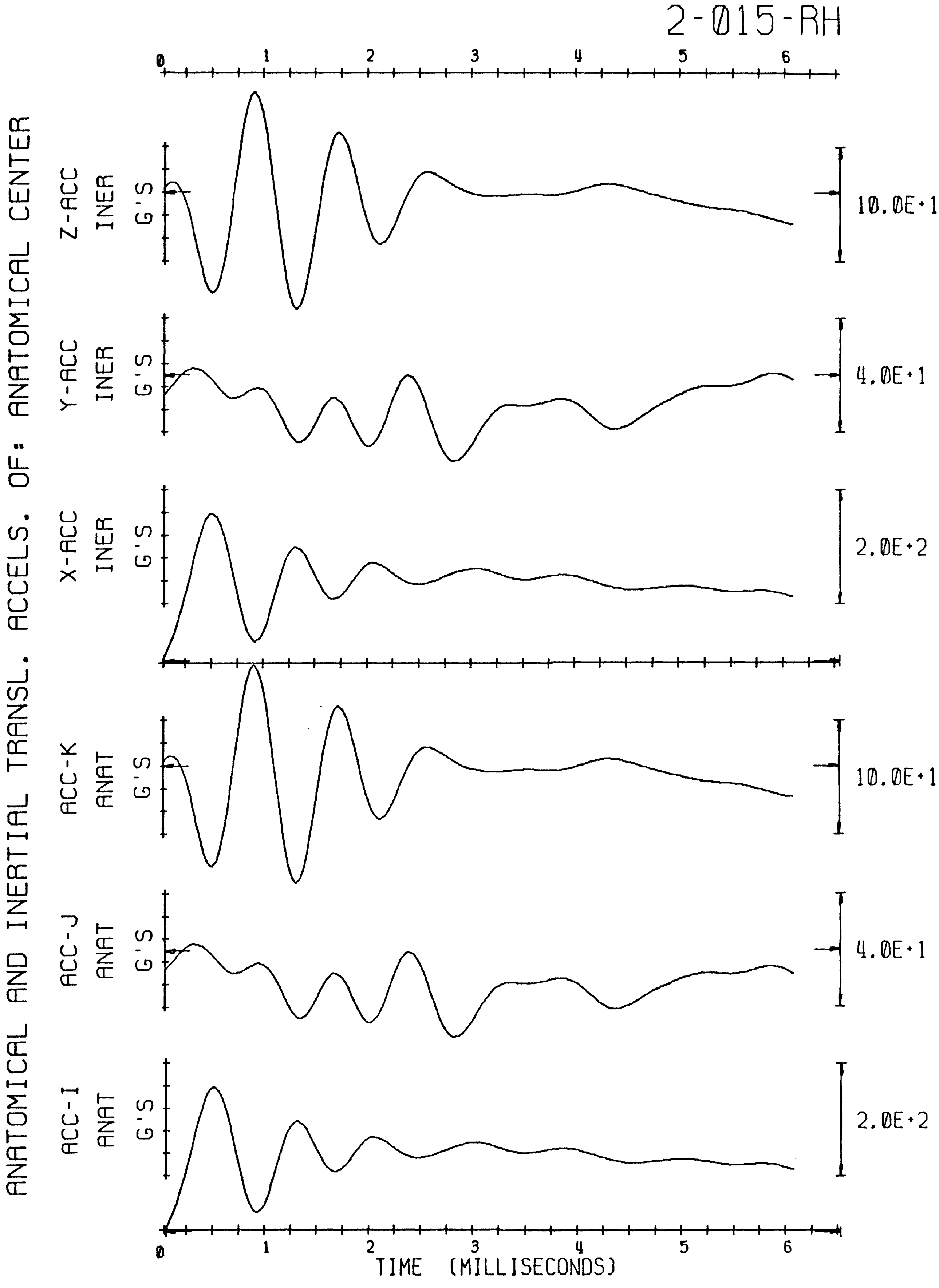
2-Ø15-RH



ANGULAR ACCELERATIONS AND VELOCITIES --- ALONG ANATOMICAL AXES



3-D RIGID BODY MOTION ANALYSIS



3-D RIGID BODY MOTION ANALYSIS

HEAD IMPACT TEST SUMMARY

TEST NO. 016 TEST DATE 1/28/75

TEST SUBJECT

SPECIES Baboon

Body Weight 24.42 lb.

Sitting Height (Top of Head to bottom of Buttocks) 23.0 in.

Head Weight 2.52 lbs

Brain Weight 0.330 lbs

Brain Volume 7.93 in^3

Skull Inside Length A 3.70 in

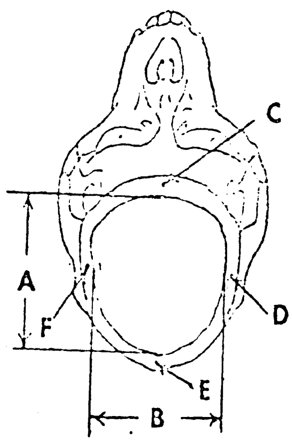
Skull Inside Width B 2.64 in

Skull Thickness at Pt. C 0.130 in

Skull Thickness at Pt. D 0.120 in

Skull Thickness at Pt. E 0.120 in

Skull Thickness at Pt. F 0.080 in



IMPACT CONDITIONS

Location of Impact Left Side of Head

Type of Impact Four inch diameter rigid impactor

Impact Velocity Lost ft/sec

TEST NO. 016

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site ______

Opposite to Impact Site ______

Epidural Pressures in Direction of Impact:

At Impact Site ______

Opposite to Impact Site ______

Strain Gage Rosettes:

Right Parietal Gage ______

Left Parietal Gage ______

Frontal Gage ______

Force: ______

High Speed Motion Pictures:

Side Camera ______

Frame Rate ______

Type II

Accelerations in Direction of Impact:

At Impact Site ----

Opposite to Impact Site Fair

Rigid Body Head Motion Analysis: Loss of data

EEG DATA: Pre-Impact Yes

Post Impact Yes

- NOT ANALYZED -

Force: Good

TEST NO. 016

High Speed Motion Pictures:

Side Camera: Good

Framing Rate: 3000 fps

Front Camera: Good

Framing Rate: 1000 fps

INJURY:

Condition Prior to Impact: Slight muscle tone, slight eye reflex and some shivering

		Time After Impact	Condition
Consciousness	1.	0 min.	Dazed
	2.	2 min.	Conscious
	3.		
	4.		
	5.		
	6.		
	7.		
	8.		
	9.		
	10.		

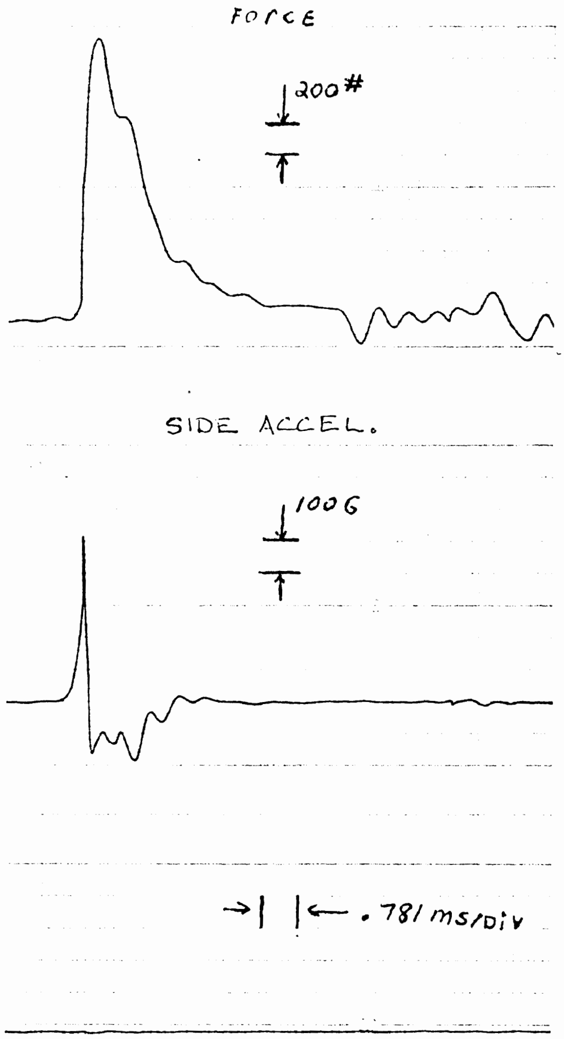
Autopsy Summary:

1. Epidural hemorrhage due to accelerometer mounts
2. Subdural hemorrhage due to accelerometer mounts
3. Daxed for 2 min.
4.
5.
6.
7.
8.
9.
10.
11.
12.
13.
14.
15.

Injuries Due to Impact only (not instrumentation)

	AIS
1. Dazed for 2 min.	1
2.	
3.	
4.	
5.	
6.	
7.	
8.	
9.	
10.	

AIS Overall 1



FORCE
200#
SIDE ACCEL.
100G
.781 ms/DIV

HEAD IMPACT TEST SUMMARY

TEST NO. 017 TEST DATE 1/28/75

TEST SUBJECT

SPECIES Baboon

Body Weight 30.36 lb.

Sitting Height (Top of Head to bottom of Buttocks) 24.50 in.

Head Weight 5.61 lbs

Brain Weight 0.329 lbs

Brain Volume 7.63 in^3

Skull Inside Length A 3.73 in

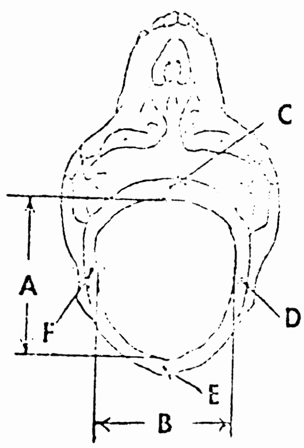
Skull Inside Width B 2.67 in

Skull Thickness at Pt. C 0.133 in

Skull Thickness at Pt. D 0.121 in

Skull Thickness at Pt. E 0.130 in

Skull Thickness at Pt. F 0.90 in



IMPACT CONDITIONS

Location of Impact Left side of head

Type of Impact Four inch diameter rigid impactor

Impact Velocity 36.42 ft/sec

TEST NO. 017

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site ______

Opposite to Impact Site ______

Epidural Pressures in Direction of Impact:

At Impact Site ______

Opposite to Impact Site ______

Strain Gage Rosettes:

Right Parietal Gage ______

Left Parietal Gage ______

Frontal Gage ______

Force: ______

High Speed Motion Pictures:

Side Camera ______

Frame Rate ______

Type II

Accelerations in Direction of Impact:

At Impact Site No

Opposite to Impact Site No

Rigid Body Head Motion Analysis: Good

EEG DATA: Pre-Impact No

Post Impact No

- NOT ANALYZED -

Force: Good

TEST NO. 017

High Speed Motion Pictures:

Side Camera Good

Framing Rate 3000 fps

Front Camera Good

Framing Rate 1000 fps

INJURY:

Condition Prior to Impact Dead about 10 min before impact

		Time After Impact	Condition
Consciousness	1.	----	----
	2.		
	3.		
	4.		
	5.		
	6.		
	7.		
	8.		
	9.		
	10.		

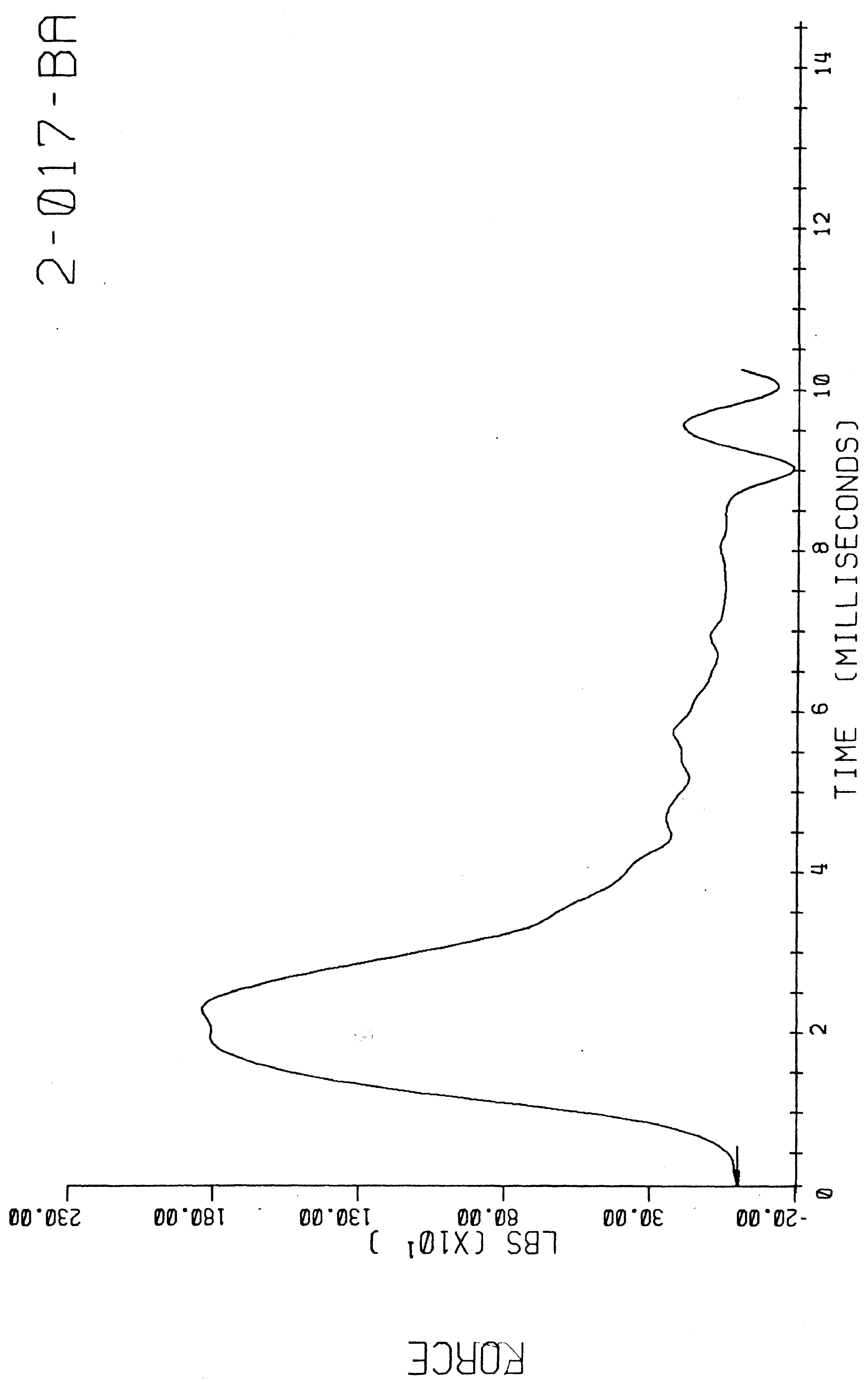
Autopsy Summary:

1. Hemorrhaging in Lt. Temporalis muscle
2. Fractured zygomatic arch - 3 places
3. Highly localized contre-coup injury
4.
5.
6.
7.
8.
9.
10.
11.
12.
13.
14.
15.

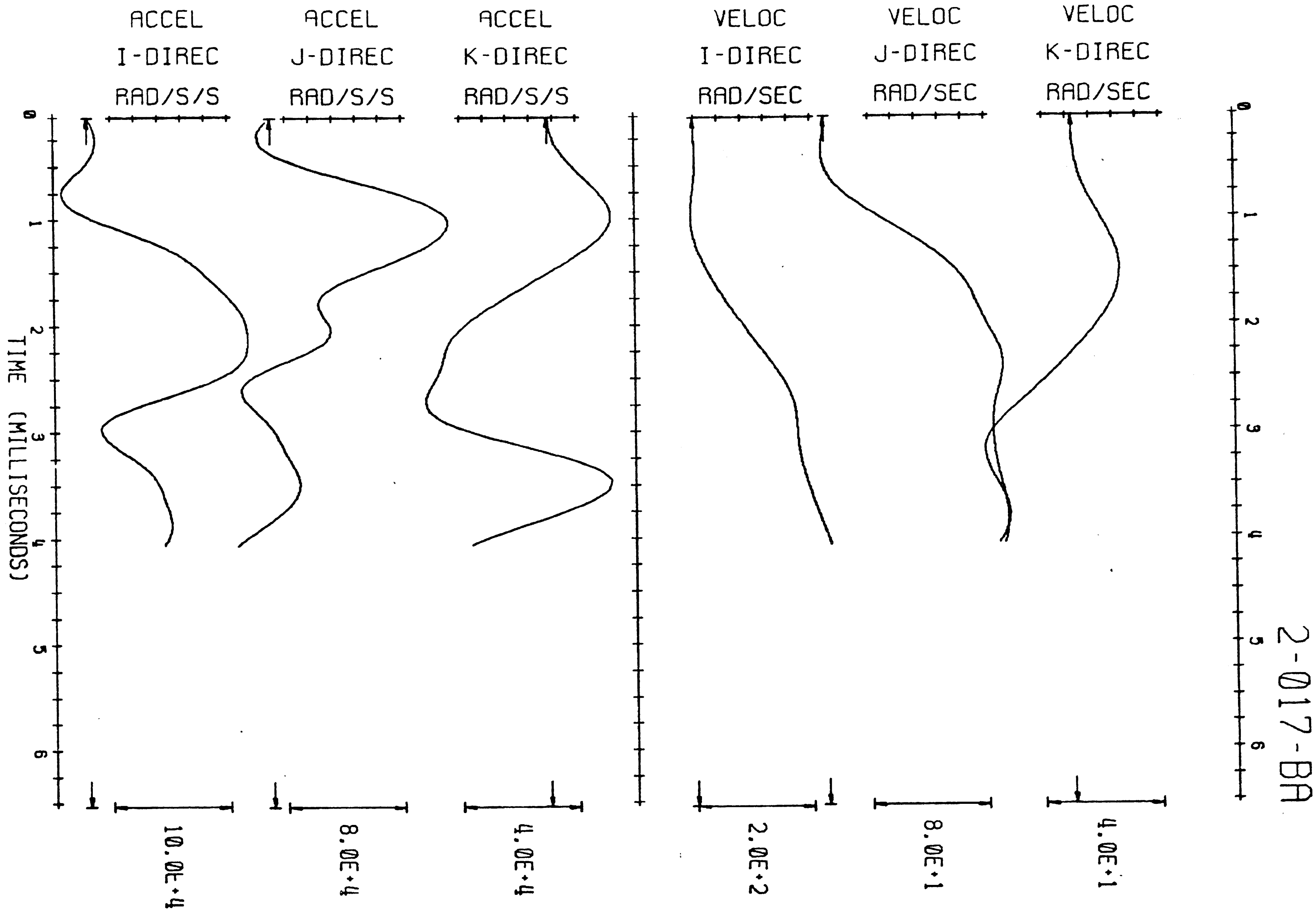
Injuries Due to Impact only (not instrumentation)

		AIS
1.	Hemorrhaging in Lt. Temporalis muscle	2
2.	Fractured zygomatic arch - 3 places	3
3.	Highly localized contre-coup injury	3
4.		
5.		
6.		
7.		
8.		
9.		
10.		

AIS Overall 3

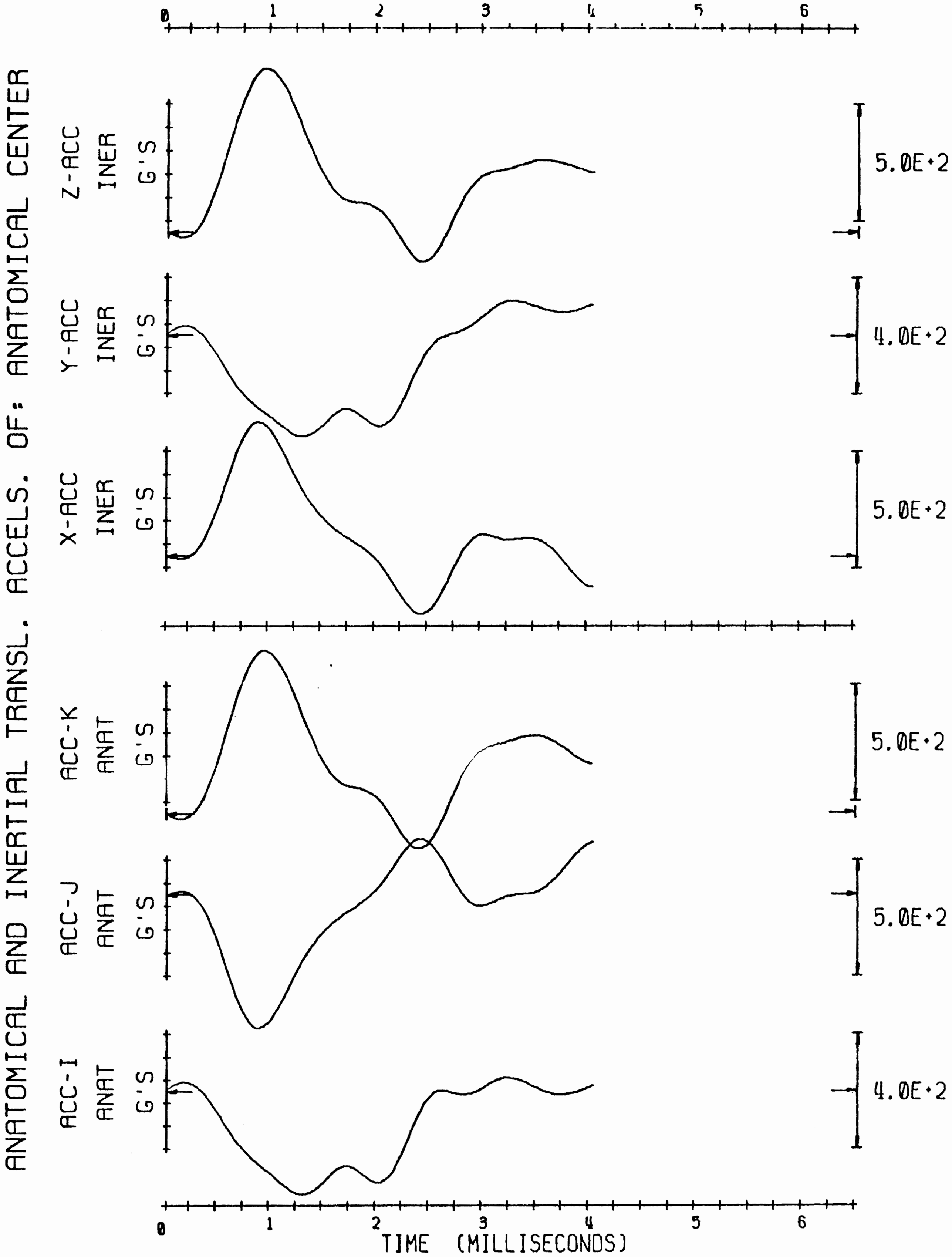

2-Ø17-BA
TIME (MILLISECONDS)
Ø
2
4
6
8
10
12
14
LBS (X1Ø1)
-20.00
30.00
80.00
130.00
180.00
230.00
FORCE

ANGULAR ACCELERATIONS AND VELOCITIES --- ALONG ANATOMICAL AXES



3-D RIGID BODY MOTION ANALYSIS

2-Ø17-BA



3-D RIGID BODY MOTION ANALYSIS

HEAD IMPACT TEST SUMMARY

TEST NO. 018 TEST DATE 1/29/75

TEST SUBJECT

SPECIES Cynomolgus

Body Weight 5.58 lb.

Sitting Height (Top of Head to bottom of Buttocks) 14.5 in.

Head Weight 0.59 lbs

Brain Weight 0.13 lbs

Brain Volume 2.89 in^3

Skull Inside Length A 2.45 in

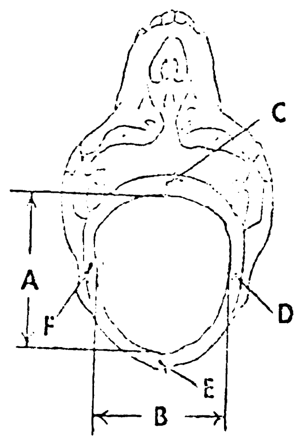
Skull Inside Width B 1.90 in

Skull Thickness at Pt. C 0.070 in

Skull Thickness at Pt. D 0.06 in

Skull Thickness at Pt. E 0.09 in

Skull Thickness at Pt. F 0.04 in



IMPACT CONDITIONS

Location of Impact Back of head

Type of Impact One and one quarter inches diameter 0.25 inch wall thickness, round cap

Impact Velocity 22.46 ft/sec

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site __________

Opposite to Impact Site __________

Epidural Pressures in Direction of Impact:

At Impact Site __________

Opposite to Impact Site __________

Strain Gage Rosettes:

Right Parietal Gage __________

Left Parietal Gage __________

Frontal Gage __________

Force: __________

High Speed Motion Pictures:

Side Camera __________

Frame Rate __________

Type II

Accelerations in Direction of Impact:

At Impact Site No

Opposite to Impact Site No

Rigid Body Head Motion Analysis: Good

EEG DATA: Pre-Impact Yes

Post Impact Yes

\- NOT ANALYZED -

Force: Good; at 9 msec cable noise

TEST NO. 018

High Speed Motion Pictures:

Side Camera: Good

Framing Rate: 3000 fps

Front Camera: Good

Framing Rate: 1000 fps

INJURY:

Condition Prior to Impact: Slight muscle tone, slight eye reflex, and some shivering

		Time After Impact	Condition
Consciousness	1.	0 min.	Unconscious
	2.	2 hrs.	Unconscious
	3.		
	4.		
	5.		
	6.		
	7.		
	8.		
	9.		
	10.		

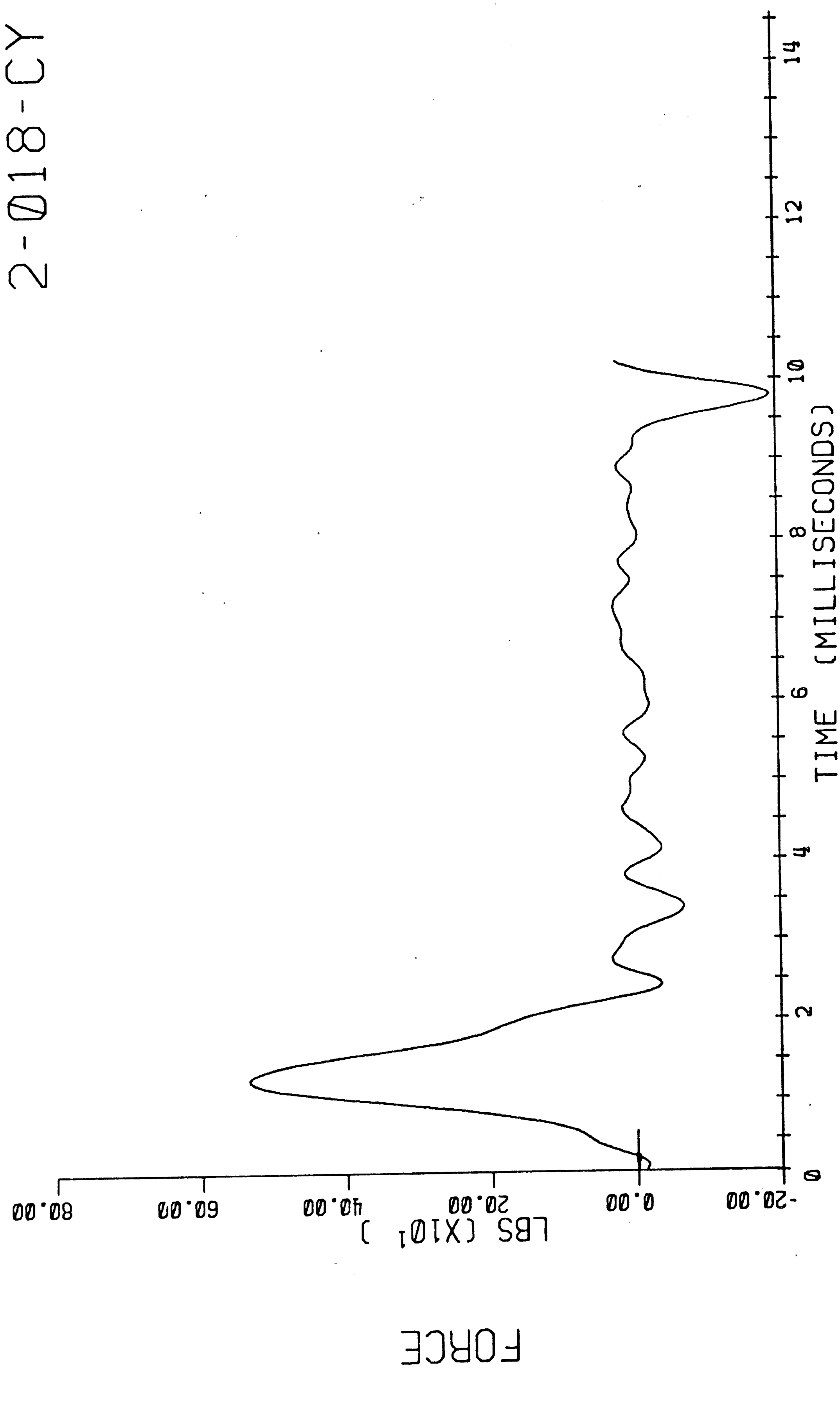
Autopsy Summary:

1. Epidural hemorrhage due to accelerometer mounts
2. Subdural hemorrhage due to accelerometer mounts
3. Unconscious with severe neurological signs > 15 min.
4.
5.
6.
7.
8.
9.
10.
11.
12.
13.
14.
15.

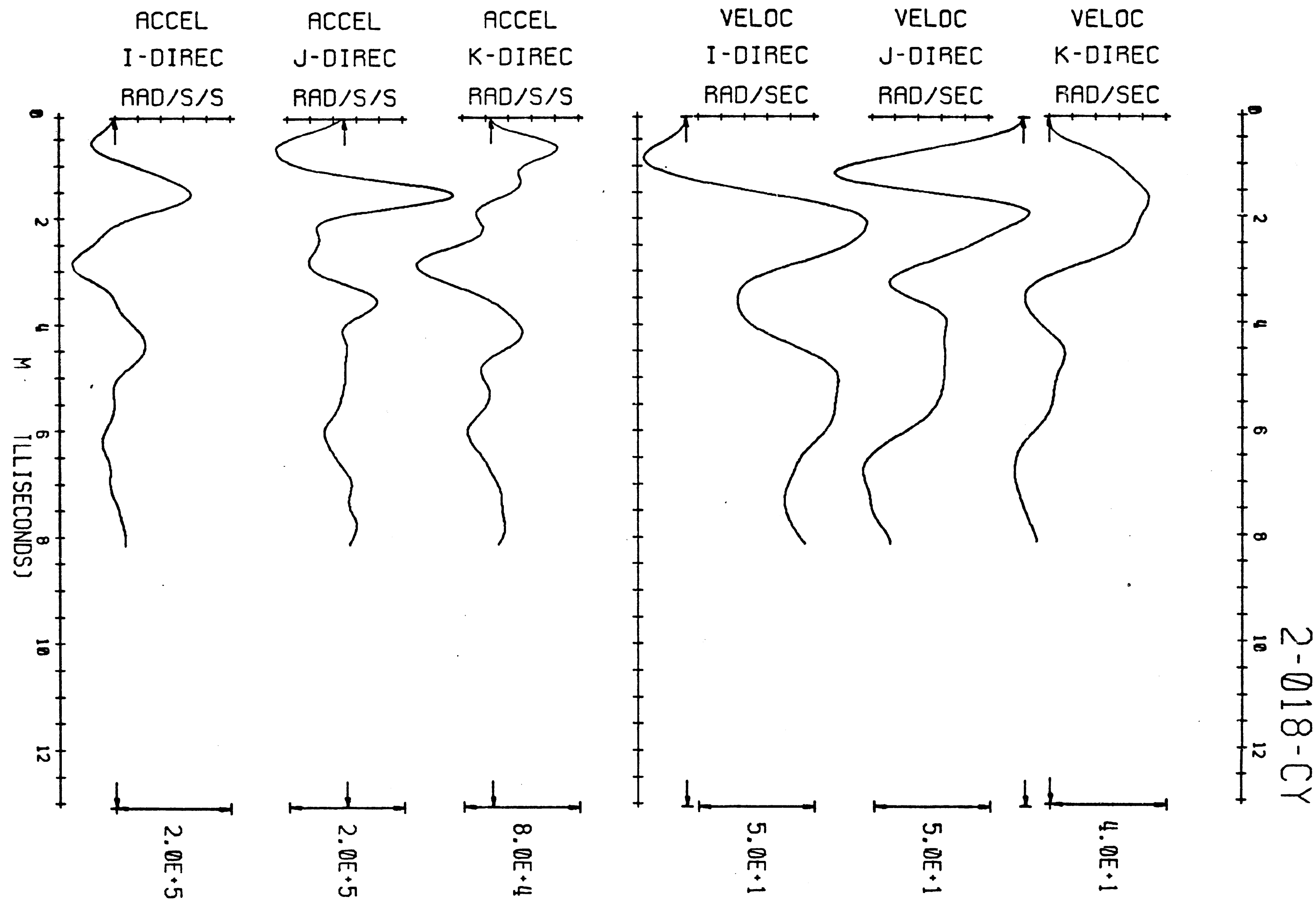
Injuries Due to Impact only (not instrumentation)

		AIS
1.	Unconscious with severe neurological signs > 15 min.	3
2.		
3.		
4.		
5.		
6.		
7.		
8.		
9.		
10.		

AIS Overall 3

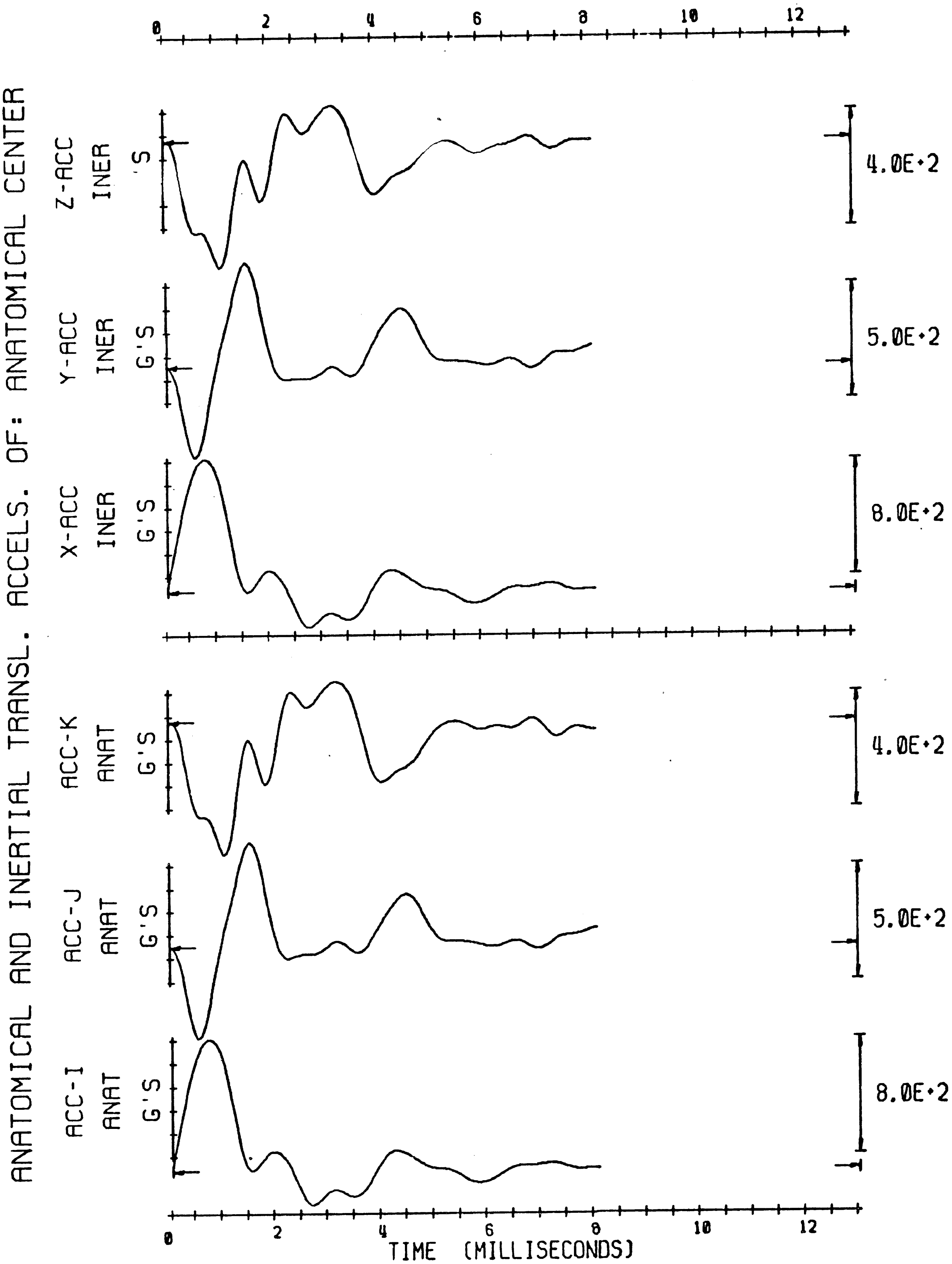

2-Ø18-CY
FORCE
LBS (X10¹)
-20.00
0.00
20.00
40.00
60.00
80.00
TIME (MILLISECONDS)
0
2
4
6
8
10
12
14

ANGULAR ACCELERATIONS AND VELOCITIES --- ALONG ANATOMICAL AXES



3-D RIGID BODY MOTION ANALYSIS

2-018-CY



3-D RIGID BODY MOTION ANALYSIS

HEAD IMPACT TEST SUMMARY

TEST NO. 019

TEST DATE 1/29/75

TEST SUBJECT

SPECIES Cynomolgus

Body Weight 6.05 lb.

Sitting Height (Top of Head to bottom of Buttocks) 14.5 in.

Head Weight 0.61 lbs

Brain Weight 0.14 lbs

Brain Volume 2.98 in^3

Skull Inside Length A 2.60 in

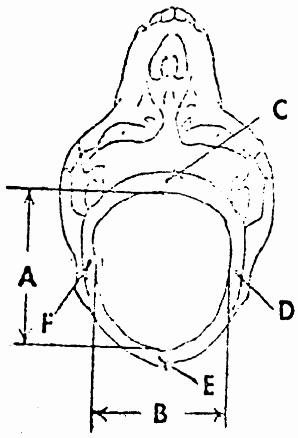
Skull Inside Width B 1.85 in

Skull Thickness at Pt. C 0.070 in

Skull Thickness at Pt. D 0.050 in

Skull Thickness at Pt. E 0.070 in

Skull Thickness at Pt. F 0.050 in



IMPACT CONDITIONS

Location of Impact Back of head

Type of Impact One and one quarter inches diameter 0.25 inch wall thickness, round cap

Impact Velocity ~ 20.00 ft/sec

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site ______________

Opposite to Impact Site ______________

Epidural Pressures in Direction of Impact:

At Impact Site ______________

Opposite to Impact Site ______________

Strain Gage Rosettes:

Right Parietal Gage ______________

Left Parietal Gage ______________

Frontal Gage ______________

Force: ______________

High Speed Motion Pictures:

Side Camera ______________

Frame Rate ______________

Type II

Accelerations in Direction of Impact:

At Impact Site No

Opposite to Impact Site No

Rigid Body Head Motion Analysis: Fair

EEG DATA: Pre-Impact Yes

Post Impact Yes

- NOT ANALYZED -

Force: Good

TEST NO. 019

High Speed Motion Pictures

Side Camera Good

Framing Rate 3000 fps

Front Camera Good

Framing Rate 1000 fps

INJURY:

Condition Prior to Impact Slight muscle tone, slight eye reflex, and some shivering

		Time After Impact	Condition
Consciousness	1.	0 min	Conscious
	2.		
	3.		
	4.		
	5.		
	6.		
	7.		
	8.		
	9.		
	10.		

Autopsy Summary:

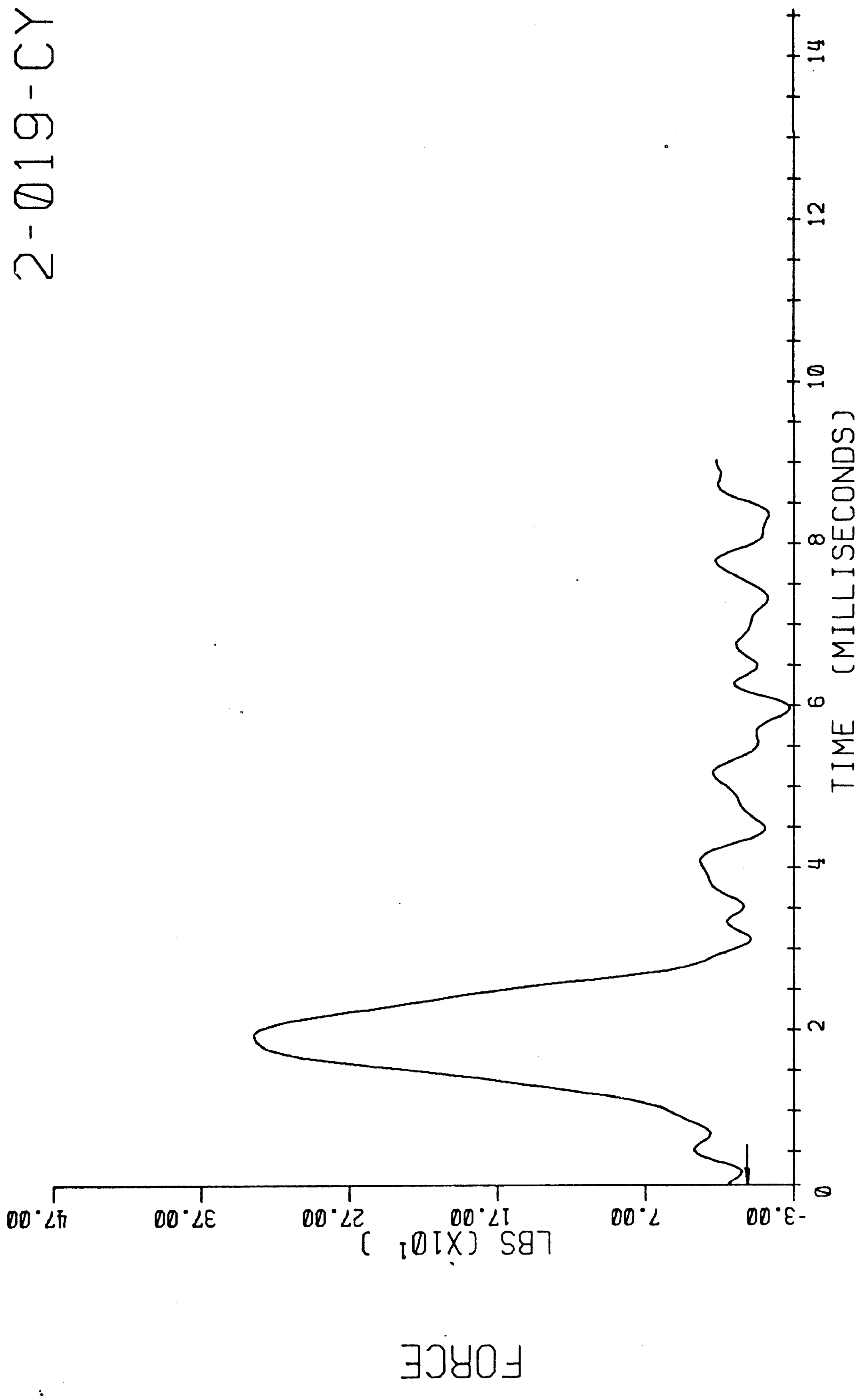
1. Epidural hemorrhaging due to transducers
2. Some decoloration around the ventricles; could be due to embalming
3.
4.
5.
6.
7.
8.
9.
10.
11.
12.
13.
14.
15.

Injuries Due to Impact only (not instrumentation)

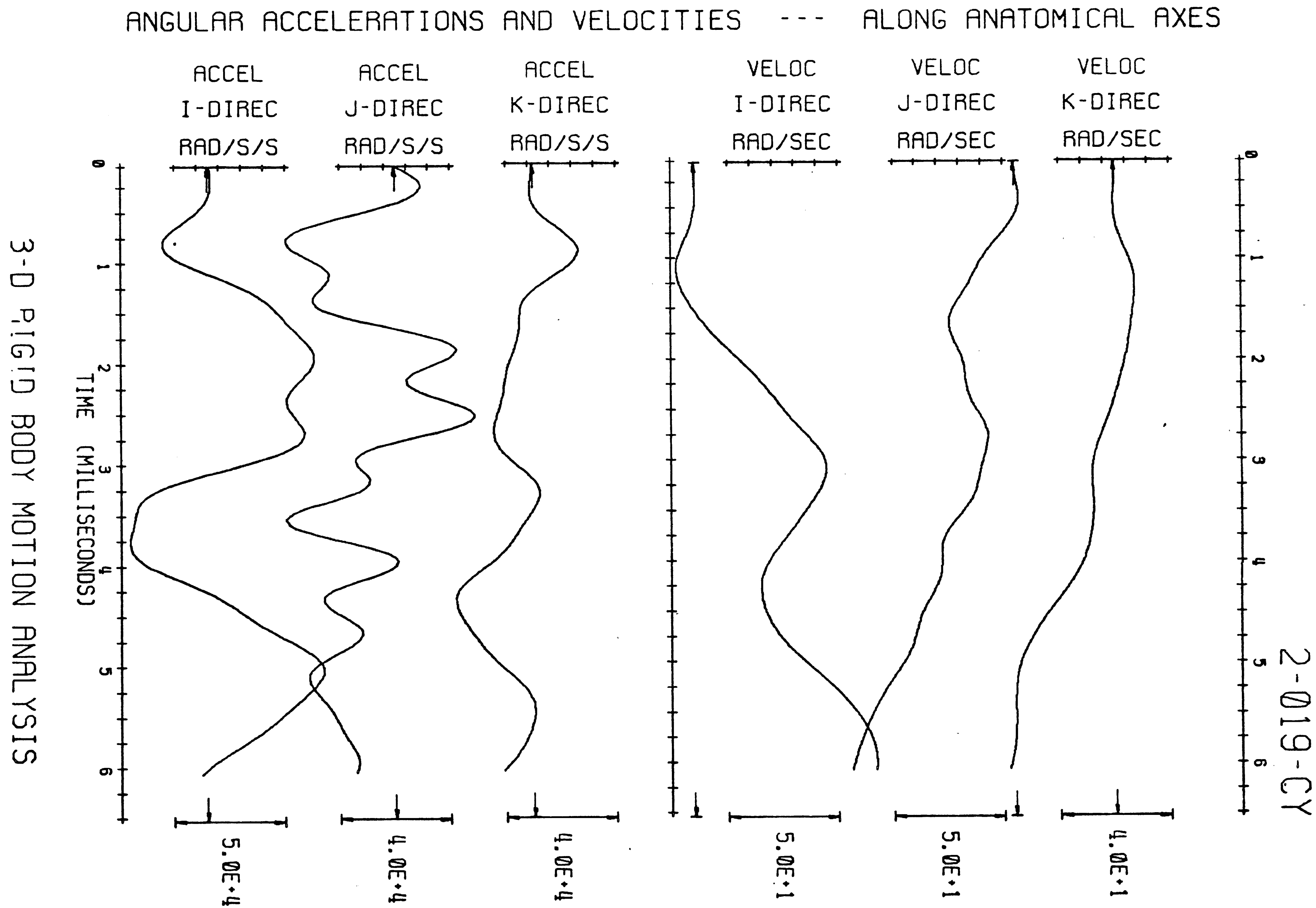
AIS

1.
2.
3.
4.
5.
6.
7.
8.
9.
10.

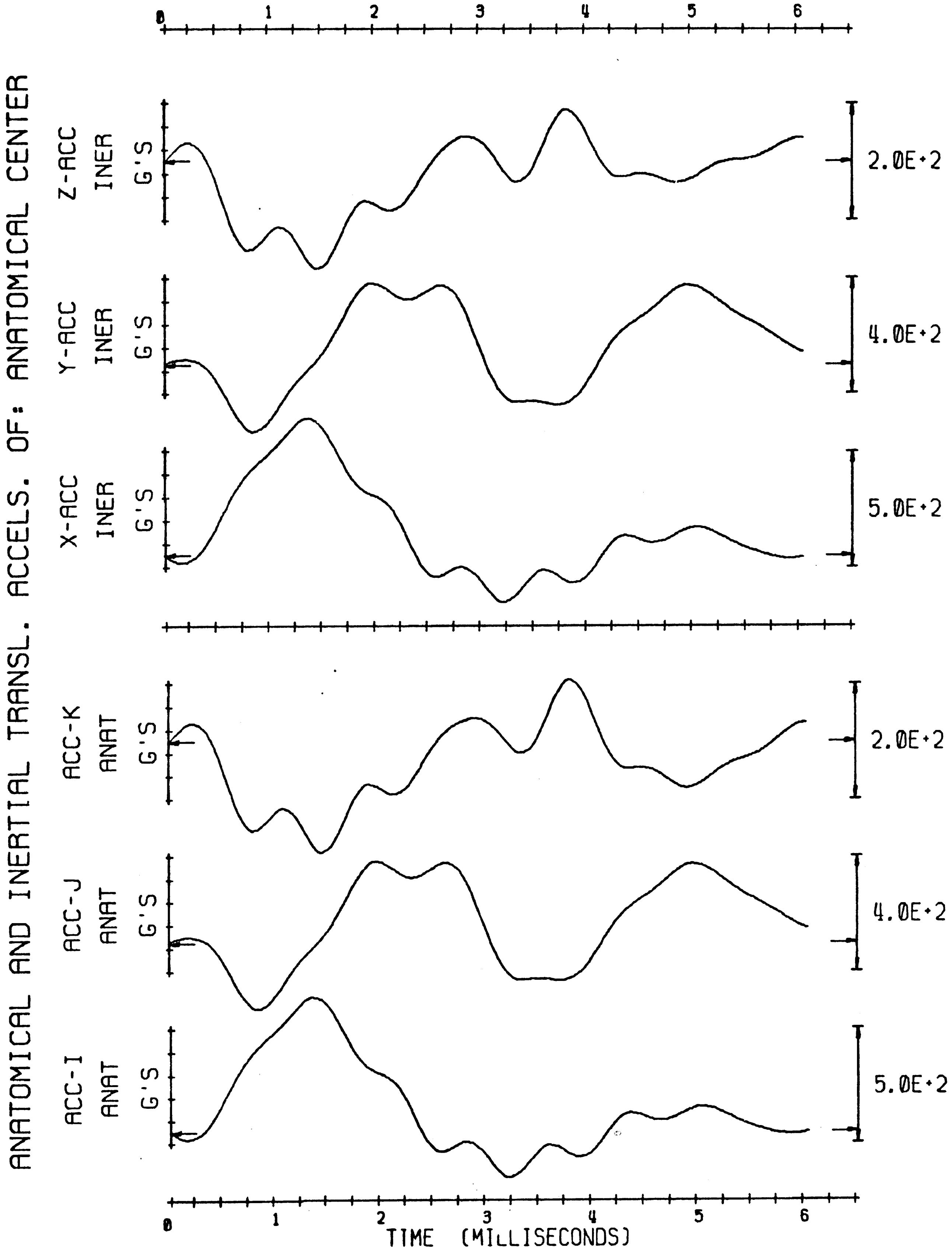
AIS Overall 0



2-019-CY
FORCE
LBS (X10¹)
-3.00
7.00
17.00
27.00
37.00
47.00
TIME (MILLISECONDS)
0
2
4
6
8
10
12
14


ANGULAR ACCELERATIONS AND VELOCITIES --- ALONG ANATOMICAL AXES
ACCEL I-DIREC RAD/S/S
ACCEL J-DIREC RAD/S/S
ACCEL K-DIREC RAD/S/S
VELOC I-DIREC RAD/SEC
VELOC J-DIREC RAD/SEC
VELOC K-DIREC RAD/SEC
TIME (MILLISECONDS)
0
1
2
3
4
5
6
5.0E+4
4.0E+4
4.0E+4
5.0E+1
5.0E+1
4.0E+1
3-D RIGID BODY MOTION ANALYSIS
2-019-CY

2-Ø19-CY



3-D RIGID BODY MOTION ANALYSIS

HEAD IMPACT TEST SUMMARY

TEST NO. 020 TEST DATE 1/30/75

TEST SUBJECT

SPECIES Cynomolgus

Body Weight 4.82 lb.

Sitting Height (Top of Head to bottom of Buttocks) 15.3 in.

Head Weight 0.53 lbs

Brain Weight 0.12 lbs

Brain Volume 2.69 in^3

Skull Inside Length A 2.30 in

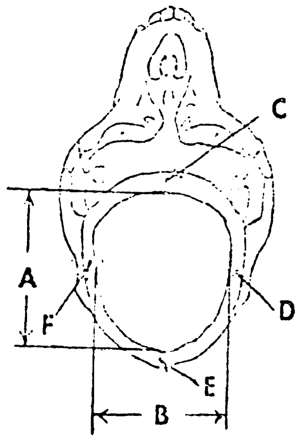
Skull Inside Width B 1.90 in

Skull Thickness at Pt. C .080 in

Skull Thickness at Pt. D .037 in

Skull Thickness at Pt. E .080 in

Skull Thickness at Pt. F .037 in



IMPACT CONDITIONS

Location of Impact Back of head

Type of Impact One and one quarter inches diameter 0.25 inch wall thickness, round cap

Impact Velocity 22.00 ft/sec

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site ______________

Opposite to Impact Site ______________

Epidural Pressures in Direction of Impact:

At Impact Site ______________

Opposite to Impact Site ______________

Strain Gage Rosettes:

Right Parietal Gage ______________

Left Parietal Gage ______________

Frontal Gage ______________

Force: ______________

High Speed Motion Pictures:

Side Camera ______________

Frame Rate ______________

Type II

Accelerations in Direction of Impact:

At Impact Site No

Opposite to Impact Site Lost

Rigid Body Head Motion Analysis: Good

EEG DATA: Pre-Impact Yes

Post Impact Yes

- NOT ANALYZED -

Force: Good, cable noise at 9 msec

TEST NO. 020

High Speed Motion Pictures:

Side Camera: Good

Framing Rate: 3000 fps

Front Camera: Good

Framing Rate: 1000 fps

INJURY:

Condition Prior to Impact: Slight muscle tone, slight eye reflex, and some shivering

		Time After Impact	Condition
Consciousness	1.	0 min	Unconscious
	2.	1 min	Slight muscle tone
	3.	2 min	Conscious
	4.		
	5.		
	6.		
	7.		
	8.		
	9.		
	10.		

TEST NO. 020

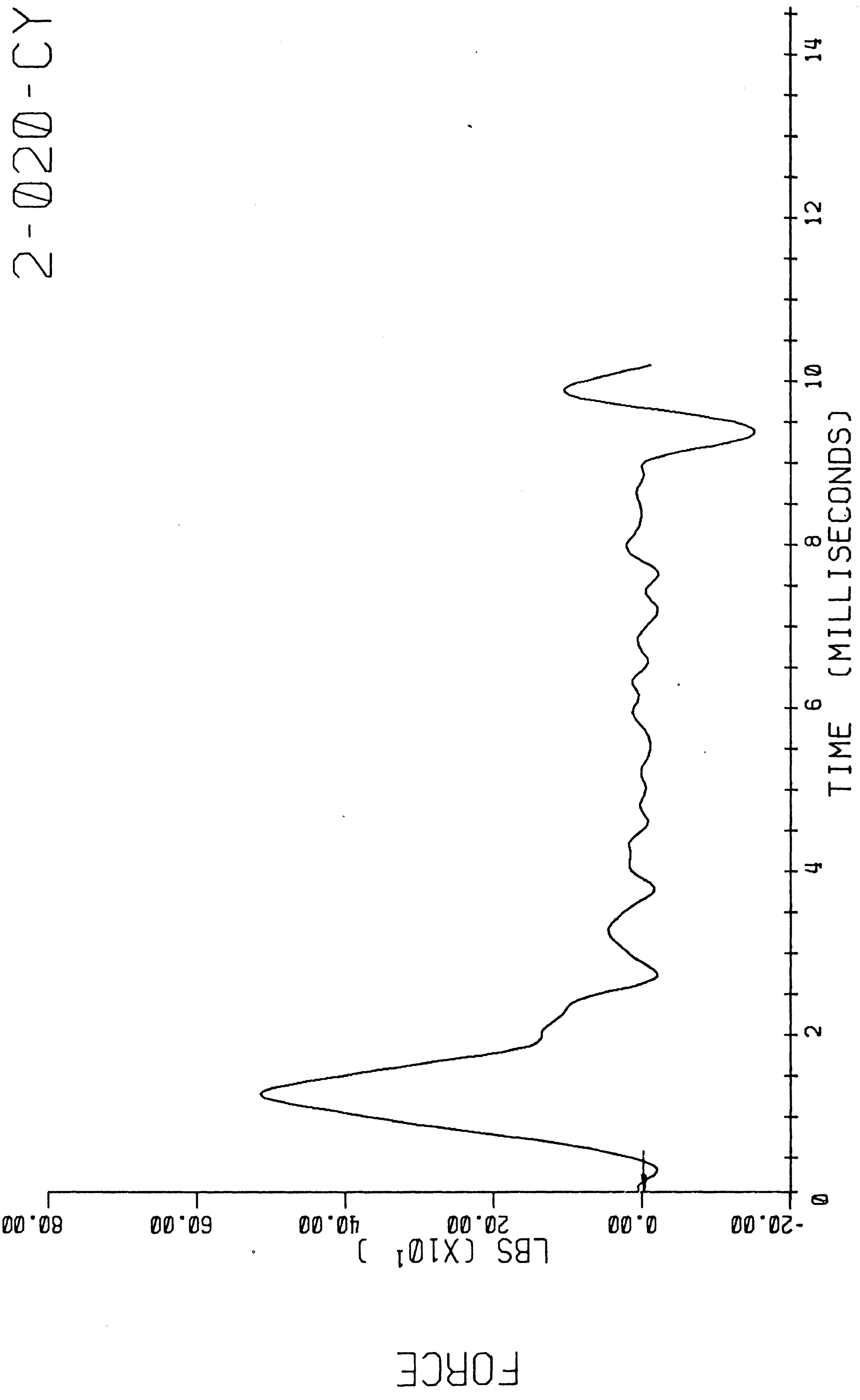
Autopsy Summary:

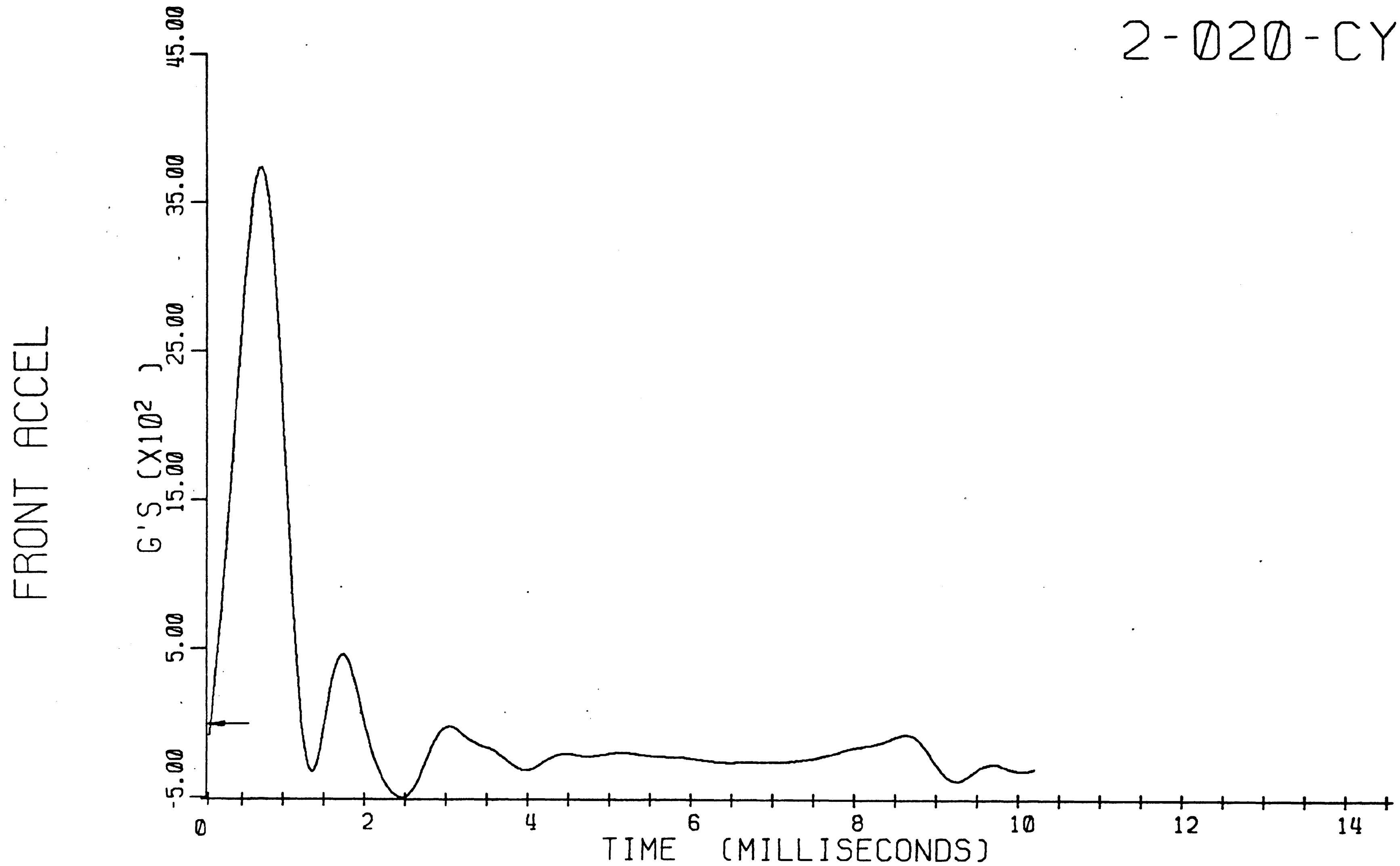
1. Subdural hemorrhage due to collets
2. Unconscious less than 15 min.
3.
4.
5.
6.
7.
8.
9.
10.
11.
12.
13.
14.
15.

Injuries Due to Impact only (not instrumentation)

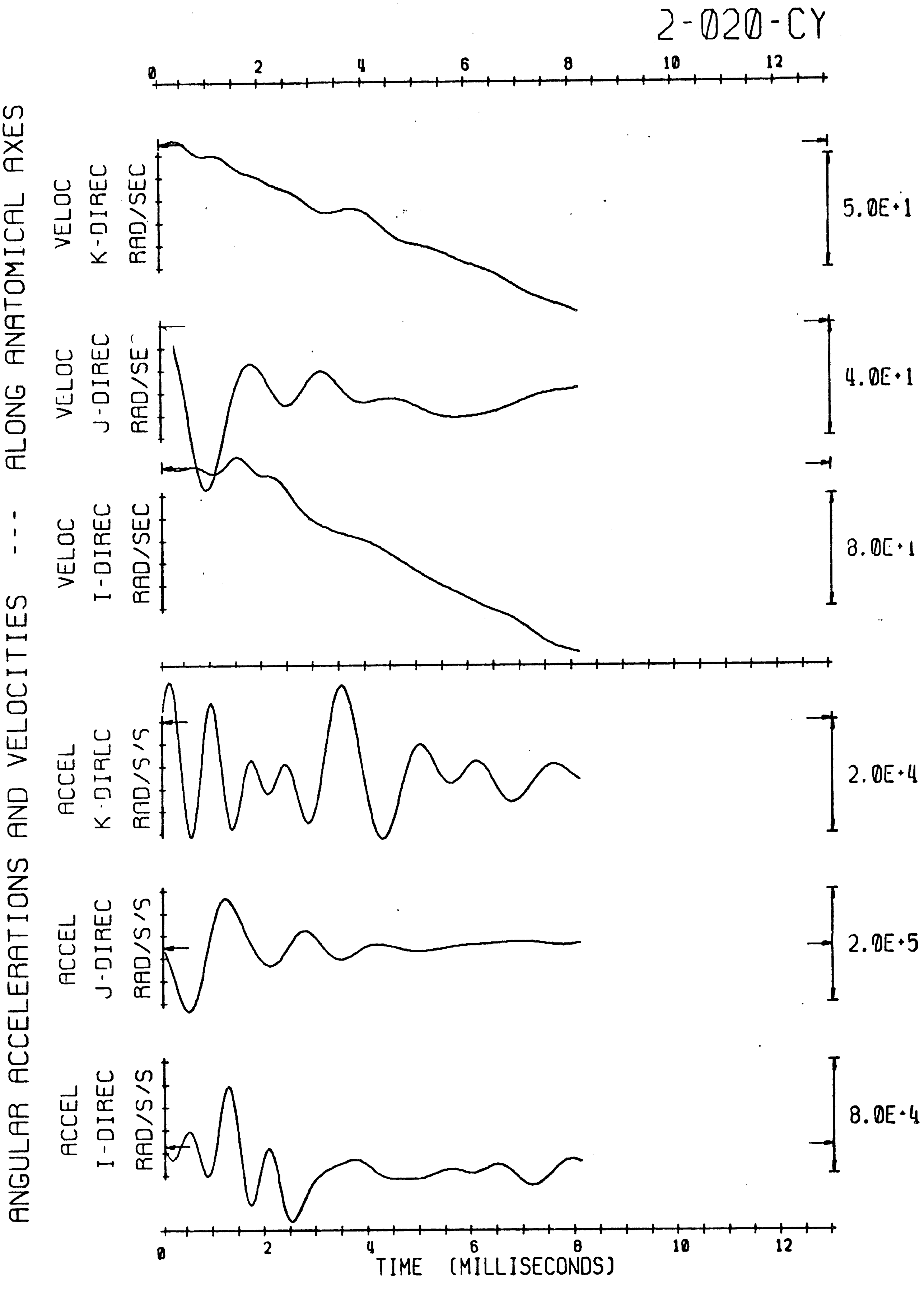
	AIS
1. Unconscious less than 15 min.	2
2.	
3.	
4.	
5.	
6.	
7.	
8.	
9.	
10.	

AIS Overall 2


2-Ø2Ø-CY
TIME (MILLISECONDS)
Ø
2
4
6
8
1Ø
12
14
FORCE
LBS (X1Ø1)
-20.00
0.00
20.00
40.00
60.00
80.00

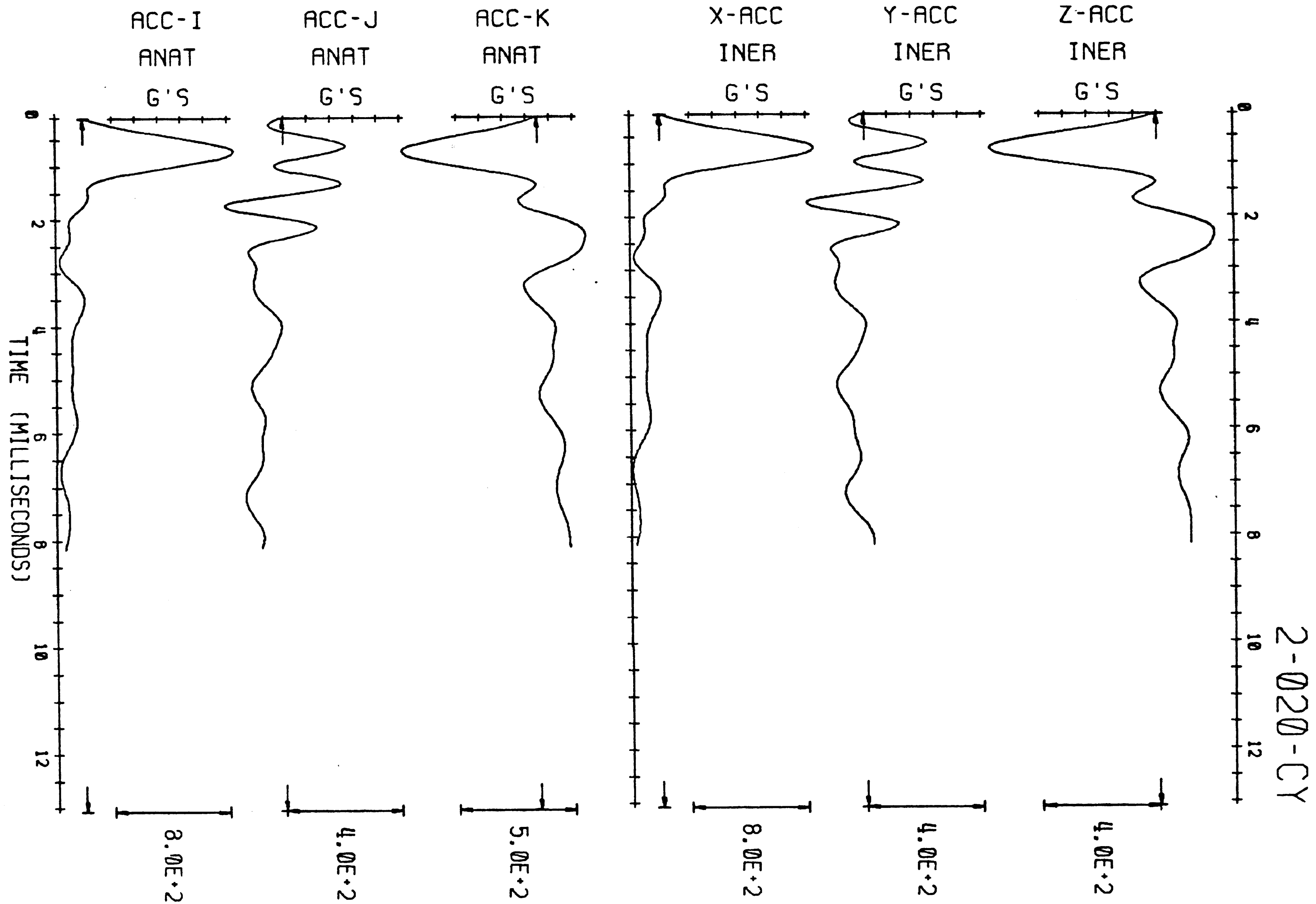


2-Ø2Ø-CY
FRONT ACCEL
G'S (X1Ø²)
45.ØØ
35.ØØ
25.ØØ
15.ØØ
5.ØØ
-5.ØØ
Ø
2
4
6
8
1Ø
12
14
TIME (MILLISECONDS)



3-D RIGID BODY MOTION ANALYSIS

ANATOMICAL AND INERTIAL TRANSL. ACCELS. OF: ANATOMICAL CENTER



3-D RIGID BODY MOTION ANALYSIS

HEAD IMPACT TEST SUMMARY

TEST NO. 021 TEST DATE 1/30/75

TEST SUBJECT

SPECIES Cynomolgus

Body Weight 4.84 lb.

Sitting Height (Top of Head to bottom of Buttocks) 14.8 in.

Head Weight 0.49 lbs

Brain Weight 0.13 lbs

Brain Volume 2.73 in^3

Skull Inside Length A 2.16 in

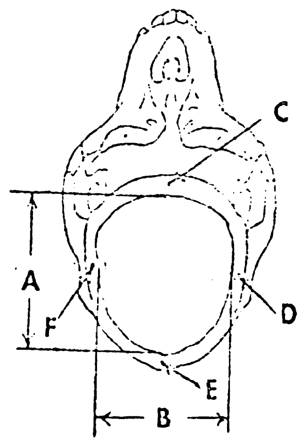
Skull Inside Width B 1.96 in

Skull Thickness at Pt. C 0.070 in

Skull Thickness at Pt. D 0.060 in

Skull Thickness at Pt. E 0.110 in

Skull Thickness at Pt. F 0.060 in



IMPACT CONDITIONS

Location of Impact Back of head

Type of Impact One and one quarter inches diameter 0.25 inch wall thickness, round cap

Impact Velocity 27.50 ft/sec

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site ______________

Opposite to Impact Site ______________

Epidural Pressures in Direction of Impact:

At Impact Site ______________

Opposite to Impact Site ______________

Strain Gage Rosettes:

Right Parietal Gage ______________

Left Parietal Gage ______________

Frontal Gage ______________

Force: ______________

High Speed Motion Pictures:

Side Camera ______________

Frame Rate ______________

Type II

Accelerations in Direction of Impact:

At Impact Site No

Opposite to Impact Site Good

Rigid Body Head Motion Analysis: Good

EEG DATA: Pre-Impact Yes

Post Impact No

- NOT ANALYZED -

Force: Good

TEST NO. 021

High Speed Motion Pictures:

Side Camera: Good

Framing Rate: 3000 fps

Front Camera: Good

Framing Rate: 1000 fps

INJURY:

Condition Prior to Impact: Breathing very slowly, may have died just before impact.

		Time After Impact	Condition
Consciousness	1.	0 min.	Dead
	2.		
	3.		
	4.		
	5.		
	6.		
	7.		
	8.		
	9.		
	10.		

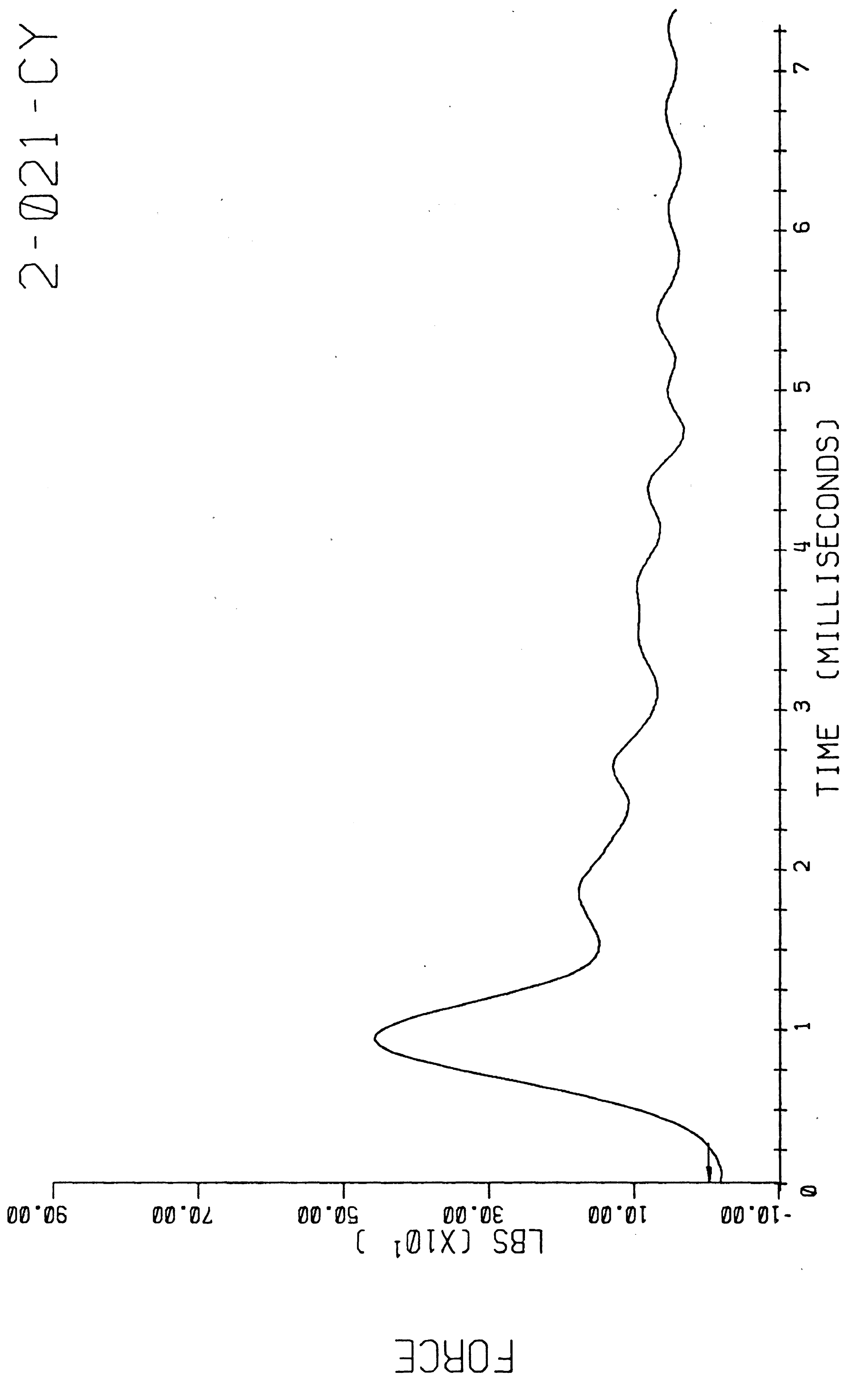
Autopsy Summary:

1. Rear neck muscles were found to be hemorrhaged
2. Three simple fractures of the Lt. Parietal bone
3. Three simple fractures of the Rt. Parietal bone
4. One simple fracture of the Occipital bone
5.
6.
7.
8.
9.
10.
11.
12.
13.
14.
15.

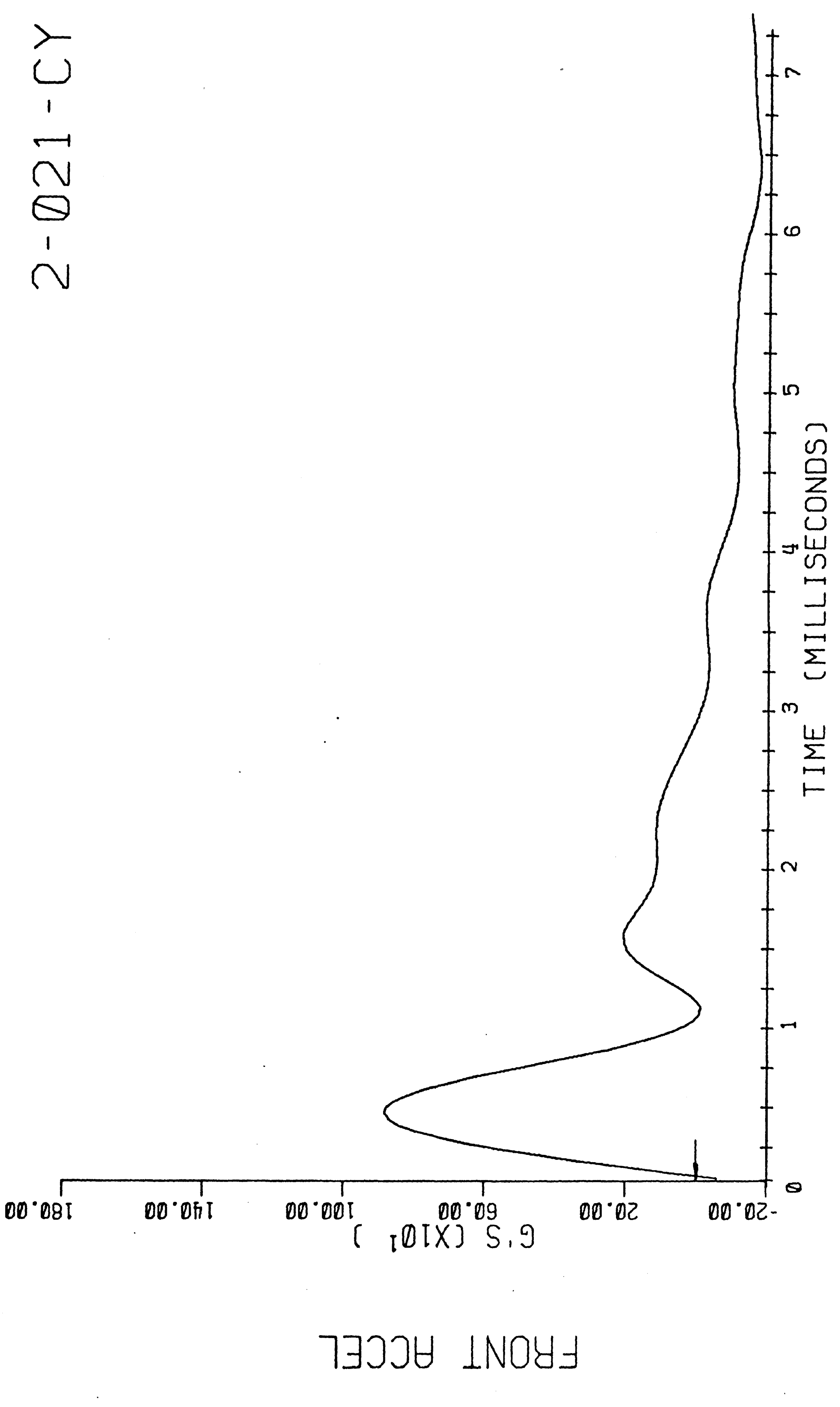
Injuries Due to Impact only (not instrumentation)

	Injury	AIS
1.	Rear neck muscles were hemorrhaged	2
2.	Three simple fractures of Rt. Parietal bone	3
3.	Three simple fractures of Lt. Parietal bone	3
4.	Simple fracture of occipital bone	2
5.		
6.		
7.		
8.		
9.		
10.		

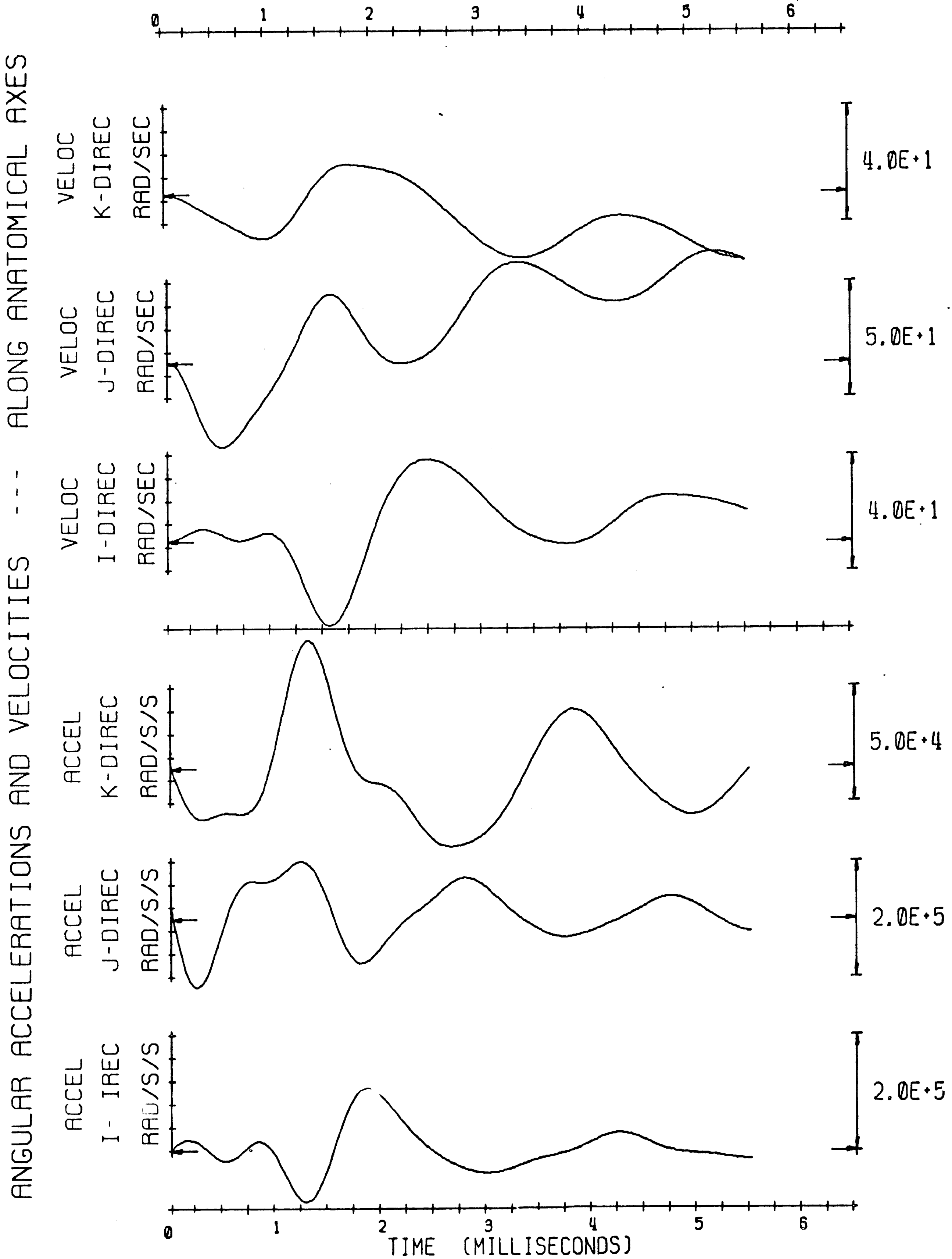
AIS Overall 4



2-Ø21-CY
FORCE
LBS (X10¹)
-10.00
10.00
30.00
50.00
70.00
90.00
TIME (MILLISECONDS)
0
1
2
3
4
5
6
7

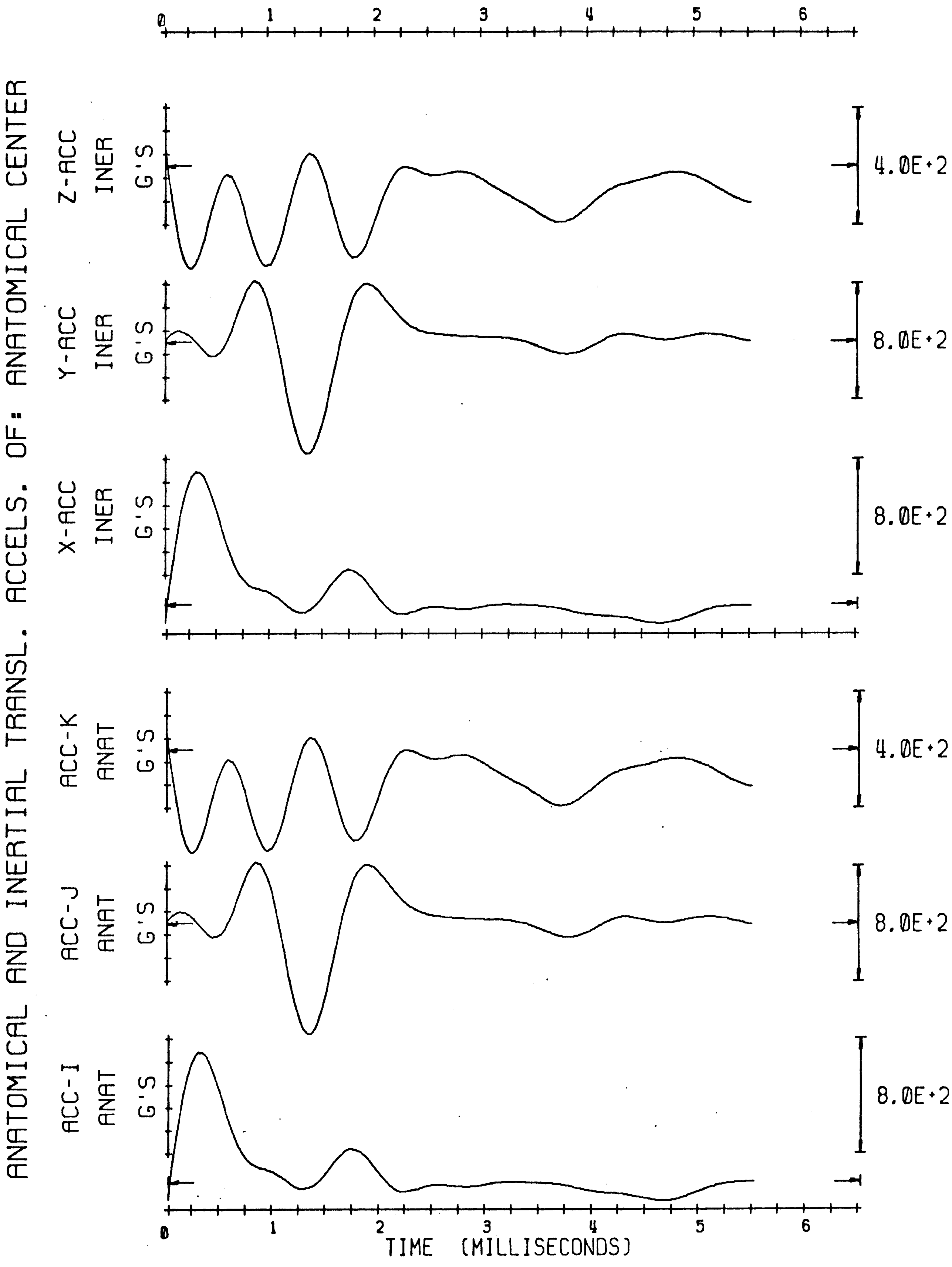

2-Ø21-CY
TIME (MILLISECONDS)
0
1
2
3
4
5
6
7
G'S (X1Ø1)
-20.00
20.00
60.00
100.00
140.00
180.00
FRONT ACCEL

2-021-CY



3-D RIGID BODY MOTION ANALYSIS

2-021-CY



3-D RIGID BODY MOTION ANALYSIS

HEAD IMPACT TEST SUMMARY

TEST NO. 022 TEST DATE 2/4/75

TEST SUBJECT

SPECIES Rhesus

Body Weight 8.80 lb.

Sitting Height (Top of Head to bottom of Buttocks) 16.3 in.

Head Weight 0.88 lbs

Brain Weight 0.177 lbs

Brain Volume 6.03 in^3

Skull Inside Length A 2.9 in

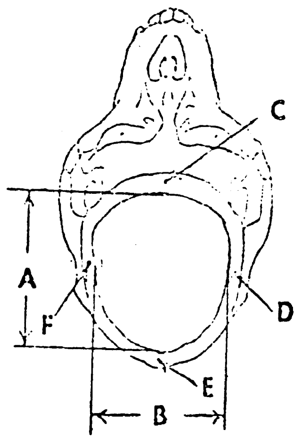
Skull Inside Width B 2.2 in

Skull Thickness at Pt. C 0.110 in

Skull Thickness at Pt. D 0.070 in

Skull Thickness at Pt. E 0.130 in

Skull Thickness at Pt. F 0.060 in



IMPACT CONDITIONS

Location of Impact Back of head

Type of Impact One and one quarter inches diameter 0.25 inch wall thickness round cap with three inches of Ensolite.

Impact Velocity 45.54 ft/sec

TEST NO. 022

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site ______

Opposite to Impact Site ______

Epidural Pressures in Direction of Impact:

At Impact Site ______

Opposite to Impact Site ______

Strain Gage Rosettes:

Right Parietal Gage ______

Left Parietal Gage ______

Frontal Gage ______

Force: ______

High Speed Motion Pictures:

Side Camera ______

Frame Rate ______

Type II

Accelerations in Direction of Impact:

At Impact Site No

Opposite to Impact Site Good

Rigid Body Head Motion Analysis: Fair

EEG DATA: Pre-Impact Yes

Post Impact Yes

- NOT ANALYZED -

Force: Fair, Data not printed out for more than 7.25 msec

TEST NO. 022

High Speed Motion Pictures:

Side Camera Good

Framing Rate 3000 fps

Front Camera Good

Framing Rate 1000 fps

INJURY:

Condition Prior to Impact Slight muscle tone, slight eye reflex, and some shivering

		Time After Impact	Condition
Consciousness	1.	0 min.	Dazed
	2.	6 min.	Conscious
	3.		
	4.		
	5.		
	6.		
	7.		
	8.		
	9.		
	10.		

TEST NO. 022

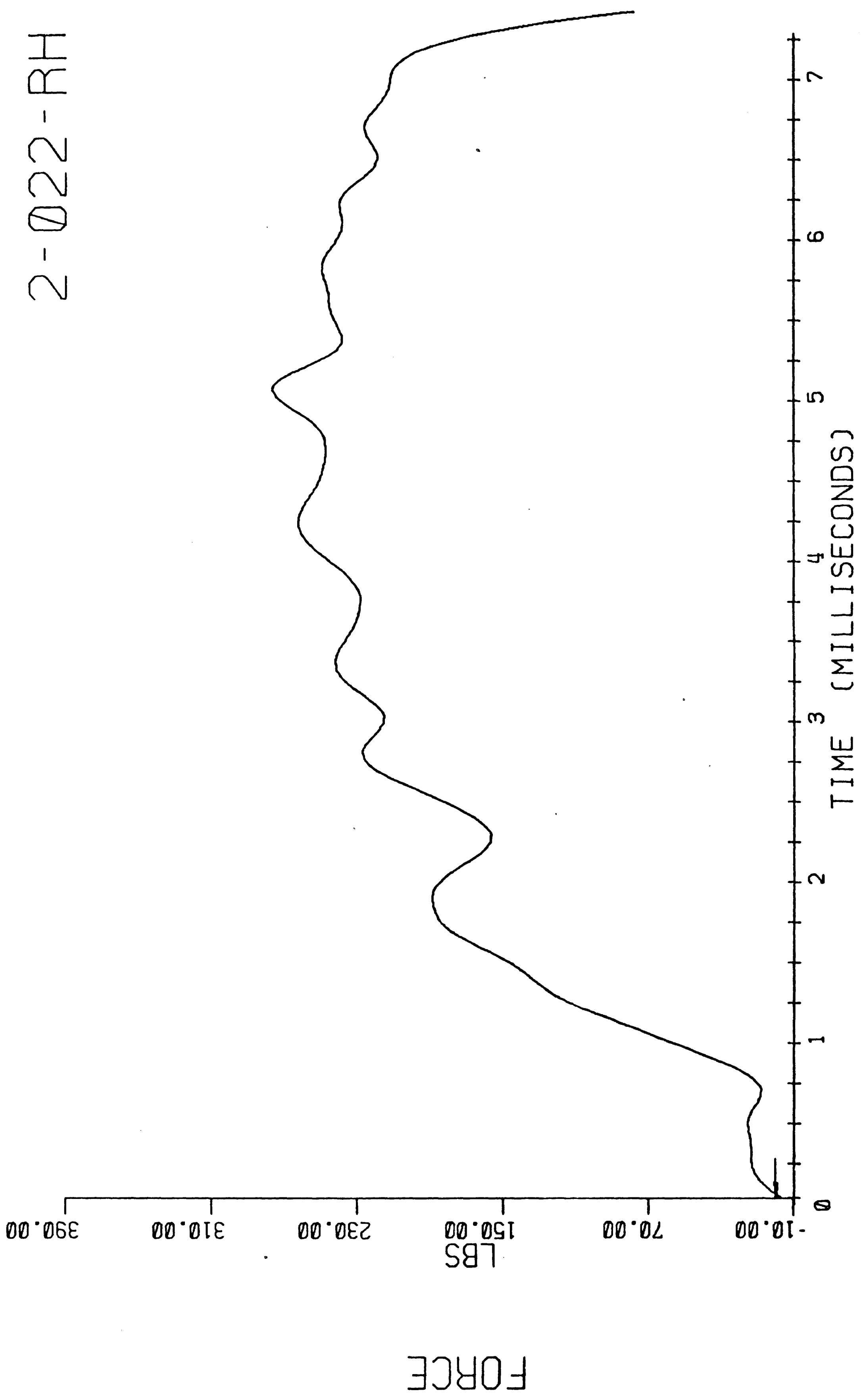
Autopsy Summary:

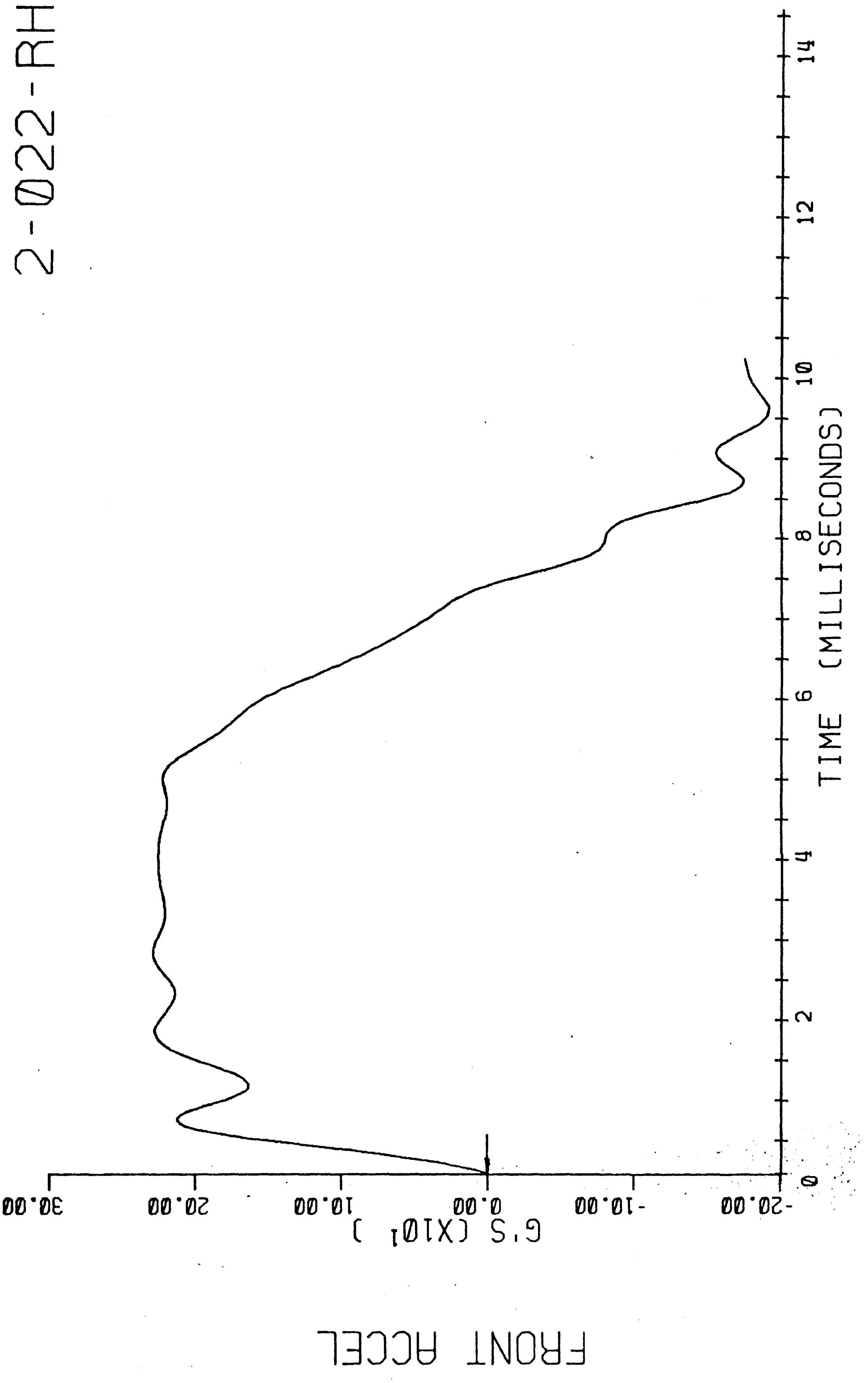
1. Circular bruise under collets
2. Dazed for 1 to 3 minutes
3. Subdural hemorrhage on Rt. Parietal lobe
4. Hemorrhage in left Butama
5.
6.
7.
8.
9.
10.
11.
12.
13.
14.
15.

Injuries Due to Impact only (not instrumentation)

	Injury	AIS
1.	Dazed for 1 to 3 min.	1
2.	Subdural hemorrhage on Rt. Parietal lobe	4
3.	Hemorrhage in left Butama	3
4.		
5.		
6.		
7.		
8.		
9.		
10.		

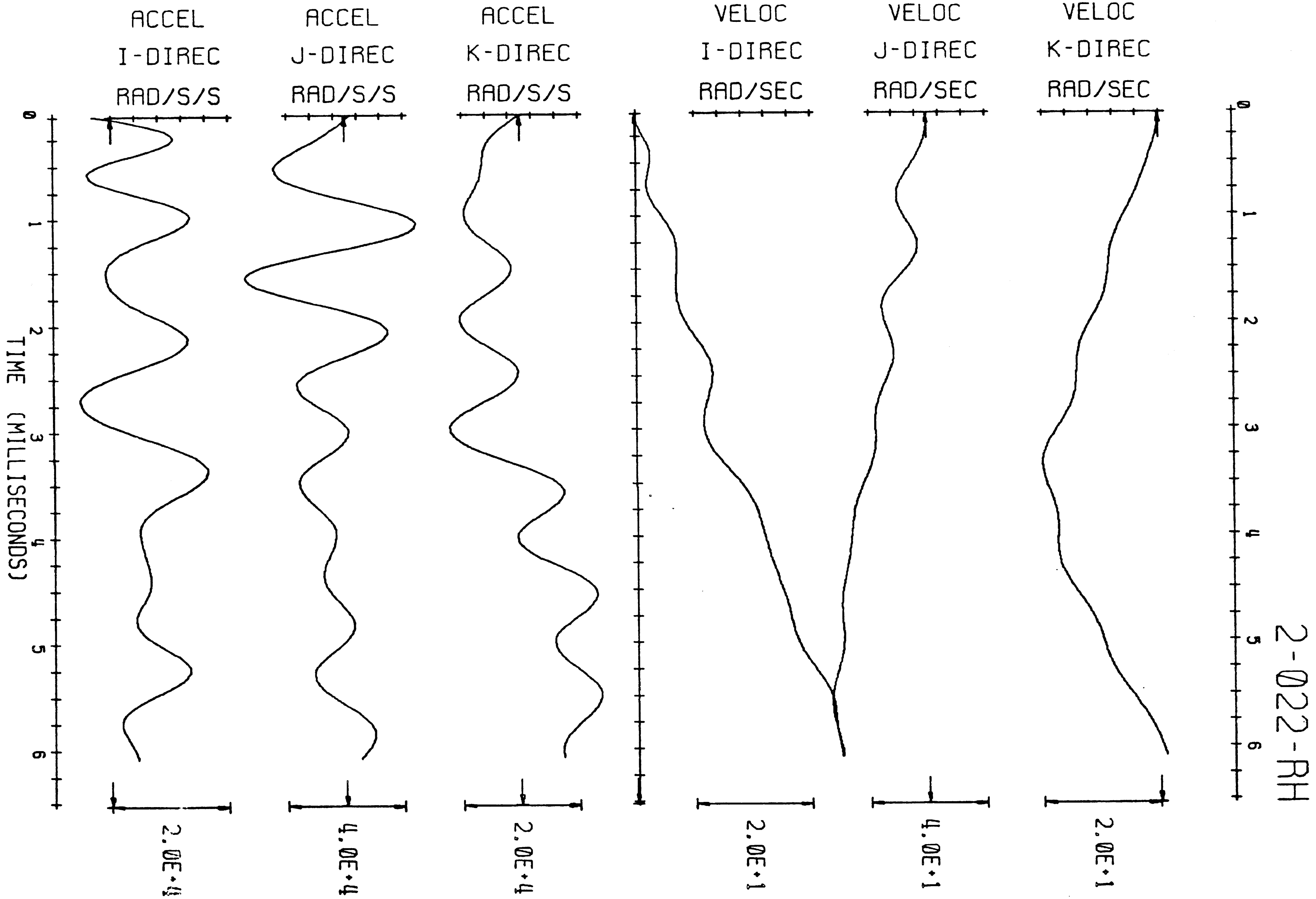
AIS Overall 5


2-Ø22-RH
TIME (MILLISECONDS)
0
1
2
3
4
5
6
7
FORCE
LBS
-10.00
70.00
150.00
230.00
310.00
390.00



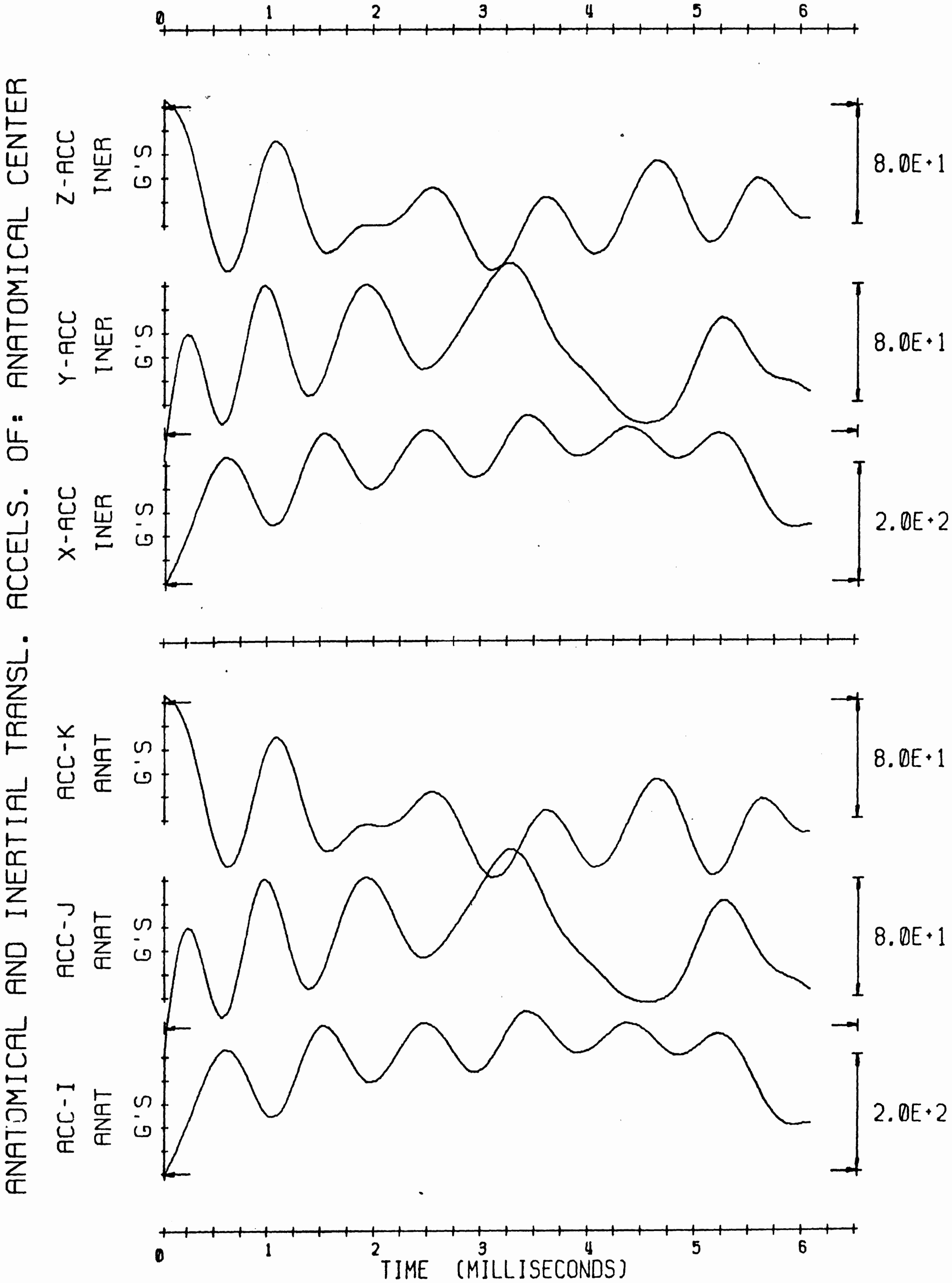
2-Ø22-RH
FRONT ACCEL
TIME (MILLISECONDS)
G'S (X10¹)
-20.00
-10.00
0.00
10.00
20.00
30.00
0
2
4
6
8
10
12
14

ANGULAR ACCELERATIONS AND VELOCITIES --- ALONG ANATOMICAL AXES



3-D RIGID BODY MOTION ANALYSIS

2-022-RH



3-D RIGID BODY MOTION ANALYSIS

HEAD IMPACT TEST SUMMARY

TEST NO. 023

TEST DATE 2/4/75

TEST SUBJECT

SPECIES Rhesus

Body Weight 10.56 lb.

Sitting Height (Top of Head to bottom of Buttocks) 19 in.

Head Weight 1.07 lbs

Brain Weight 0.224 lbs

Brain Volume 6.28 in^3

Skull Inside Length A 2.85 in

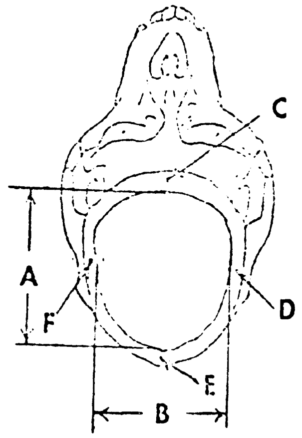
Skull Inside Width B 2.25 in

Skull Thickness at Pt. C 0.100 in

Skull Thickness at Pt. D 0.075 in

Skull Thickness at Pt. E 0.100 in

Skull Thickness at Pt. F 0.075 in



IMPACT CONDITIONS

Location of Impact Back of head

Type of Impact One and one quarter inches diameter 0.25 inch wall thickness round cap, with three inches of Ensolite.

Impact Velocity 57.55 ft/sec

TEST NO. 023

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site ______________

Opposite to Impact Site ______________

Epidural Pressures in Direction of Impact:

At Impact Site ______________

Opposite to Impact Site ______________

Strain Gage Rosettes:

Right Parietal Gage ______________

Left Parietal Gage ______________

Frontal Gage ______________

Force: ______________

High Speed Motion Pictures:

Side Camera ______________

Frame Rate ______________

Type II

Accelerations in Direction of Impact:

At Impact Site No

Opposite to Impact Site No

Rigid Body Head Motion Analysis: Good, but short

EEG DATA: Pre-Impact Yes

Post Impact Yes

- NOT ANALYZED -

Force: Good, but short

TEST NO. 023

High Speed Motion Pictures:

Side Camera Good

Framing Rate 3000 fps

Front Camera Good

Framing Rate 1000 fps

INJURY:

Condition Prior to Impact Slight muscle tone, slight eye reflex, and some shivering

		Time After Impact	Condition
Consciousness	1.	0 min.	Unconscious
	2.	2 min.	Leg twitch
	3.	5 min.	Begin EEG tape
	4.	6 min 10 sec.	Started to move; no eye reflex
	5.	9 min 30 sec.	No eye reflex; quivering
	6.	10 min 30 sec.	Whole body shivering
	7.	13 min. 30 sec.	Good eye reflex
	8.		
	9.		
	10.		

Autopsy Summary:

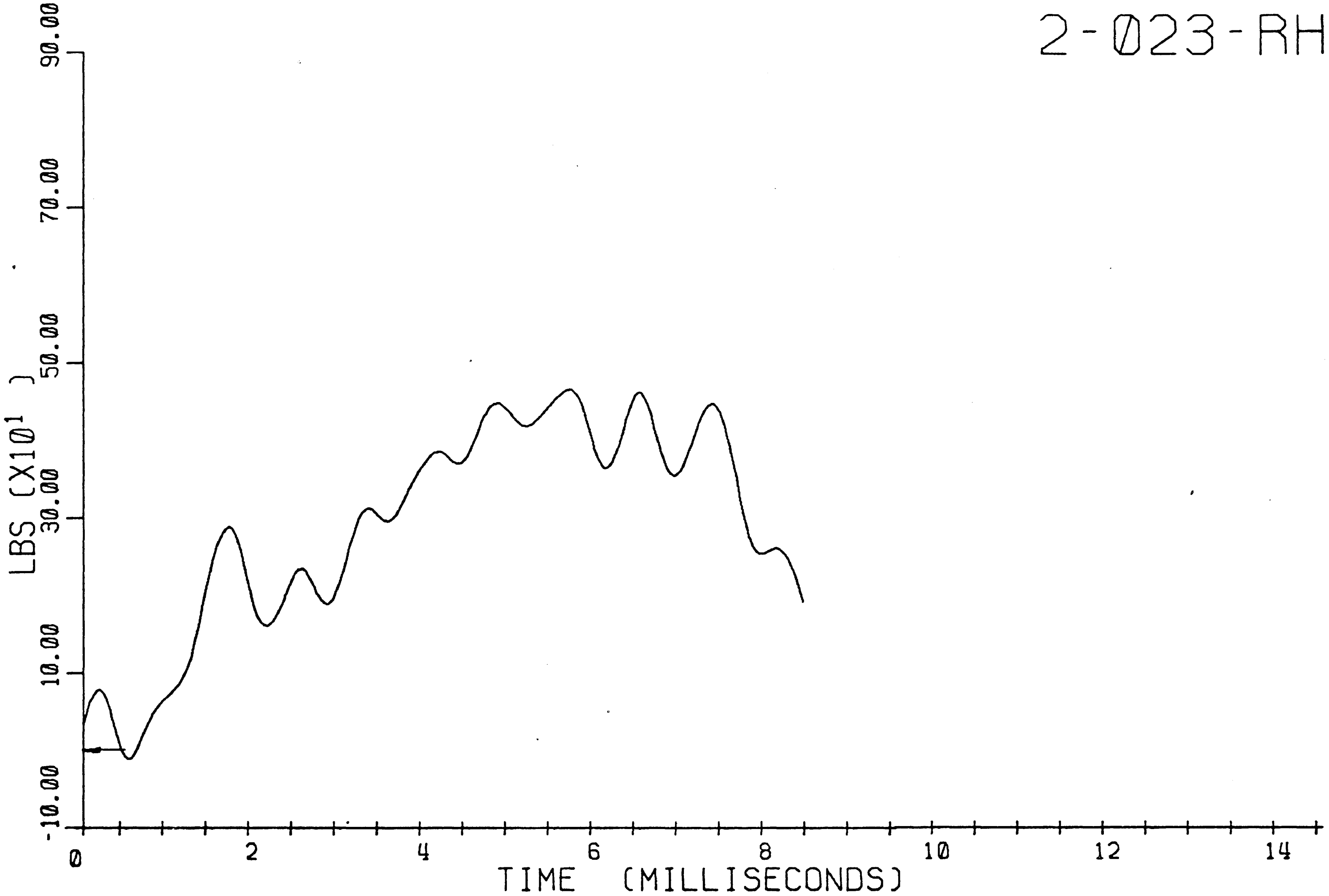
1. Neck muscle torn away from skull
2. Subdural hemorrhage frontal lobe
3. Intraventricular extravasation of blood in ventricular
4. Less than 15 min. unconscious
5.
6.
7.
8.
9.
10.
11.
12.
13.
14.
15.

Injuries Due to Impact only (not instrumentation)

	Injury	AIS
1.	Neck muscle torn away from skull	2
2.	Subdural hemorrhage frontal lobe	4
3.	Intraventricular extravasation of blood in vent.	3
4.	Less than 15 min. unconscious	2
5.		
6.		
7.		
8.		
9.		
10.		

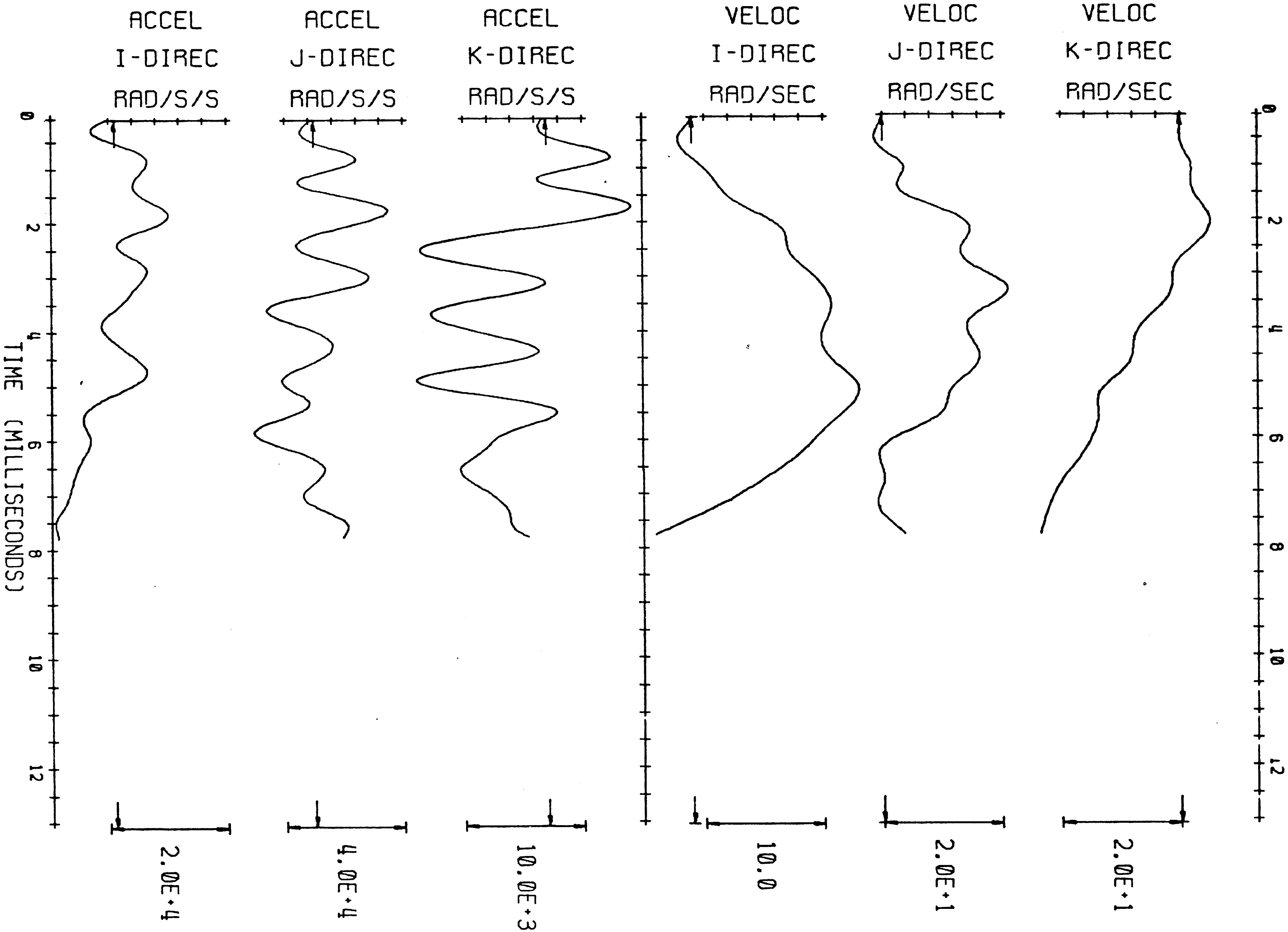
AIS Overall 5

FORCE



2-Ø23-RH
LBS (X10¹)
90.00
70.00
50.00
30.00
10.00
-10.00
Ø
2
4
6
8
10
12
14
TIME (MILLISECONDS)

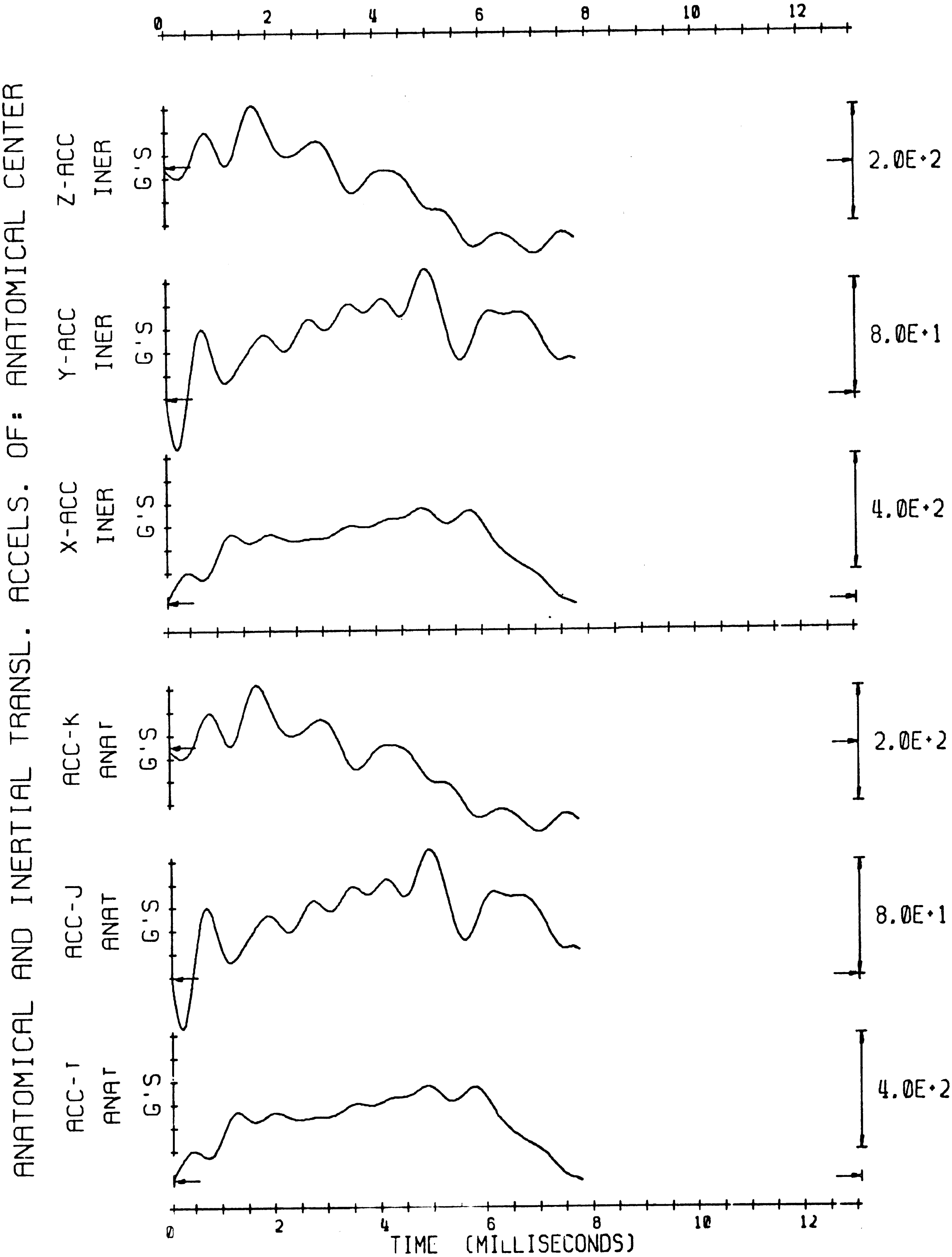
ANGULAR ACCELERATIONS AND VELOCITIES --- ALONG ANATOMICAL AXES



2-023-RH

3-D RIGID BODY MOTION ANALYSIS

2-023-RH



3-D RIGID BODY MOTION ANALYSIS

HEAD IMPACT TEST SUMMARY

TEST NO. 024 TEST DATE 2/5/75

TEST SUBJECT

SPECIES Rhesus

Body Weight 13.20 lb.

Sitting Height (Top of Head to bottom of Buttocks) 19.0 in.

Head Weight 1.34 lbs

Brain Weight 0.245 lbs

Brain Volume 7.09 in^3

Skull Inside Length A 2.80 in

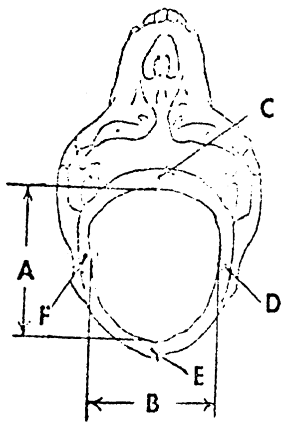
Skull Inside Width B 2.26 in

Skull Thickness at Pt. C 0.150 in

Skull Thickness at Pt. D 0.080 in

Skull Thickness at Pt. E 0.150 in

Skull Thickness at Pt. F 0.070 in



IMPACT CONDITIONS

Location of Impact Left side of head

Type of Impact 4" round rigid, with 0.50 inch thick 1 5/16 x 1 5/8 blue styrofoam

Impact Velocity 31.78 ft/sec

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site ______

Opposite to Impact Site ______

Epidural Pressures in Direction of Impact:

At Impact Site ______

Opposite to Impact Site ______

Strain Gage Rosettes:

Right Parietal Gage ______

Left Parietal Gage ______

Frontal Gage ______

Force: ______

High Speed Motion Pictures:

Side Camera ______

Frame Rate ______

Type II

Accelerations in Direction of Impact:

At Impact Site No

Opposite to Impact Site Good

Rigid Body Head Motion Analysis: Fair

EEG DATA: Pre-Impact Yes

Post Impact Yes

- NOT ANALYZED -

Force: Fair

High Speed Motion Pictures

Side Camera Good

Framing Rate 3000 fps

Front Camera Good

Framing Rate 1000 fps

INJURY:

Condition Prior to Impact Slight muscle tone, slight eye reflex, and some shivering

		Time After Impact	Condition
Consciousness	1.	0 min.	Dazed
	2.	2 min. 15 sec.	Conscious
	3.		
	4.		
	5.		
	6.		
	7.		
	8.		
	9.		
	10.		

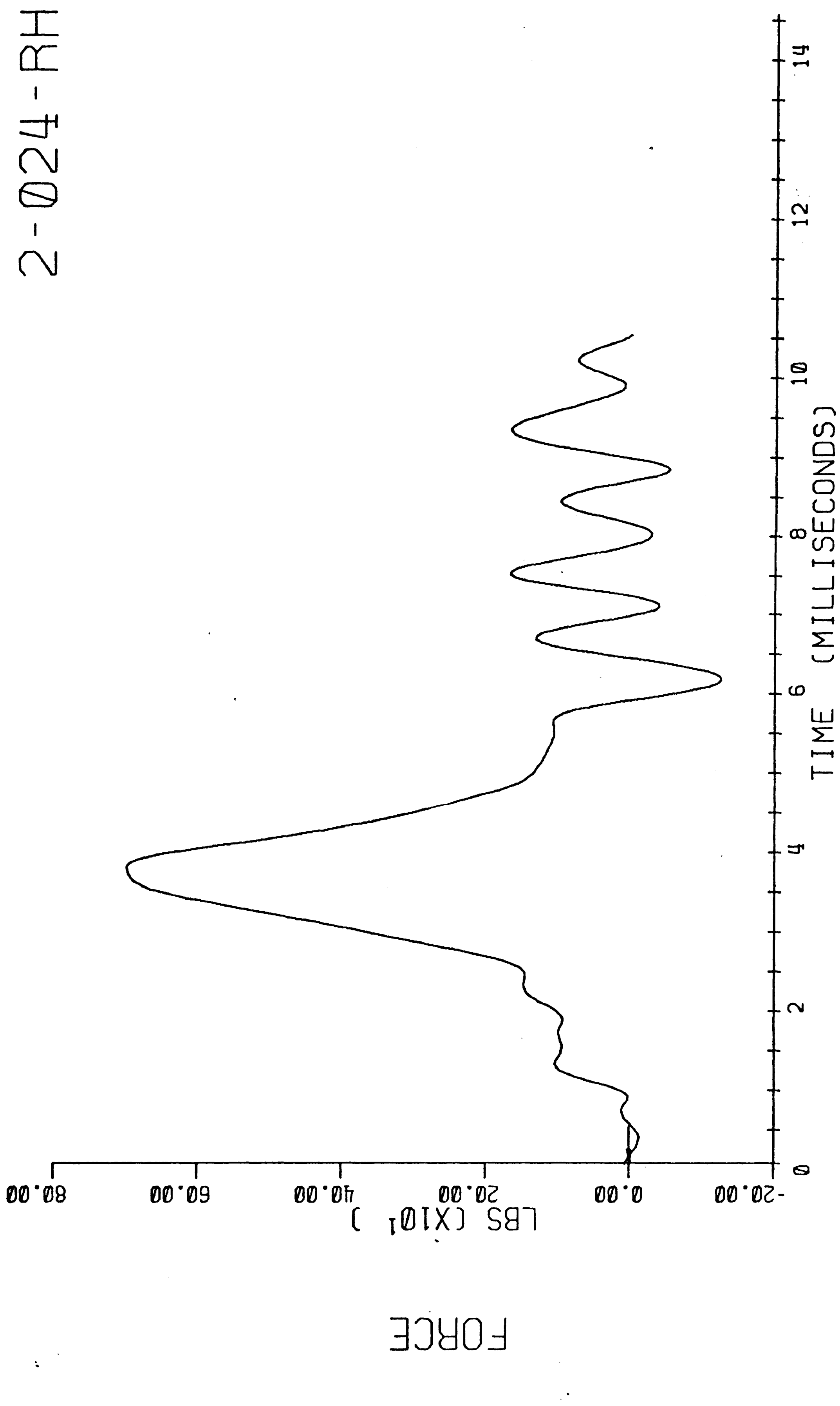
Autopsy Summary:

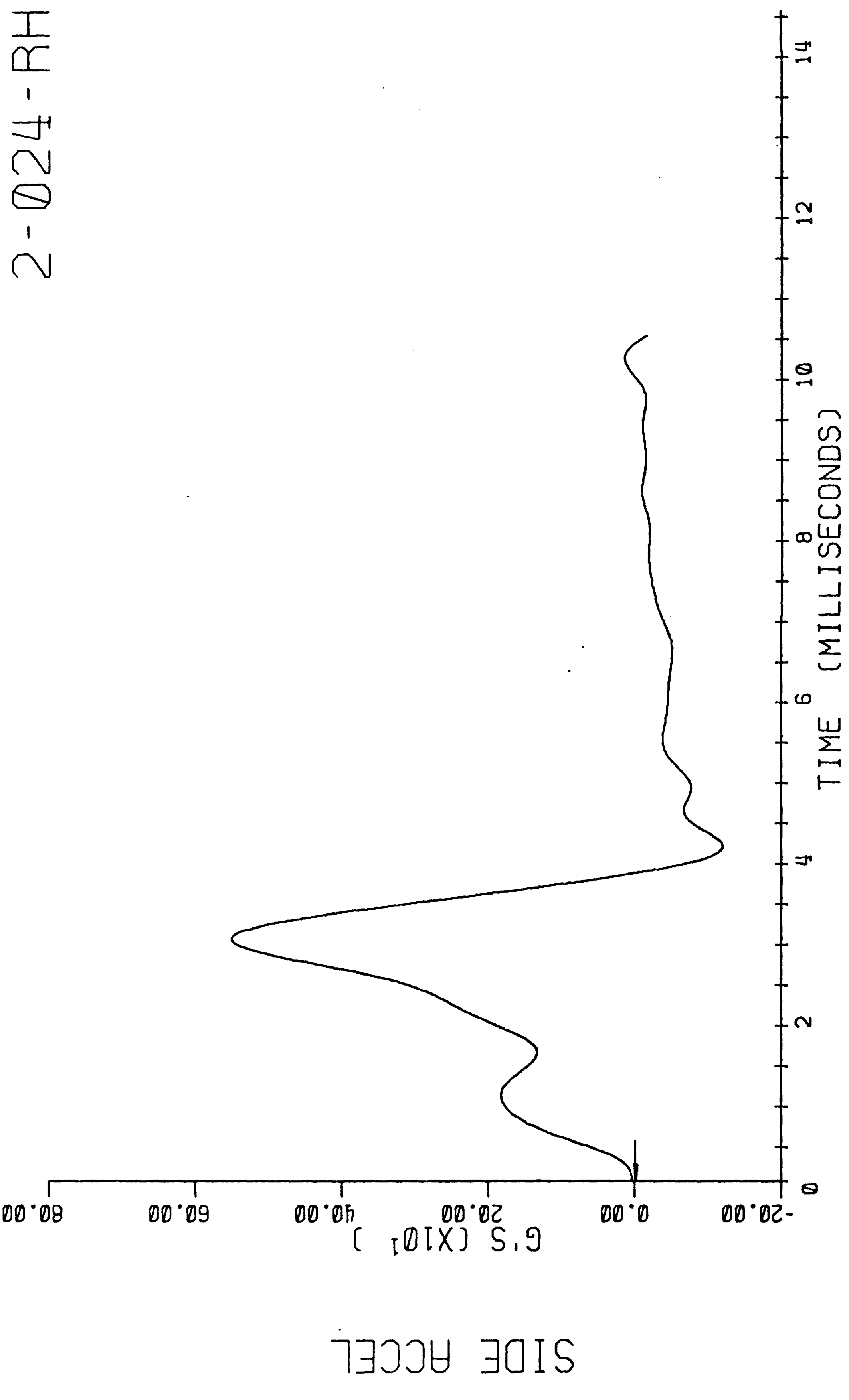
1. Small bruise on parietal lobe from collets
2. Dazed 2 min.
3. Invraventricular extravasation of blood in vent.
4.
5.
6.
7.
8.
9.
10.
11.
12.
13.
14.
15.

Injuries Due to Impact only (not instrumentation)

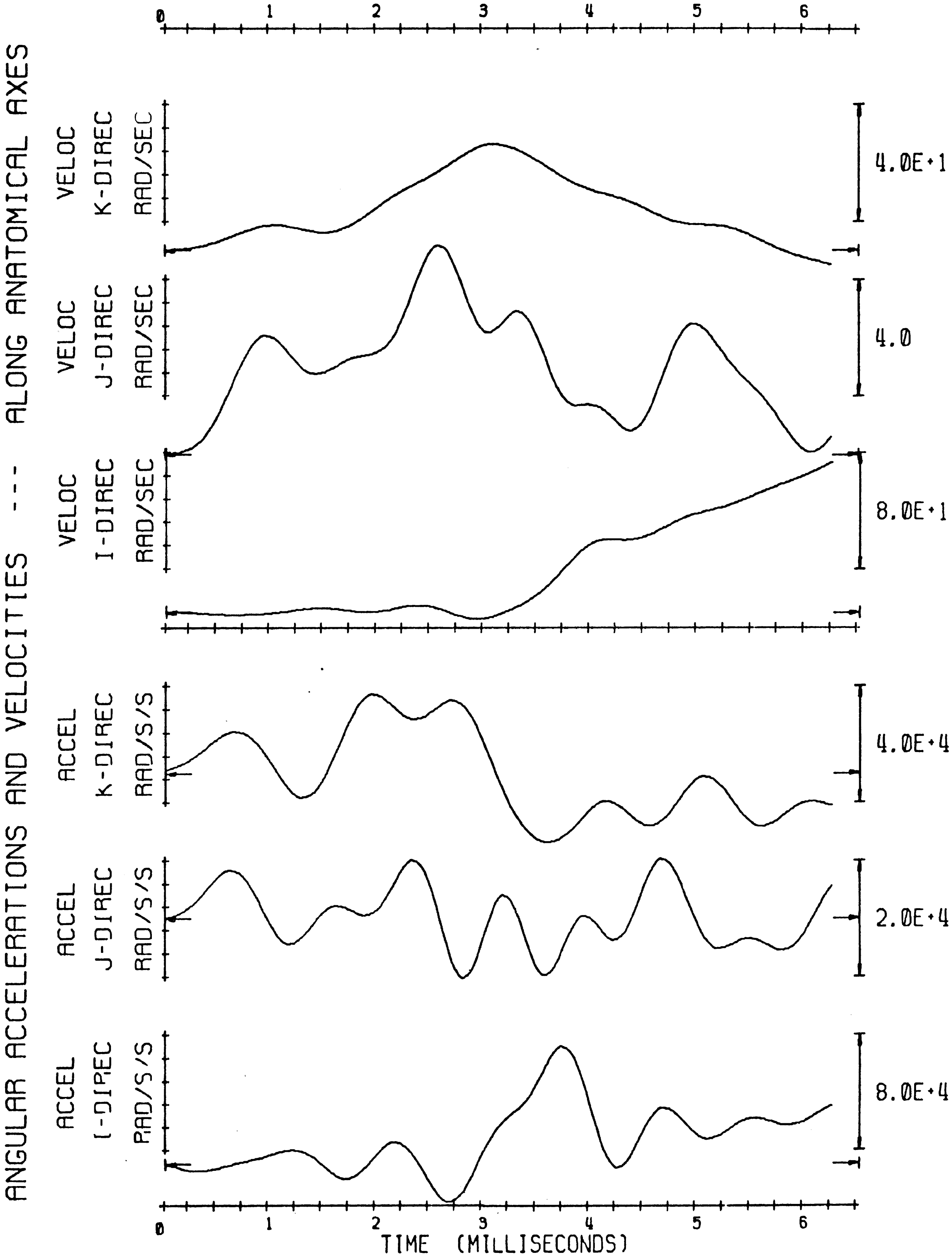
		AIS
1.	Intraventricular extravasation of blood in vent.	3
2.	Dazed 2 min.	2
3.		
4.		
5.		
6.		
7.		
8.		
9.		
10.		

AIS Overall 3


2-Ø24-RH
TIME (MILLISECONDS)
0
2
4
6
8
10
12
14
80.00
60.00
40.00
20.00
0.00
-20.00
LBS (X10¹)
FORCE

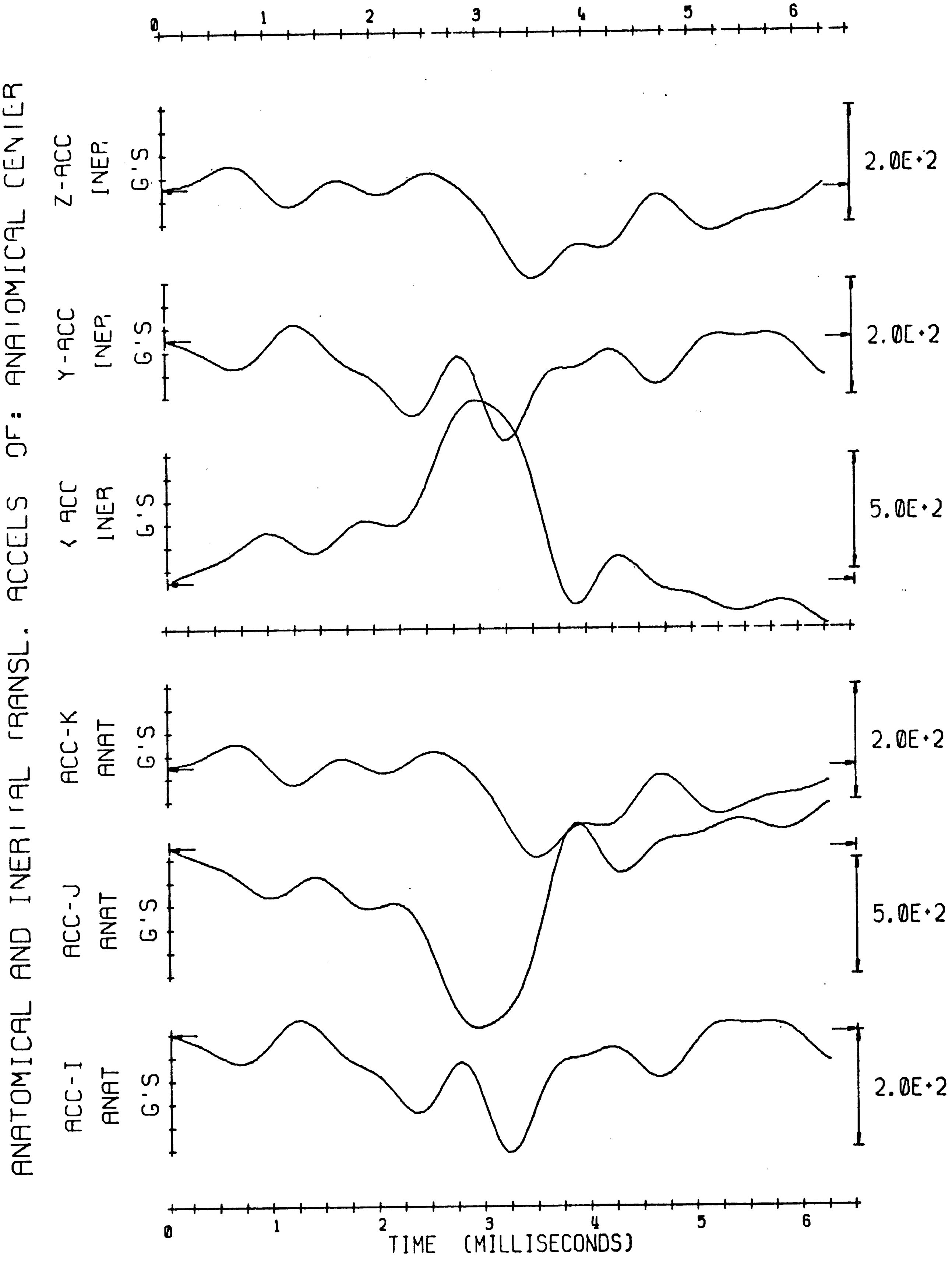

2-024-RH
TIME (MILLISECONDS)
0
2
4
6
8
10
12
14
G'S (X10¹)
-20.00
0.00
20.00
40.00
60.00
80.00
SIDE ACCEL

2-024-RH



3-D RIGID BODY MOTION ANALYSIS

2-024-RH



3-D RIGID BODY MOTION ANALYSIS

HEAD IMPACT TEST SUMMARY

TEST NO. 025 TEST DATE 2/5/75

TEST SUBJECT

SPECIES Rhesus

Body Weight 14.30 lb.

Sitting Height (Top of Head to bottom of Buttocks) 19.50 in.

Head Weight 1.42 lbs

Brain Weight 0.232 lbs

Brain Volume 7.11 in^3

Skull Inside Length A 2.70 in

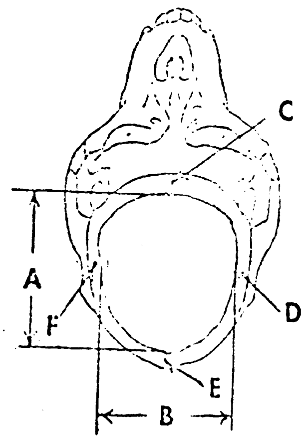
Skull Inside Width B 2.20 in

Skull Thickness at Pt. C 0.110 in

Skull Thickness at Pt. D 0.078 in

Skull Thickness at Pt. E 0.110 in

Skull Thickness at Pt. F 0.078 in



IMPACT CONDITIONS

Location of Impact Left side of head

Type of Impact 4" round rigid, with 0.50 inch thick 1 5/16 x 1 5/8 blue styrofoam

Impact Velocity 38.16 ft/sec

TEST NO. 025

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site ______________

Opposite to Impact Site ______________

Epidural Pressures in Direction of Impact:

At Impact Site ______________

Opposite to Impact Site ______________

Strain Gage Rosettes:

Right Parietal Gage ______________

Left Parietal Gage ______________

Frontal Gage ______________

Force: ______________

High Speed Motion Pictures:

Side Camera ______________

Frame Rate ______________

Type II

Accelerations in Direction of Impact:

At Impact Site No

Opposite to Impact Site Lost

Rigid Body Head Motion Analysis: Fair

EEG DATA: Pre-Impact Yes

Post Impact Yes

- NOT ANALYZED -

Force: Lost

TEST NO. 025

High Speed Motion Pictures:

Side Camera: Good

Framing Rate: 3000 fps

Front Camera: Good

Framing Rate: 1000 fps

INJURY:

Condition Prior to Impact: Slight muscle tone, slight eye reflex, and some shivering

		Time After Impact	Condition
Consciousness	1.	0 min.	Unconscious
	2.	1 min. 30 sec.	Little muscle tone
	3.	2 min. 30 sec.	Conscious
	4.		
	5.		
	6.		
	7.		
	8.		
	9.		
	10.		

TEST NO. 025

Autopsy Summary:

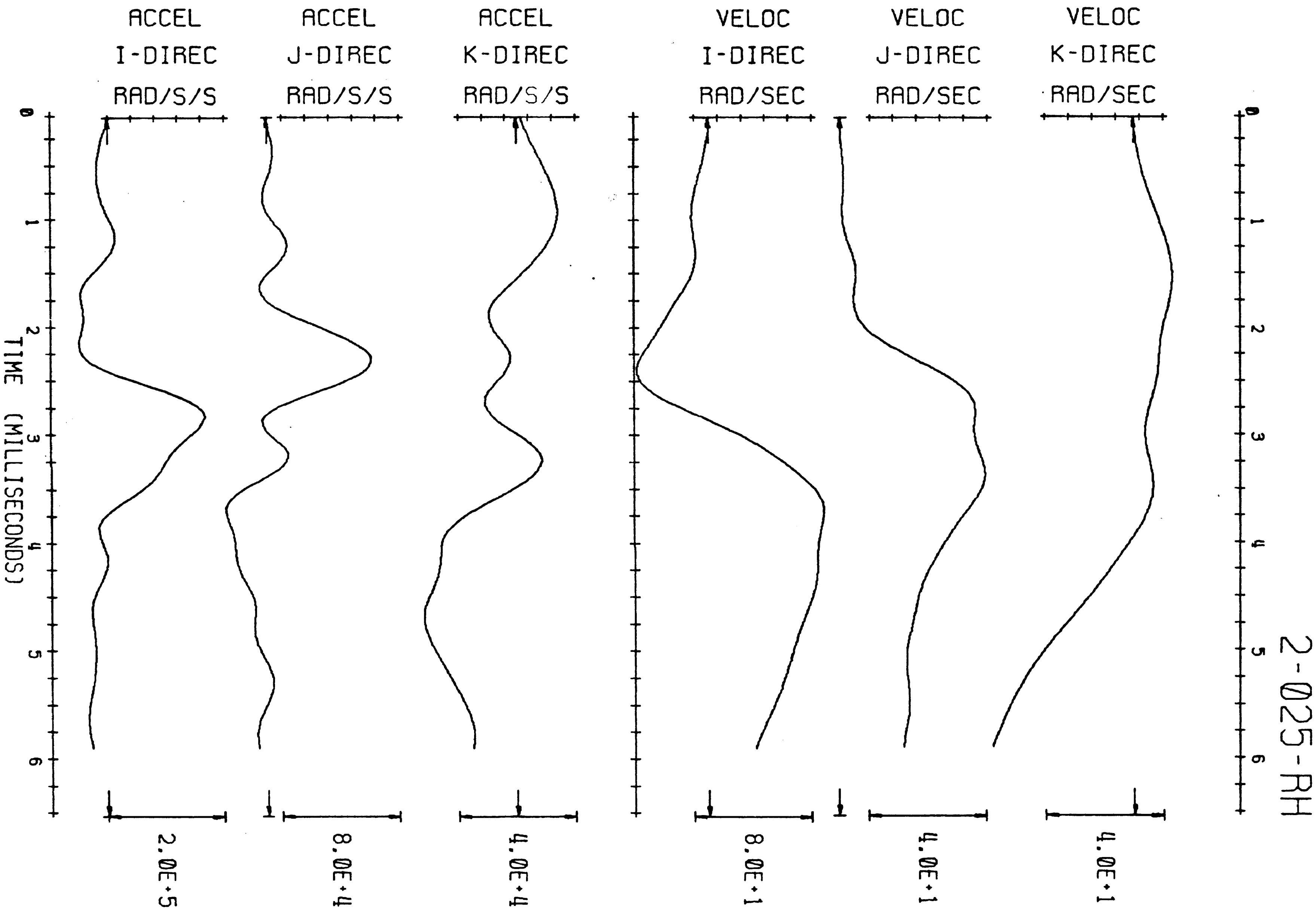
1. Minor haematome over Lt. zygomatic arch
2. Two simple fractures of Lt. zygomatic arch
3. Small bruise on parietal lobe from collet
4. Less than 15 min. unconscious
5.
6.
7.
8.
9.
10.
11.
12.
13.
14.
15.

Injuries Due to Impact only (not instrumentation)

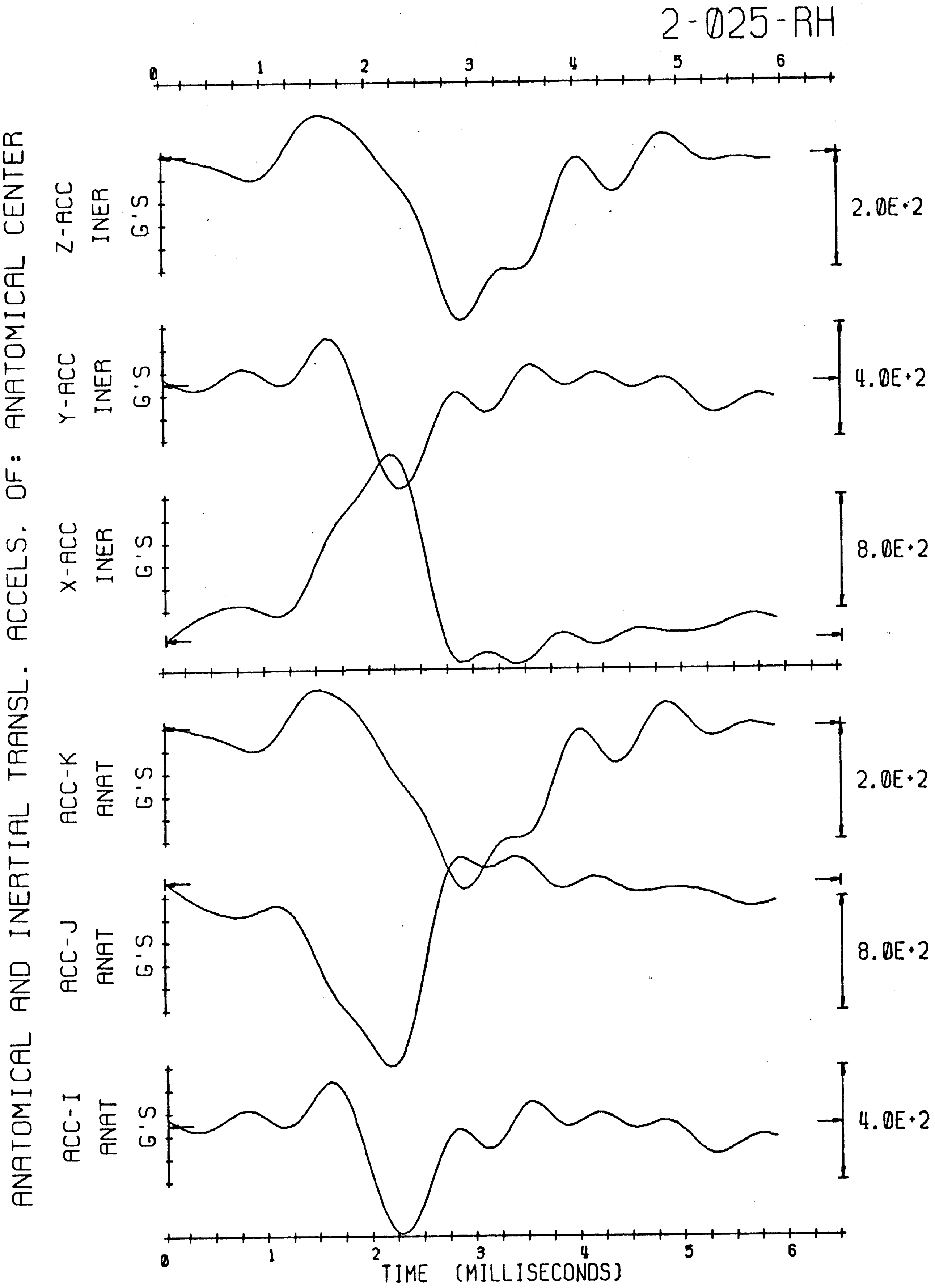
		AIS
1.	Minor haematome over Lt. zygomatic arch	1
2.	Two simple fractures of Lt. zygomatic arch	2
3.	Less than 15 min. unconscious	2
4.		
5.		
6.		
7.		
8.		
9.		
10.		

AIS Overall 3

ANGULAR ACCELERATIONS AND VELOCITIES --- ALONG ANATOMICAL AXES



3-D RIGID BODY MOTION ANALYSIS



3-D RIGID BODY MOTION ANALYSIS

HEAD IMPACT TEST SUMMARY

TEST NO. 026 **TEST DATE** 2/6/75

TEST SUBJECT

SPECIES Rhesus

Body Weight 11.88 lb.

Sitting Height (Top of Head to bottom of Buttocks) 18.3 in.

Head Weight 1.18 lbs

Brain Weight 0.257 lbs

Brain Volume 6.81 in^3

Skull Inside Length A 3.10 in

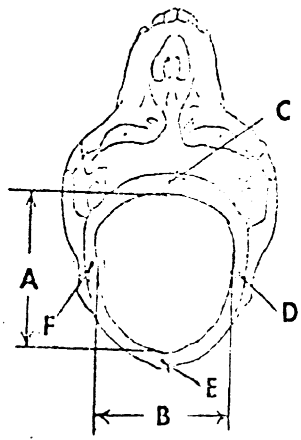
Skull Inside Width B 2.30 in

Skull Thickness at Pt. C 0.120 in

Skull Thickness at Pt. D 0.100 in

Skull Thickness at Pt. E 0.120 in

Skull Thickness at Pt. F 0.100 in



IMPACT CONDITIONS

Location of Impact Left side of head

Type of Impact 4" round rigid, with 0.50 inch thick, 1 5/16 x 1 5/8 blue styrofoam

Impact Velocity 30.91 ft/sec

TEST NO. 026

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site ______

Opposite to Impact Site ______

Epidural Pressures in Direction of Impact:

At Impact Site ______

Opposite to Impact Site ______

Strain Gage Rosettes:

Right Parietal Gage ______

Left Parietal Gage ______

Frontal Gage ______

Force: ______

High Speed Motion Pictures:

Side Camera ______

Frame Rate ______

Type II

Accelerations in Direction of Impact:

At Impact Site No

Opposite to Impact Site Good

Rigid Body Head Motion Analysis: Good

EEG DATA: Pre-Impact Yes

Post Impact Yes

- NOT ANALYZED -

Force: Good

TEST NO. 026

High Speed Motion Pictures:

Side Camera	Good
Framing Rate	3000 fps
Front Camera	Good
Framing Rate	1000 fps

INJURY:

Condition Prior to Impact Slight muscle tone, slight eye reflex, and some shivering

		Time After Impact	Condition
Consciousness	1.	0 min.	Unconscious
	2.	2 min.	Conscious
	3.	4 min.	Unconscious
	4.	15 min.	Conscious
	5.		
	6.		
	7.		
	8.		
	9.		
	10.		

TEST NO. 026

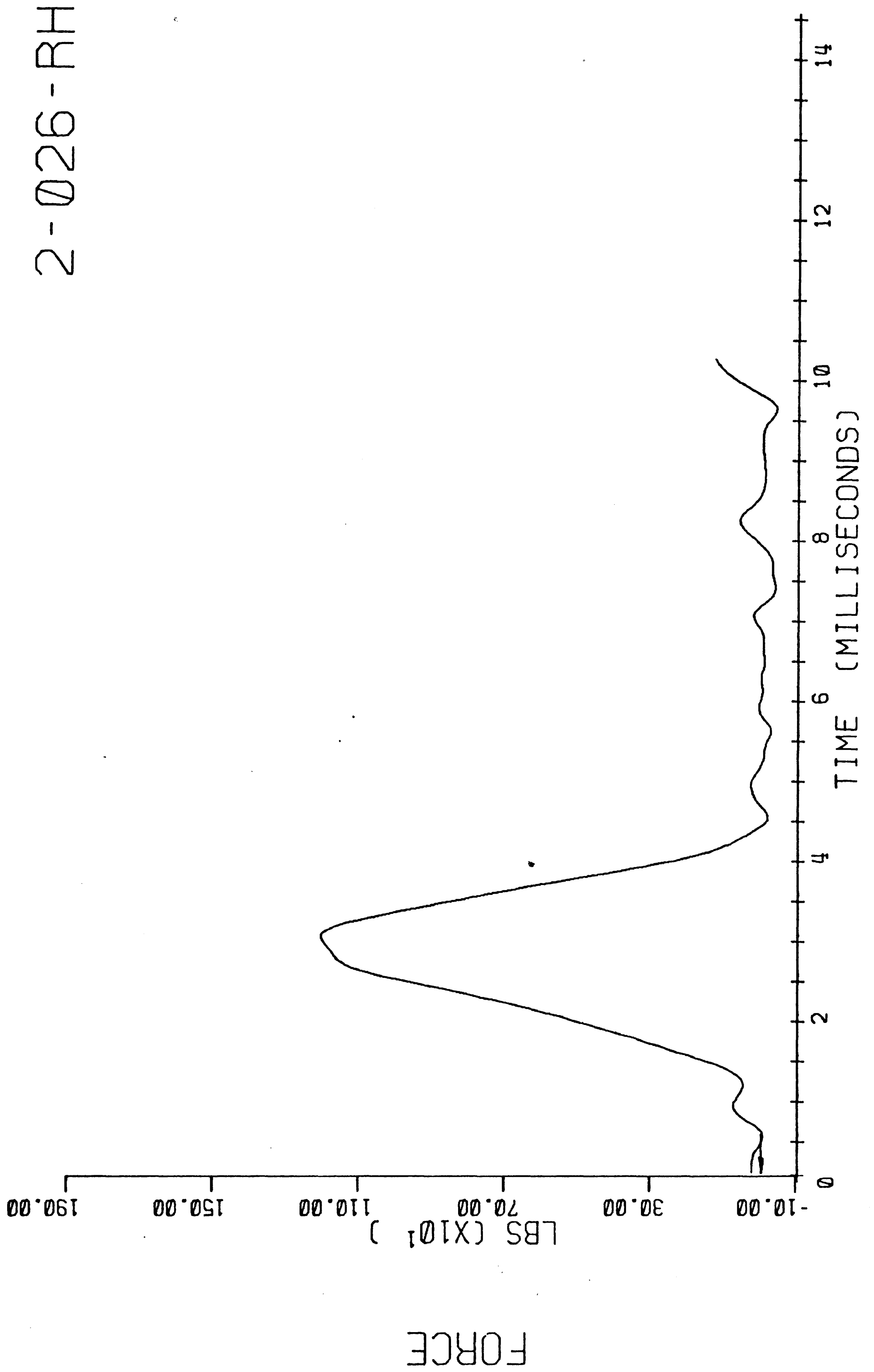
Autopsy Summary

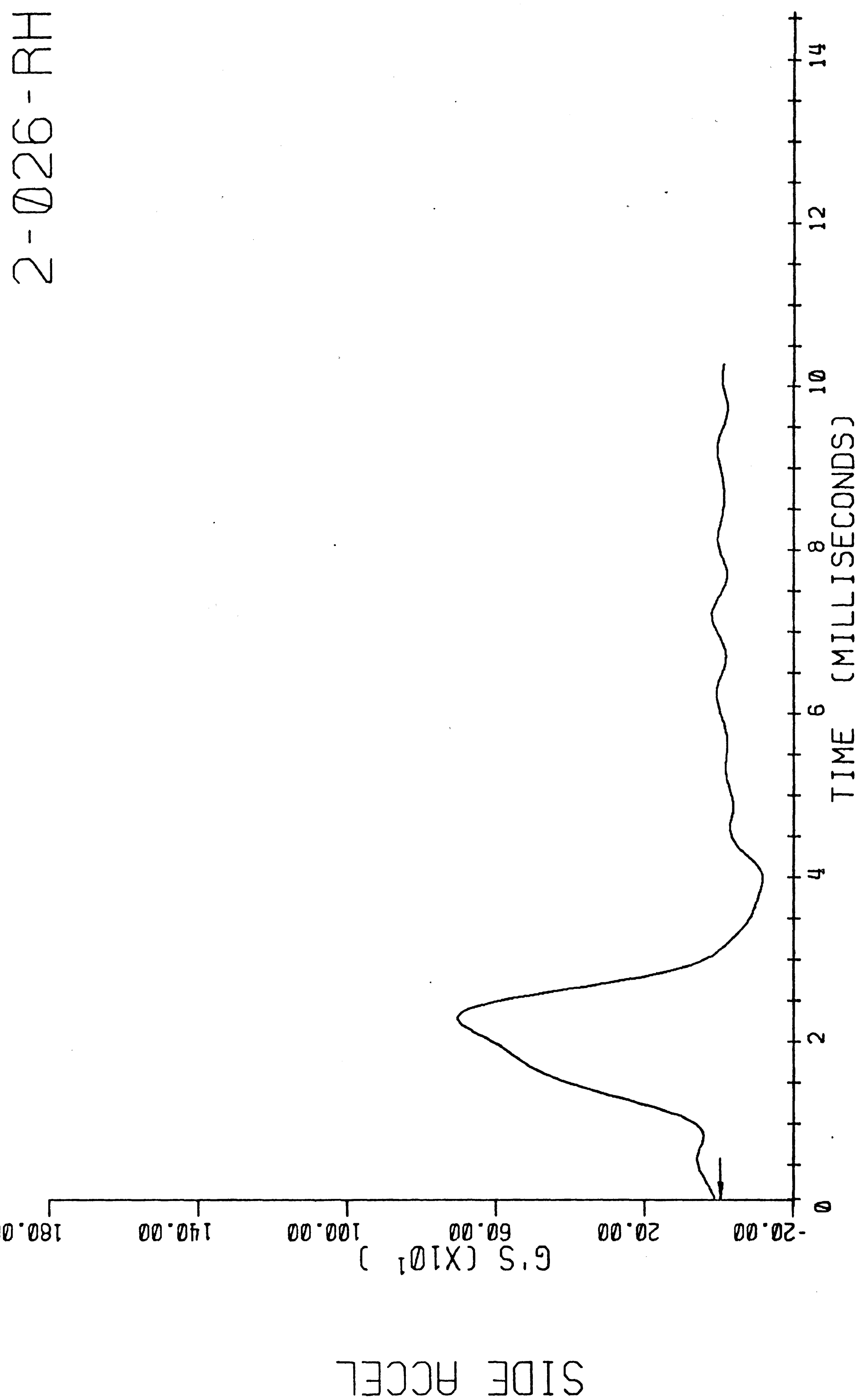
1. Minor haematome over Lt. zygomatic arch
2. Simple fracture of Lt. zygomatic arch
3. Small bruises on parietal lobe from collet
4. Less than 15 min unconscious
5. Intraventricular extravasation of blood in ventricular
6. Highly localized and focussed injury on left parietal lobe
7.
8.
9.
10.
11.
12.
13.
14.
15.

Injuries Due to Impact only (not instrumentation)

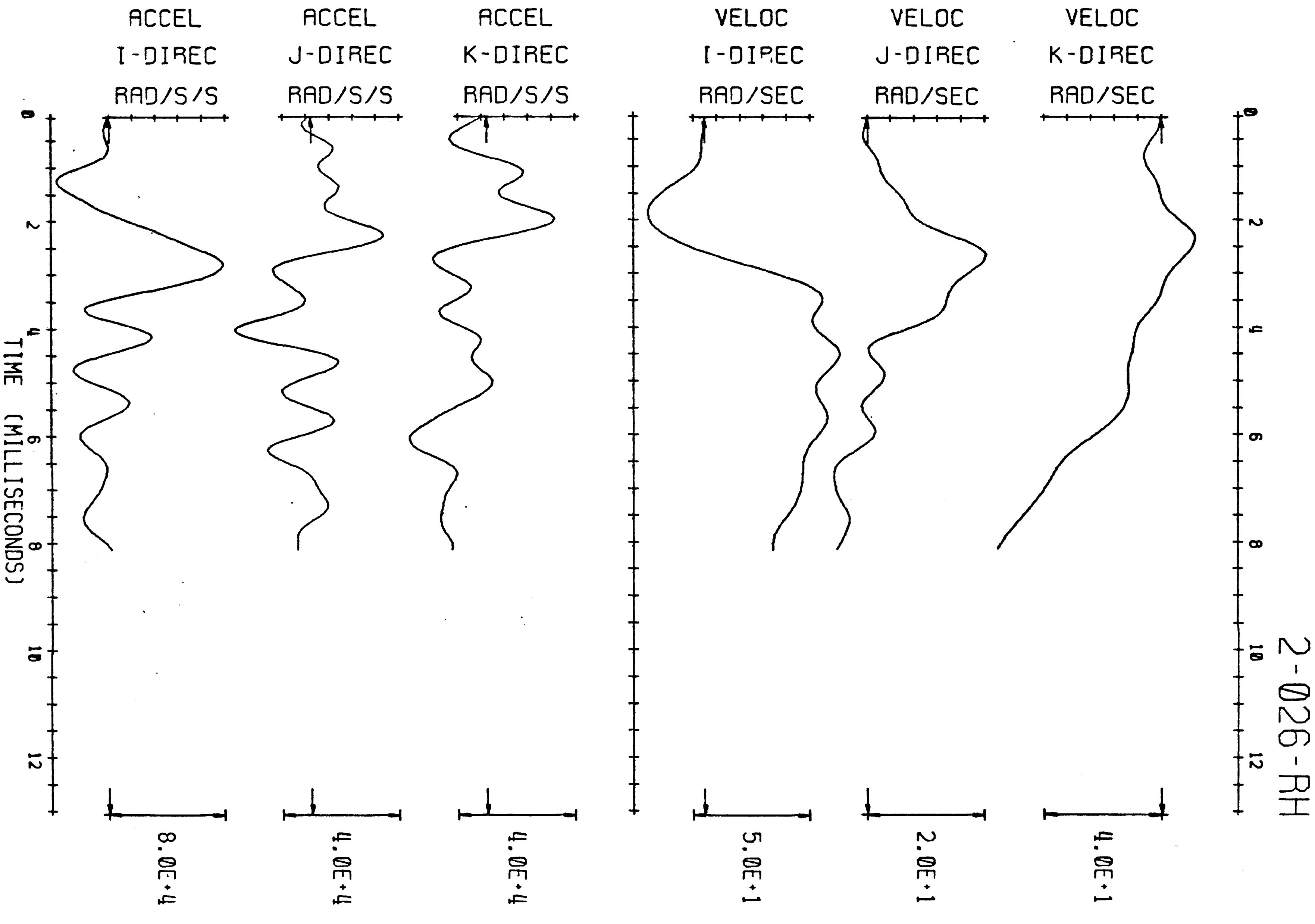
	Injury	AIS
1.	Minor haematome over Lt. zygomatic arch	1
2.	Simple fracture of Lt. zygomatic arch	2
3.	Less than 15 min. unconscious	2
4.	Intraventricular extravasation of blood in vent.	3
5.	Localized injury on Lt. front parietal lobe	3
6.		
7.		
8.		
9.		
10.		

AIS Overall 4


2-026-RH
FORCE
LBS (X10¹)
-10.00
30.00
70.00
110.00
150.00
190.00
TIME (MILLISECONDS)
0
2
4
6
8
10
12
14

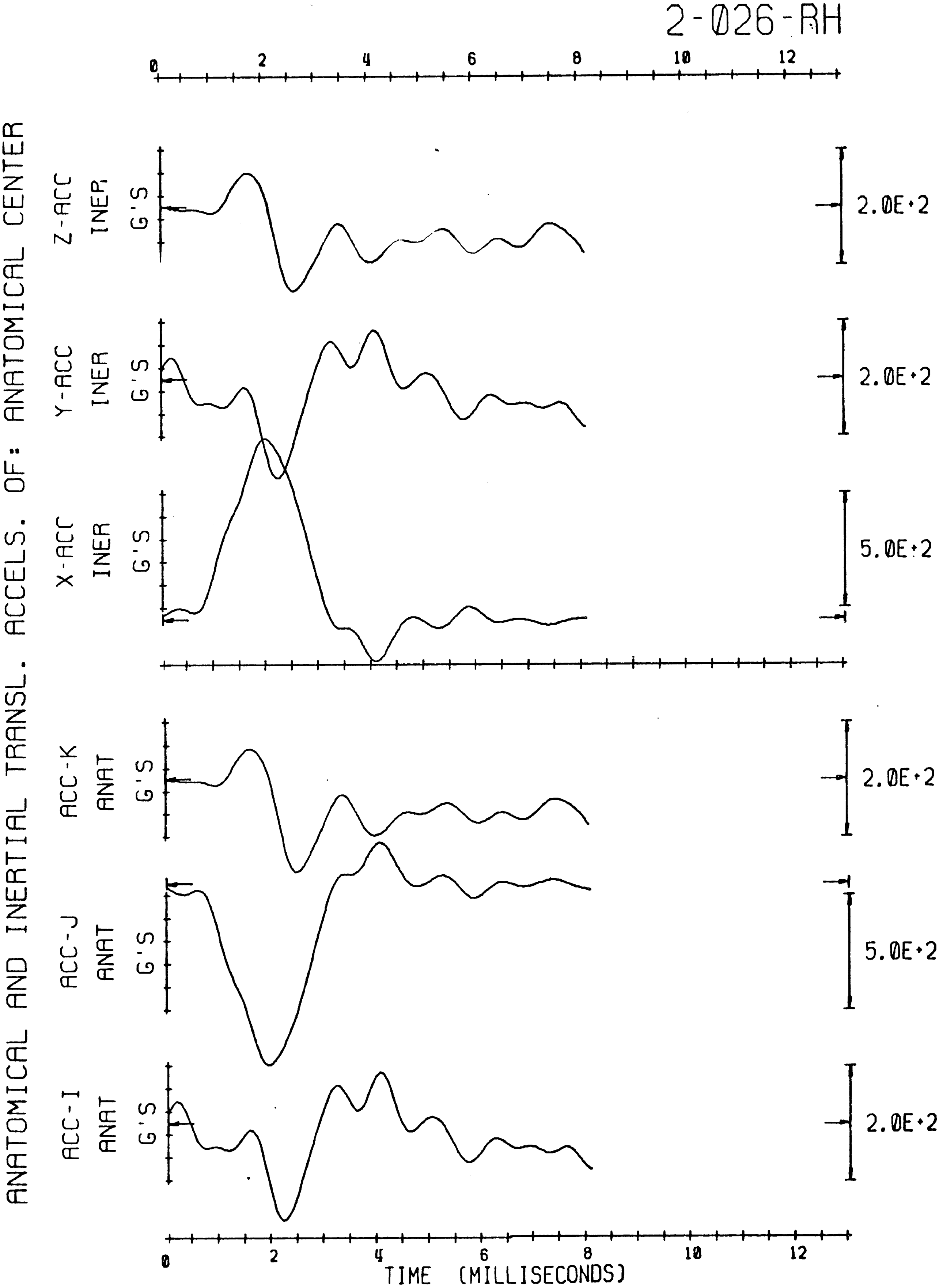

2-026-RH
SIDE ACCEL
G'S (X10¹)
-20.00
20.00
60.00
100.00
140.00
180.00
TIME (MILLISECONDS)
0
2
4
6
8
10
12
14

ANGULAR ACCELERATIONS AND VELOCITIES --- ALONG ANATOMICAL AXES



2-026-RH

3-D RIGID BODY MOTION ANALYSIS



3-D RIGID BODY MOTION ANALYSIS

HEAD IMPACT TEST SUMMARY

TEST NO. 027 TEST DATE 2/6/75

TEST SUBJECT

SPECIES Rhesus

Body Weight 9.88 lb.

Sitting Height (Top of Head to bottom of Buttocks) 18.8 in.

Head Weight 0.98 lbs

Brain Weight 0.220 lbs

Brain Volume 6.18 in^3

Skull Inside Length A 2.80 in

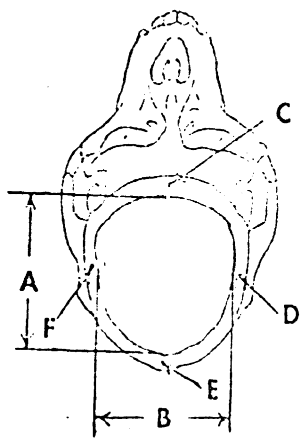
Skull Inside Width B 2.35 in

Skull Thickness at Pt. C 0.120 in

Skull Thickness at Pt. D 0.075 in

Skull Thickness at Pt. E 0.120 in

Skull Thickness at Pt. F 0.075 in



IMPACT CONDITIONS

Location of Impact Left side of head

Type of Impact 4" round rigid, with 0.50 inch thick 1 5/16 x 1 5/8 blue styrofoam

Impact Velocity 34.52 ft/sec

TEST NO. 027

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site ______

Opposite to Impact Site ______

Epidural Pressures in Direction of Impact:

At Impact Site ______

Opposite to Impact Site ______

Strain Gage Rosettes:

Right Parietal Gage ______

Left Parietal Gage ______

Frontal Gage ______

Force: ______

High Speed Motion Pictures:

Side Camera ______

Frame Rate ______

Type II

Accelerations in Direction of Impact:

At Impact Site No

Opposite to Impact Site Good

Rigid Body Head Motion Analysis: Good

EEG DATA: Pre-Impact Yes

Post Impact Yes

- NOT ANALYZED -

Force: Good

TEST NO. 027

High Speed Motion Pictures:

Side Camera Good

Framing Rate 3000 fps

Front Camera Good

Framing Rate 1000 fps

INJURY:

Condition Prior to Impact Slight muscle tone, slight eye reflex, and some shivering

		Time After Impact	Condition
Consciousness	1.	0 min.	Unconscious
	2.	15 min.	Unconscious
	3.	18 min.	Beginning to move
	4.	20 min.	Slight eye reflex
	5.	26 min.	Rapid breathing
	6.	35 min.	Deep breathing
	7.	50 min.	Conscious
	8.		
	9.		
	10.		

TEST NO. 027

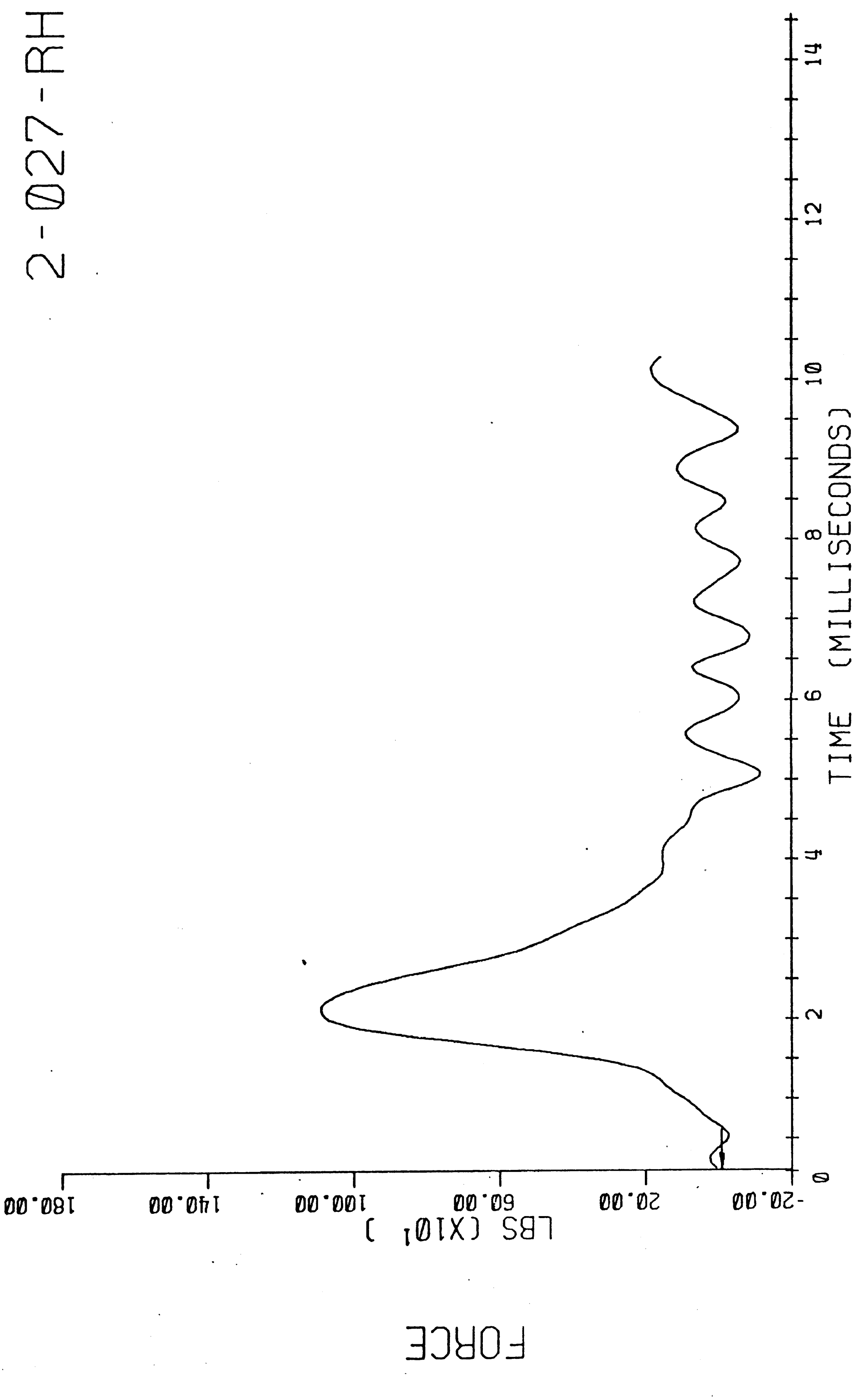
Autopsy Summary:

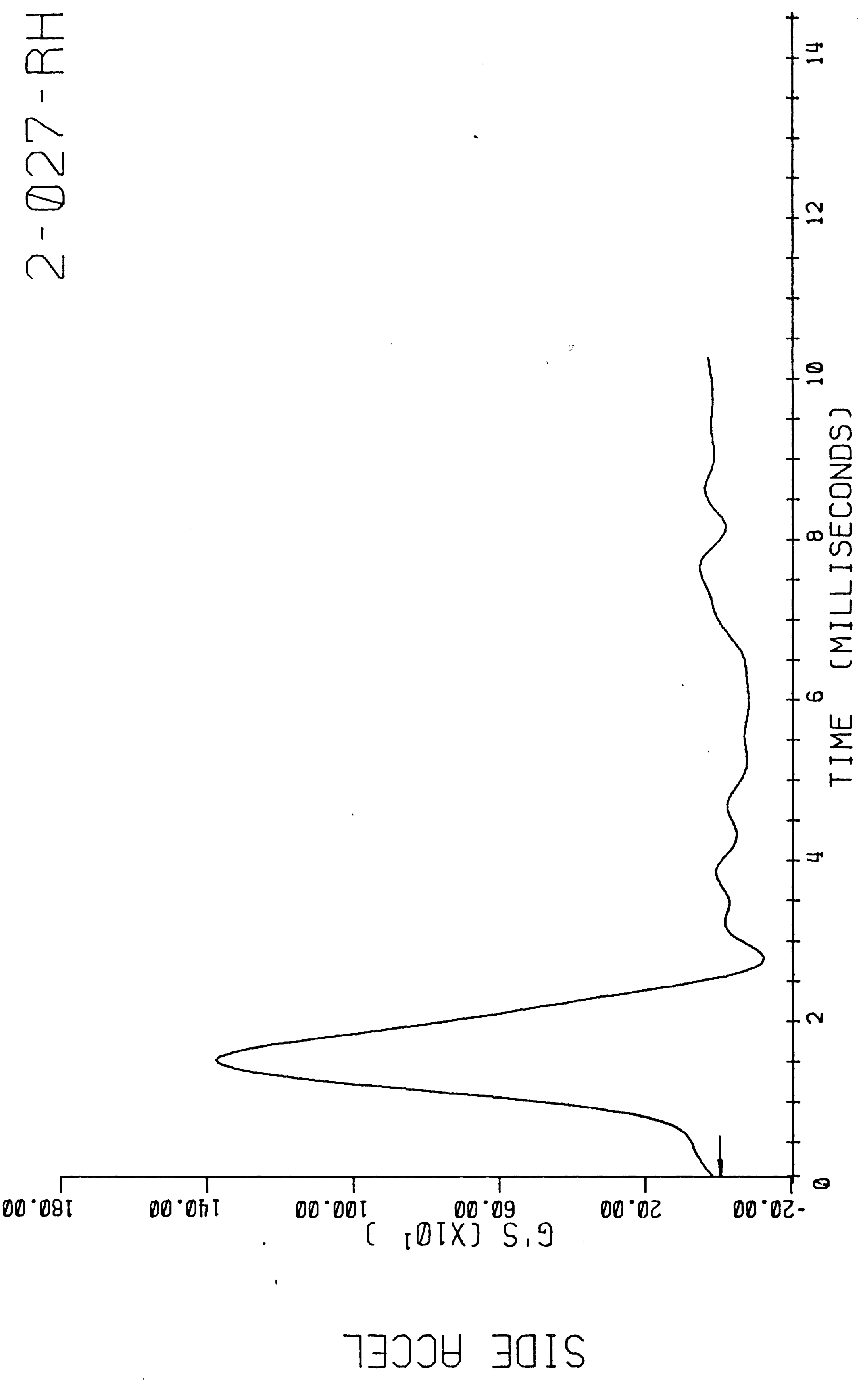
1. Small bruise on parietal lobe from collets and accelerometers
2. Unconscious with severe neurological signs > 15 min.
3. Highly localized and focussed injury on Rt. parietal lobe
4.
5.
6.
7.
8.
9.
10.
11.
12.
13.
14.
15.

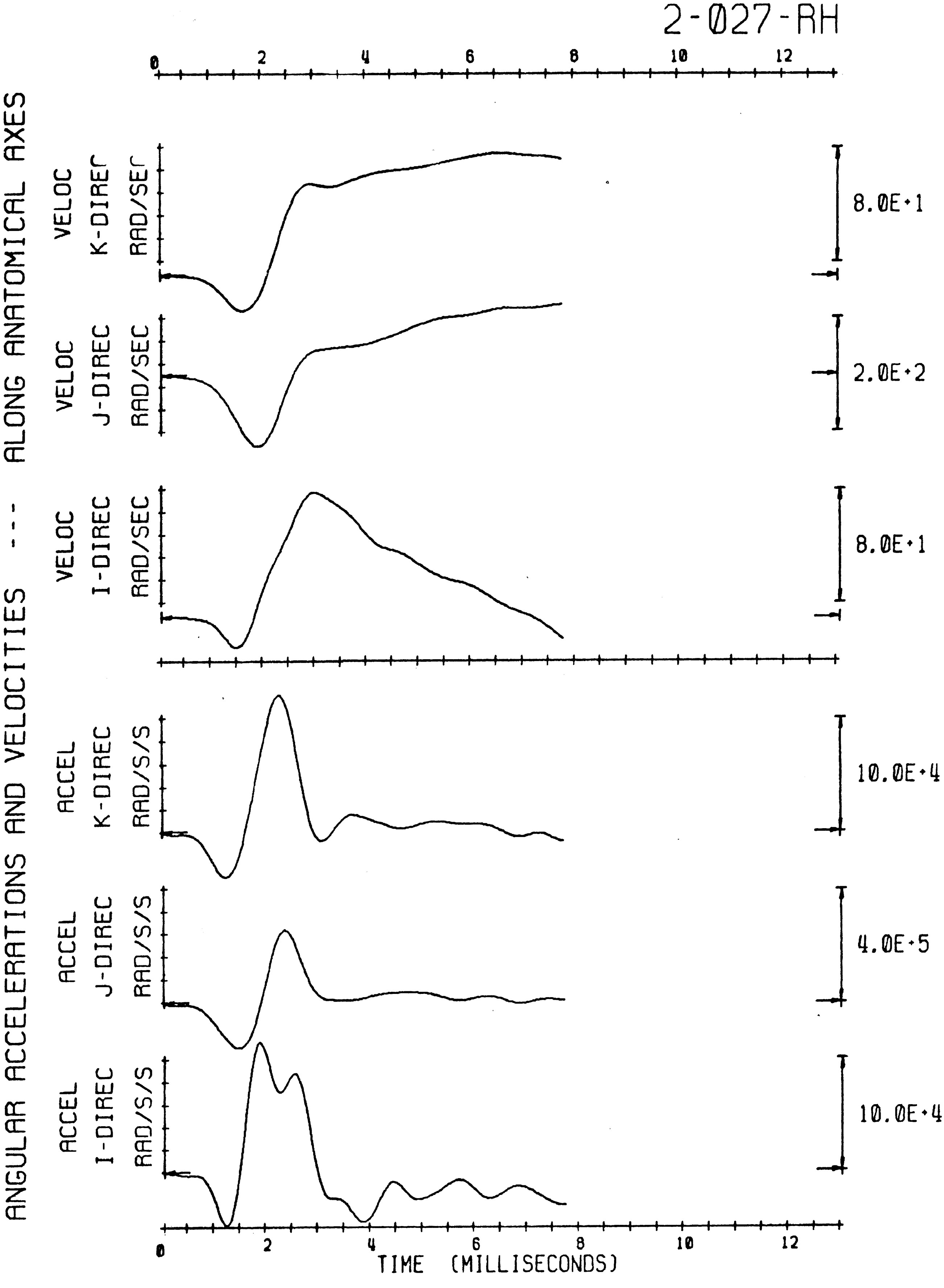
Injuries Due to Impact only (not instrumentation)

	Injury	AIS
1.	Unconscious with severe neurological signs > 15 min.	4
2.	Highly localized and focussed injury on Rt. parietal lobe	3
3.		
4.		
5.		
6.		
7.		
8.		
9.		
10.		

AIS Overall 4

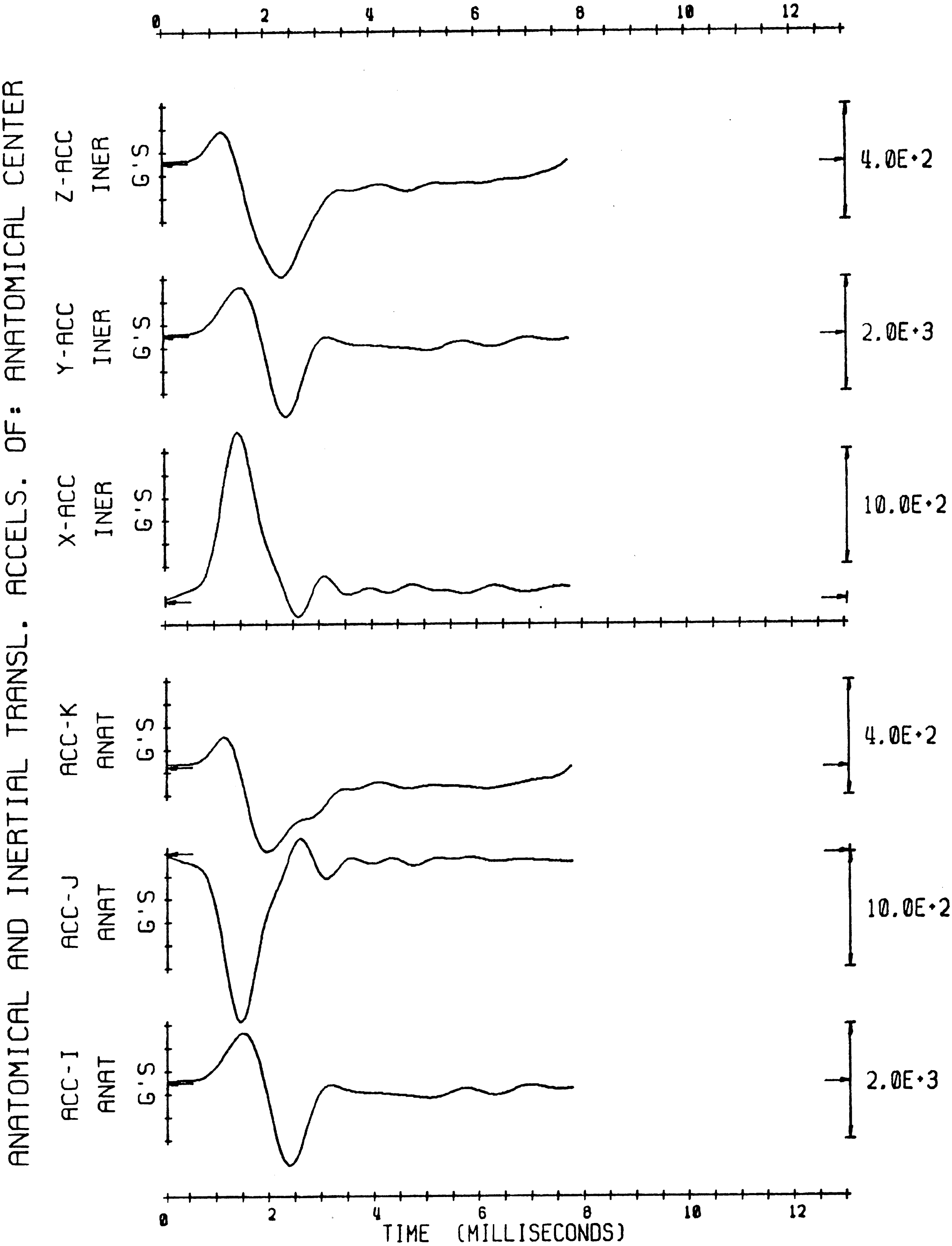

2-027-RH
TIME (MILLISECONDS)
0
2
4
6
8
10
12
14
-20.00
20.00
60.00
100.00
140.00
180.00
LBS (X10¹)
FORCE


2-Ø27-RH
TIME (MILLISECONDS)
0
2
4
6
8
1Ø
12
14
G'S (X1Ø1)
-20.00
20.00
60.00
100.00
140.00
180.00
SIDE ACCEL



3-D RIGID BODY MOTION ANALYSIS

2-027-RH



3-D RIGID BODY MOTION ANALYSIS

HEAD IMPACT TEST SUMMARY

TEST NO. 030 TEST DATE 2/14/75

TEST SUBJECT

SPECIES Rhesus

Body Weight 13.86 lb.

Sitting Height (Top of Head to bottom of Buttocks) 20.50 in.

Head Weight 1.38 lbs

Brain Weight 0.247 lbs

Brain Volume 6.89 in^3

Skull Inside Length A 2.95 in

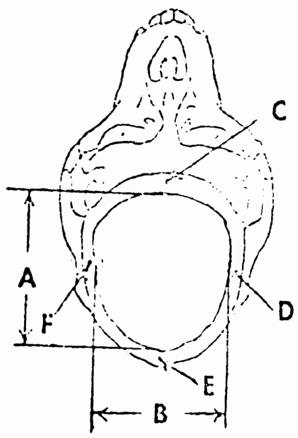
Skull Inside Width B 2.31 in

Skull Thickness at Pt. C 0.220 in

Skull Thickness at Pt. D 0.095 in

Skull Thickness at Pt. E 0.170 in

Skull Thickness at Pt. F 0.100 in



IMPACT CONDITIONS

Location of Impact Left side of head

Type of Impact 4" round rigid, with 0.50 inch thick 1 x 1 blue styrofoam

Impact Velocity 30.02 ft/sec

TEST NO. 030

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site ______________

Opposite to Impact Site ______________

Epidural Pressures in Direction of Impact:

At Impact Site ______________

Opposite to Impact Site ______________

Strain Gage Rosettes:

Right Parietal Gage ______________

Left Parietal Gage ______________

Frontal Gage ______________

Force: ______________

High Speed Motion Pictures:

Side Camera ______________

Frame Rate ______________

Type II

Accelerations in Direction of Impact:

At Impact Site No

Opposite to Impact Site Good

Rigid Body Head Motion Analysis: Good

EEG DATA: Pre-Impact Yes

Post Impact Yes

- NOT ANALYZED -

Force: Good

TEST NO. 030

High Speed Motion Pictures

Side Camera	Good
Framing Rate	3000 fps
Front Camera	Good
Framing Rate	1000 fps

INJURY:

Condition Prior to Impact Slight muscle tone, slight eye reflex, and some shivering

Consciousness		Time After Impact	Condition
	1.	0 min.	Dazed
	2.	1 min. 30 secs.	Conscious
	3.		
	4.		
	5.		
	6.		
	7.		
	8.		
	9.		
	10.		

TEST NO. 030

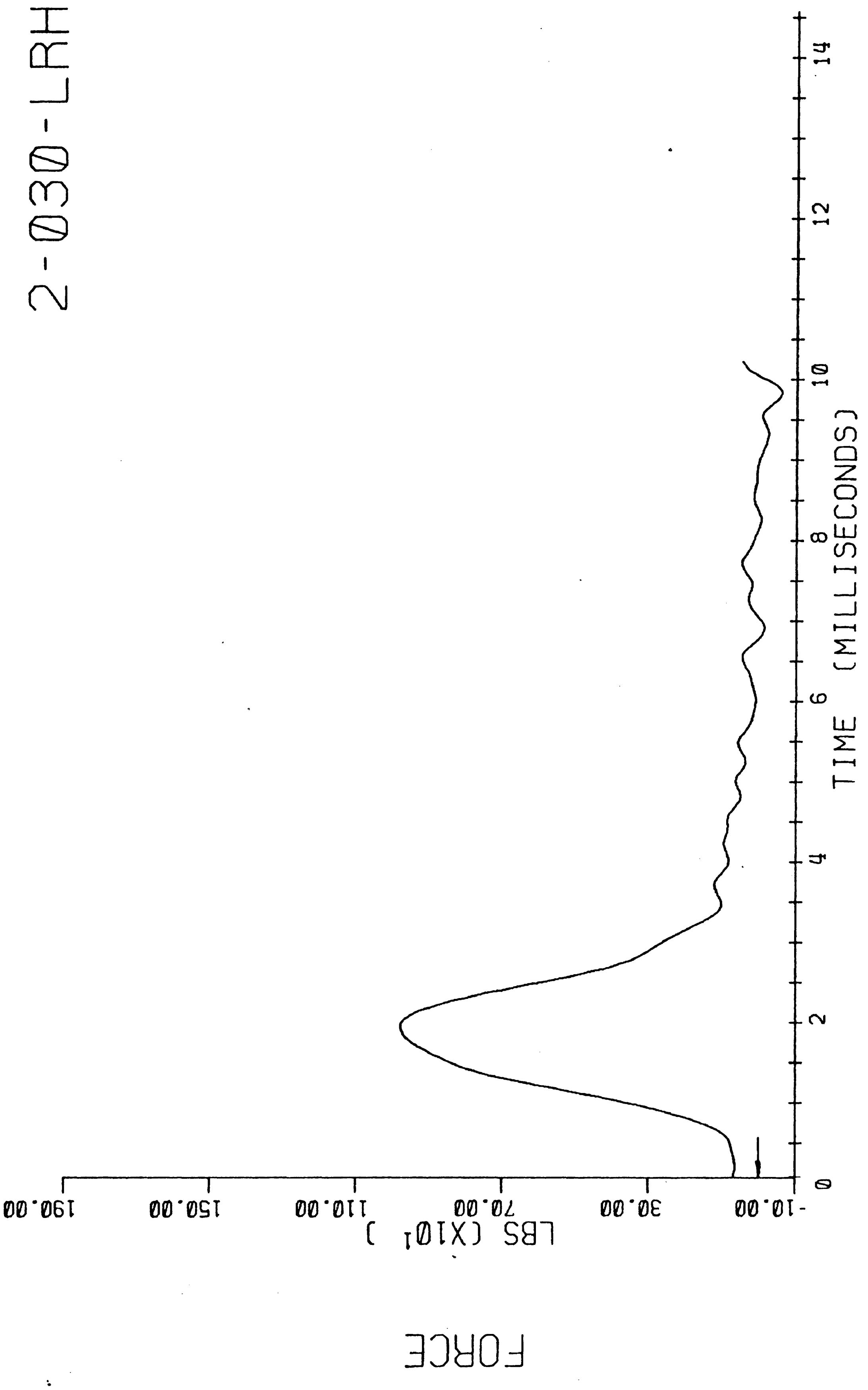
Autopsy Summary:

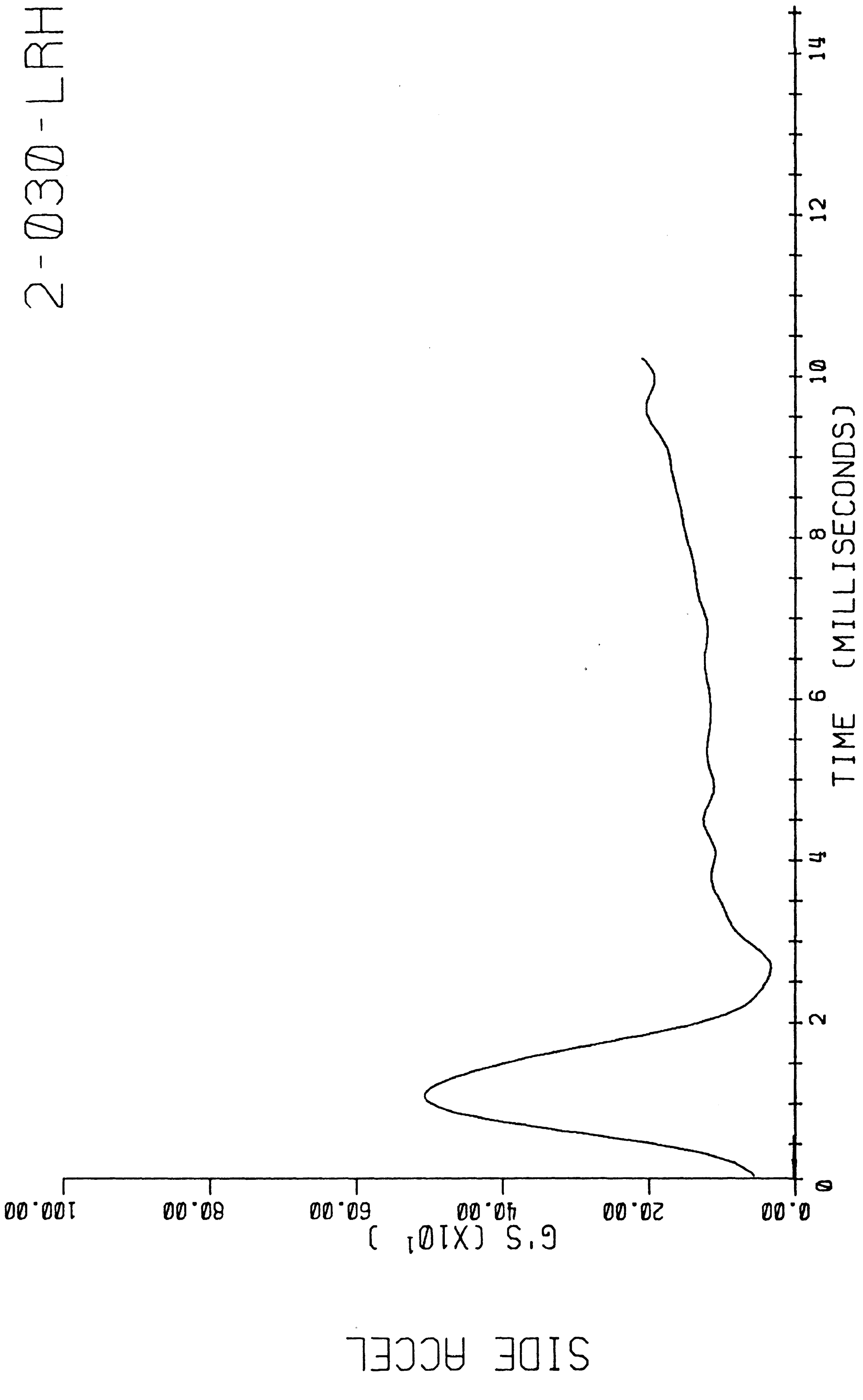
1. Minor hematome over Lt. zygomatic arch
2. Simple fracture of Lt. zygomatic arch
3. Small bruises on parietal lobe from collets
4. Dazed 1 min.
5.
6.
7.
8.
9.
10.
11.
12.
13.
14.
15.

Injuries Due to Impact only (not instrumentation)

	Injury	AIS
1.	Minor hematome over Lt. zygomatic arch	1
2.	Simple fracture of Lt. zygomatic arch	2
3.	Dazed 1 min.	1
4.		
5.		
6.		
7.		
8.		
9.		
10.		

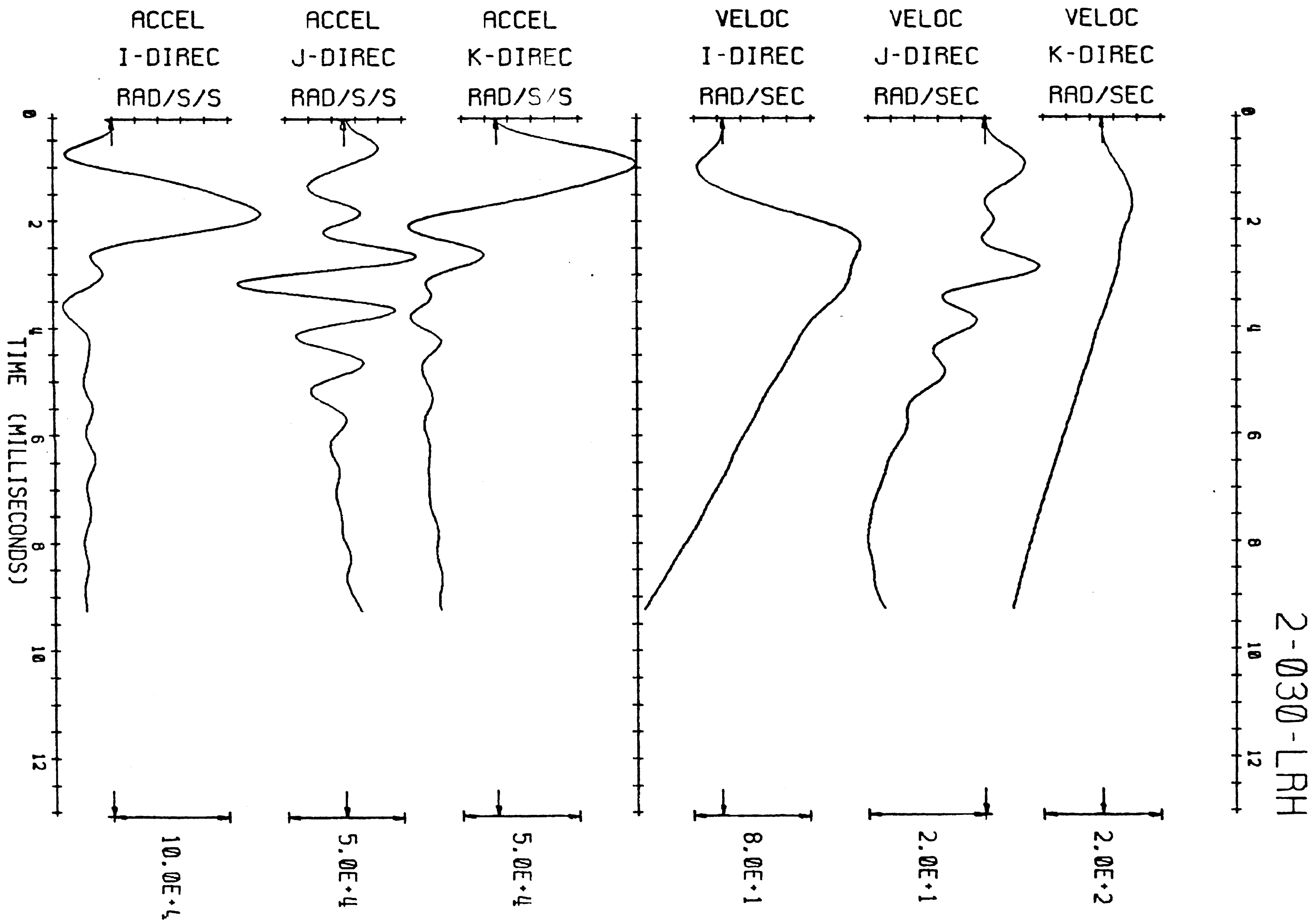
AIS Overall 2


2-Ø30-LRH
TIME (MILLISECONDS)
0
2
4
6
8
10
12
14
FORCE
LBS (X1Ø1)
-10.00
30.00
70.00
110.00
150.00
190.00

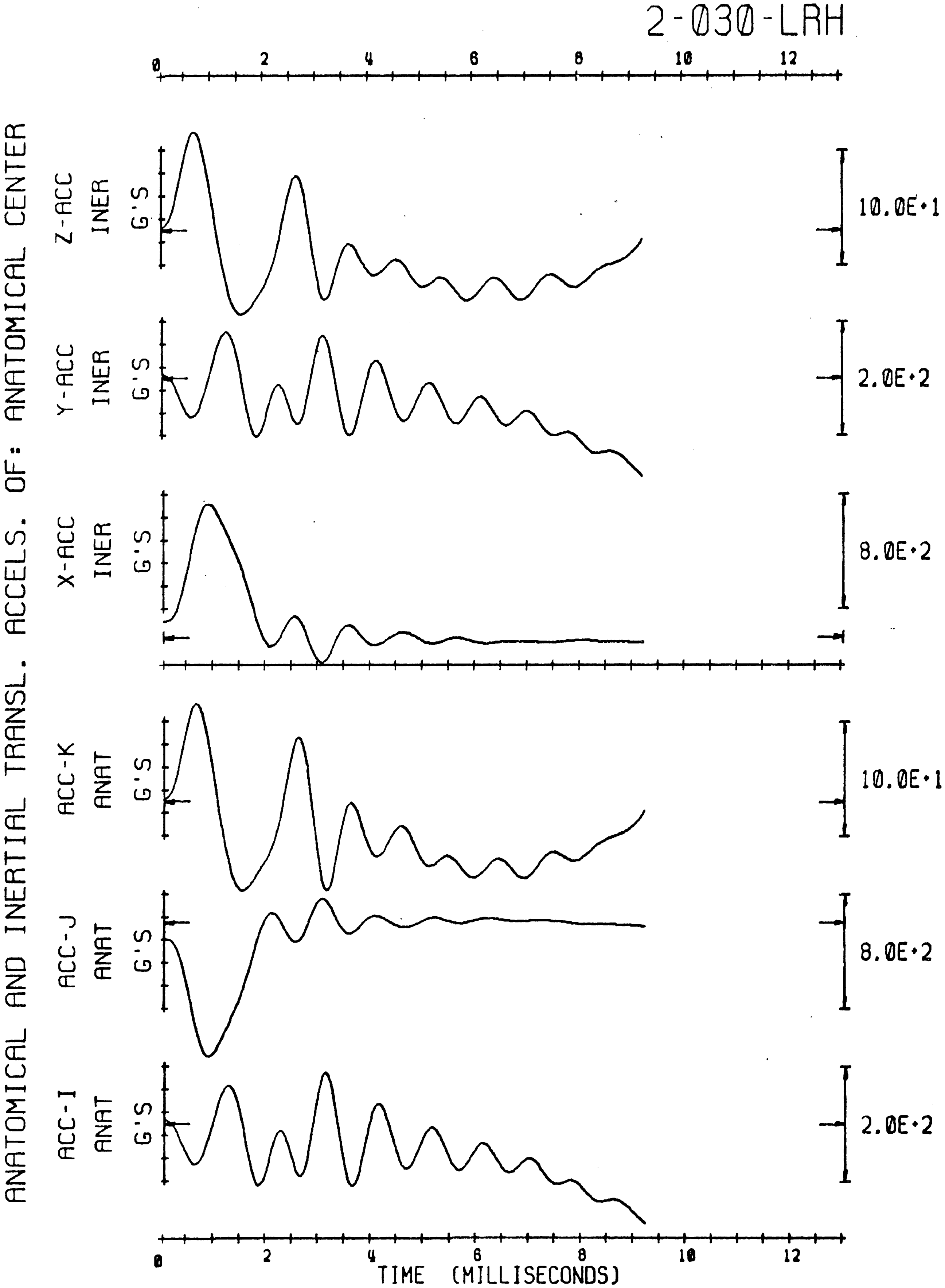


2-Ø3Ø-LRH
TIME (MILLISECONDS)
0
2
4
6
8
10
12
14
G'S (X10¹)
0.00
20.00
40.00
60.00
80.00
100.00
SIDE ACCEL

ANGULAR ACCELERATIONS AND VELOCITIES --- ALONG ANATOMICAL AXES



3-D RIGID BODY MOTION ANALYSIS



3-D RIGID BODY MOTION ANALYSIS

HEAD IMPACT TEST SUMMARY

TEST NO. 031 TEST DATE 2/14/75

TEST SUBJECT

SPECIES Rhesus

Body Weight 13.88 lb.

Sitting Height (Top of Head to bottom of Buttocks) 19.50 in.

Head Weight 1.38 lbs

Brain Weight 0.248 lbs

Brain Volume 6.98 in^3

Skull Inside Length A 2.97 in

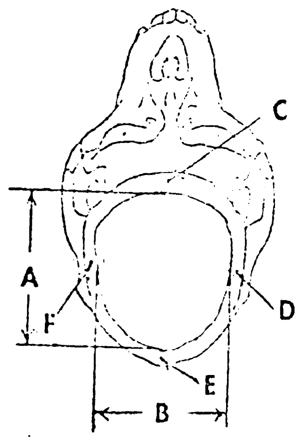
Skull Inside Width B 2.48 in

Skull Thickness at Pt. C 0.200 in

Skull Thickness at Pt. D 0.065 in

Skull Thickness at Pt. E 0.110 in

Skull Thickness at Pt. F 0.065 in



IMPACT CONDITIONS

Location of Impact Left side of head

Type of Impact 4" round rigid, with 0.50 inch thick 1 x 1 blue styrofoam

Impact Velocity 39.49 ft/sec

TEST NO. 031

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site ____________

Opposite to Impact Site ____________

Epidural Pressures in Direction of Impact:

At Impact Site ____________

Opposite to Impact Site ____________

Strain Gage Rosettes:

Right Parietal Gage ____________

Left Parietal Gage ____________

Frontal Gage ____________

Force: ____________

High Speed Motion Pictures:

Side Camera ____________

Frame Rate ____________

Type II

Accelerations in Direction of Impact:

At Impact Site No

Opposite to Impact Site Lost

Rigid Body Head Motion Analysis: Fair

EEG DATA: Pre-Impact Yes

Post Impact Yes

- NOT ANALYZED -

Force: Fair

High Speed Motion Pictures:

Side Camera Good

Framing Rate 3000 fps

Front Camera Good

Framing Rate 1000 fps

INJURY:

Condition Prior to Impact Slight muscle tone, slight eye reflex, and some shivering

		Time After Impact	Condition
Consciousness	1.	0 min.	Unconscious
	2.	12 min.	Conscious
	3.		
	4.		
	5.		
	6.		
	7.		
	8.		
	9.		
	10.		

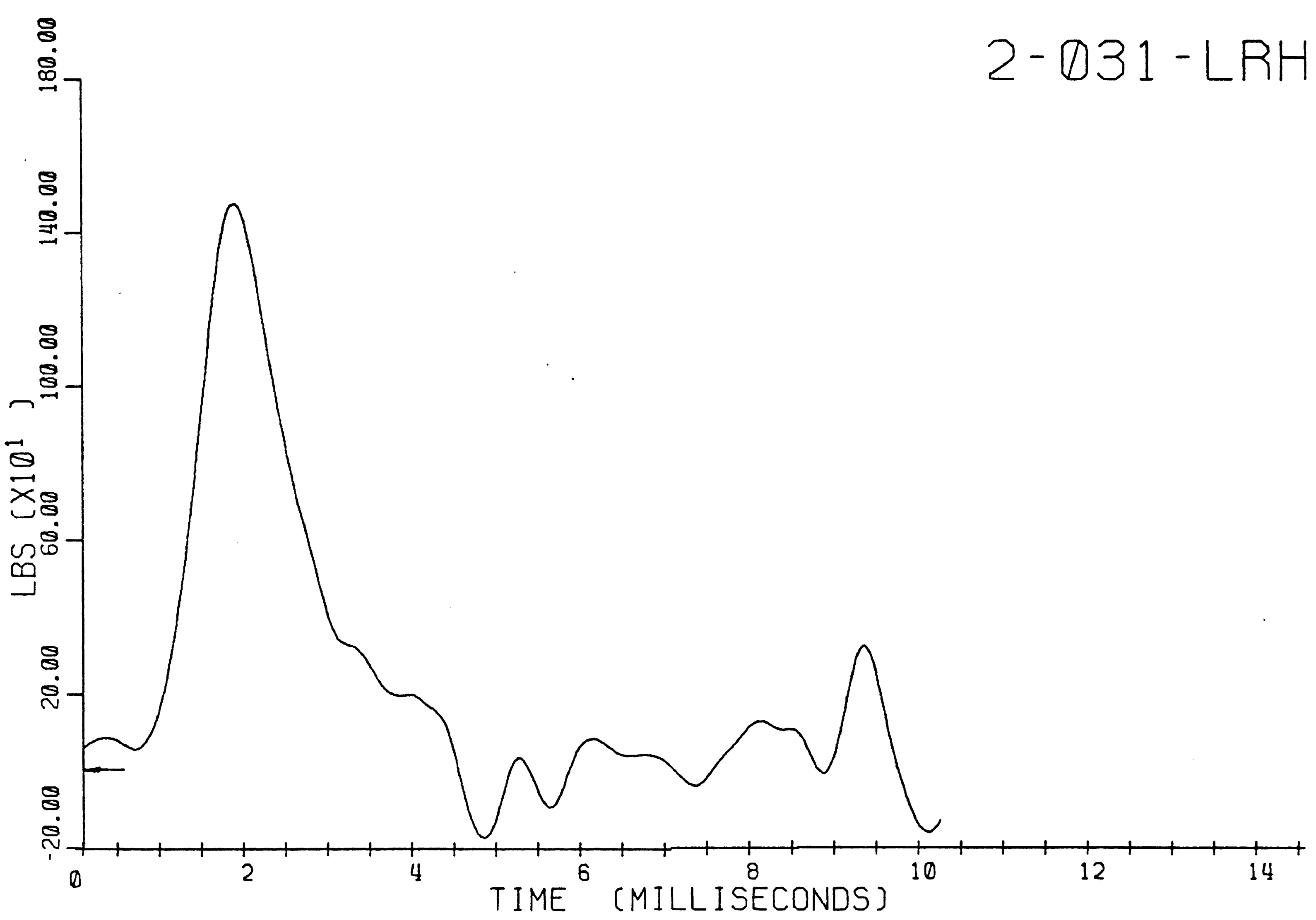
Autopsy Summary:

1. Laceration over Lt. zygomatic arch, vessel involvement
2. Simple fracture of Lt. zygomatic arch
3. Small bruises on parietal lobes from collets
4. Unconscious less than 15 min.
5.
6.
7.
8.
9.
10.
11.
12.
13.
14.
15.

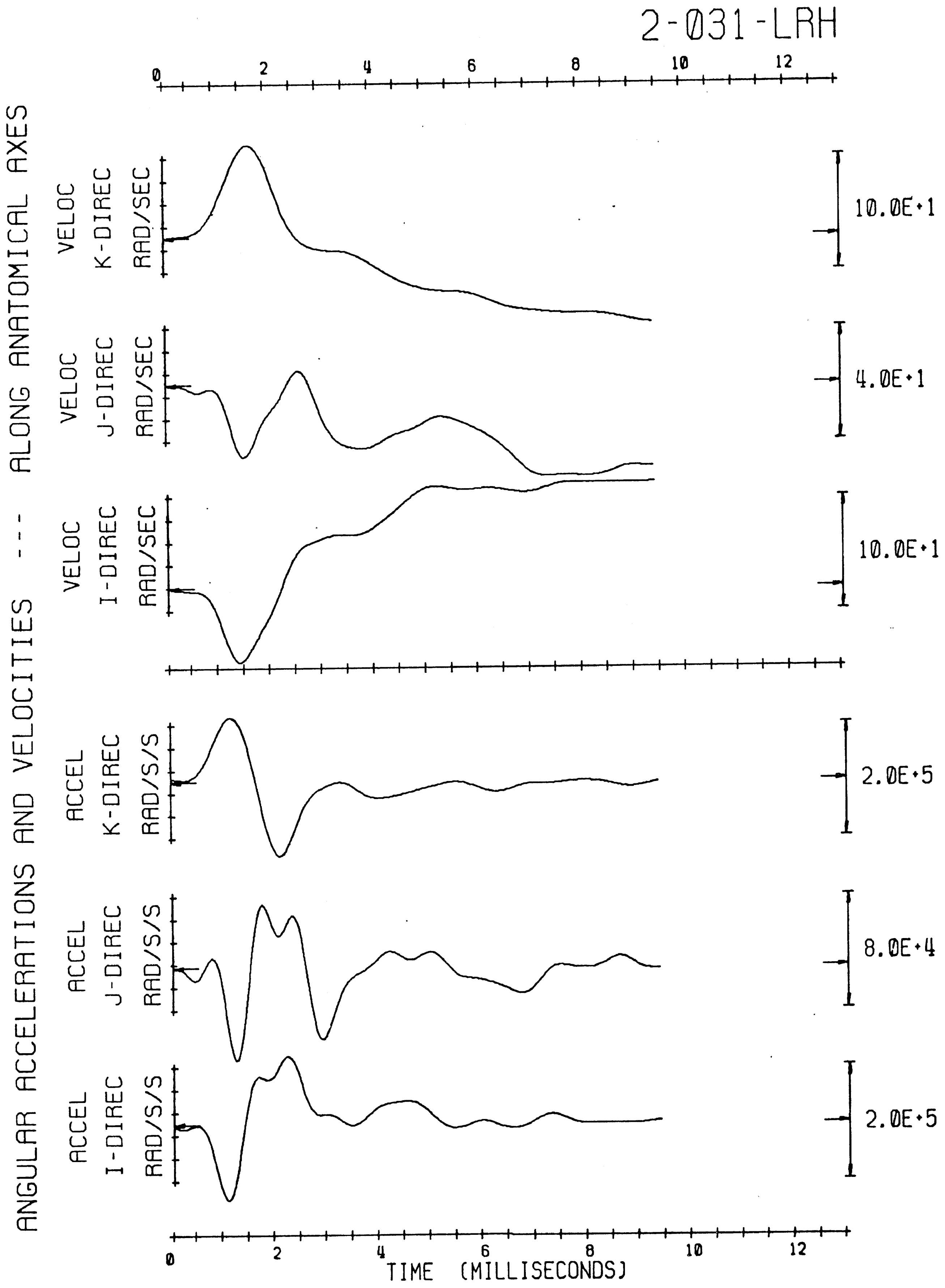
Injuries Due to Impact only (not instrumentation)

	Injury	AIS
1.	Laceration over Lt. zygomatic arch, vessel involvement	3
2.	Simple fracture of Lt. zygomatic arch	2
3.	Unconscious less than 15 min.	2
4.		
5.		
6.		
7.		
8.		
9.		
10.		

AIS Overall 3

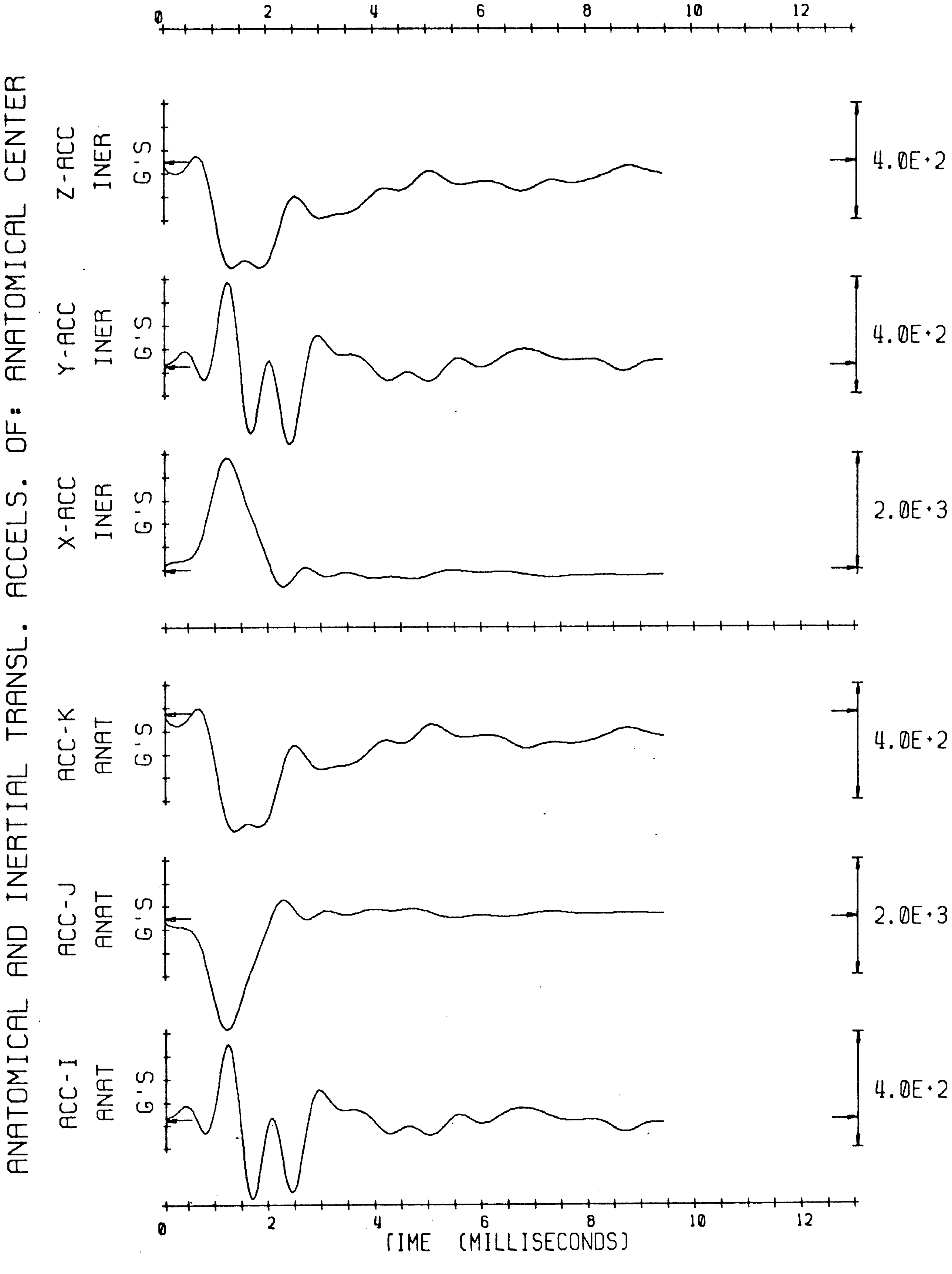


2-Ø31-LRH
FORCE
LBS (X1Ø¹)
180.00
140.00
100.00
60.00
20.00
-20.00
0
2
4
6
8
10
12
14
TIME (MILLISECONDS)



3-D RIGID BODY MOTION ANALYSIS

2-031-LRH



3-D RIGID BODY MOTION ANALYSIS

HEAD IMPACT TEST SUMMARY

TEST NO. 086 TEST DATE 8/7/75

TEST SUBJECT

SPECIES Cynomolgus

Body Weight 6.60 lb.

Sitting Height (Top of Head to bottom of Buttocks) 15.25 in.

Head Weight 0.75 lbs

Brain Weight 0.119 lbs

Brain Volume 3.05 in^3

Skull Inside Length A 2.356 in

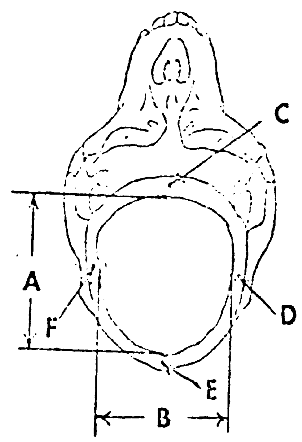
Skull Inside Width B 1.830 in

Skull Thickness at Pt. C 0.134 in

Skull Thickness at Pt. D 0.085 in

Skull Thickness at Pt. E 0.125 in

Skull Thickness at Pt. F 0.045 in



IMPACT CONDITIONS

Location of Impact Back of head

Type of Impact Four inch diameter rigid impactor

Impact Velocity 42.96 ft/sec

TEST NO. 086

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site ______________

Opposite to Impact Site ______________

Epidural Pressures in Direction of Impact:

At Impact Site ______________

Opposite to Impact Site ______________

Strain Gage Rosettes:

Right Parietal Gage ______________

Left Parietal Gage ______________

Frontal Gage ______________

Force: ______________

High Speed Motion Pictures:

Side Camera ______________

Frame Rate ______________

Type II

Accelerations in Direction of Impact:

At Impact Site No

Opposite to Impact Site No

Rigid Body Head Motion Analysis: Loss of one channel

EEG DATA: Pre-Impact No

Post Impact No

- NOT ANALYZED -

Force: Good

TEST NO. 086

High Speed Motion Pictures:

Side Camera: Good

Framing Rate: 3000 fps

Front Camera: Good

Framing Rate: 1000 fps

INJURY:

Condition Prior to Impact: Good muscle tone and eye reflex, conscious and shivering

		Time After Impact	Condition
Consciousness	1.	0 min.	Unconscious
	2.	3 min.	Dead
	3.		
	4.		
	5.		
	6.		
	7.		
	8.		
	9.		
	10.		

TEST NO. 086

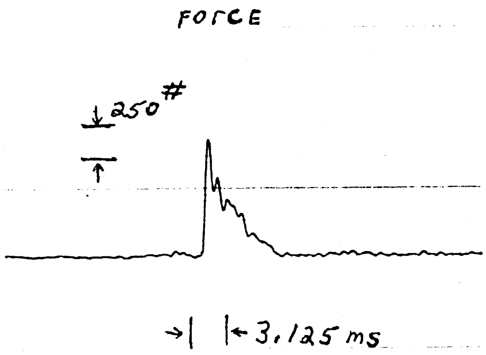
Autopsy Summary:

1. Three occipital skull fractures
2. Three Rt. parietal skull fractures
3. Two basilar skull fractures
4. Abrasion neck muscle (occipital)
5. Subdural hematoma Lt. temporal lobe
6. Laceration at intersection of parietal and occipital lobes
7. Laceration of Rt. frontal lobe
8. Laceration of Rt. parietal lobe
9. Laceration of Lt. frontal lobe
10. Massive subarachnoid hemorrhage
11. Circular bruise under accelerometer collet Lt. parietal lobe
12. Circular bruise under accelerometer collet Rt. parietal lobe
13.
14.
15.

Injuries Due to Impact only (not instrumentation)

	Injury	AIS
1.	Occipital skull fractures	4
2.	Parietal skull fractures	4
3.	Basilar skull fractures	3
4.	Abrasion neck muscle	1
5.	Subdural hematoma Lt. temporal	4
6.	Laceration Rt. frontal lobe	4
7.	Laceration Lt. frontal lobe	4
8.	Laceration Rt. parietal lobe	4
9.	Laceration Parietal & Occipital lobe	4
10.	Massive subarachnoid hemorrhage	5

AIS Overall 6


FORCE
250#
3.125 ms

HEAD IMPACT TEST SUMMARY

TEST NO. 087

TEST DATE 8/7/75

TEST SUBJECT

SPECIES Cynomolgous

Body Weight 9.24 lb.

Sitting Height (Top of Head to bottom of Buttocks) 16.00 in.

Head Weight 1.09 lbs

Brain Weight 0.125 lbs

Brain Volume 2.746 in^3

Skull Inside Length A 2.16 in

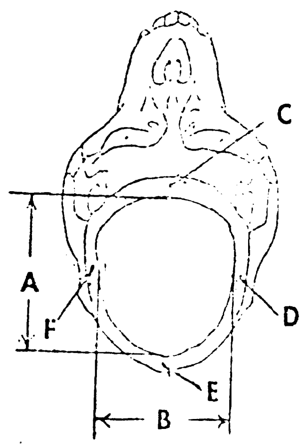
Skull Inside Width B 2.037 in

Skull Thickness at Pt. C 0.092 in

Skull Thickness at Pt. D 0.080 in

Skull Thickness at Pt. E 0.082 in

Skull Thickness at Pt. F 0.062 in



IMPACT CONDITIONS

Location of Impact Back of head

Type of Impact 4 inch round rigid, with two inches of Ensolite

Impact Velocity 43.22 ft/sec

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site ______________

Opposite to Impact Site ______________

Epidural Pressures in Direction of Impact:

At Impact Site ______________

Opposite to Impact Site ______________

Strain Gage Rosettes:

Right Parietal Gage ______________

Left Parietal Gage ______________

Frontal Gage ______________

Force: ______________

High Speed Motion Pictures:

Side Camera ______________

Frame Rate ______________

Type II

Accelerations in Direction of Impact:

At Impact Site No

Opposite to Impact Site No

Rigid Body Head Motion Analysis: Loss of one channel

EEG DATA: Pre-Impact No

Post Impact No

- NOT ANALYZED -

Force: Good

TEST NO. 087

High Speed Motion Pictures:

Side Camera Good

Framing Rate 3000 fps

Front Camera Good

Framing Rate 1000 fps

INJURY:

Condition Prior to Impact Slight muscle tone, slight eye reflex, and some shivering

		Time After Impact	Condition
Consciousness	1.	0 min.	Unconscious
	2.	5 min.	Conscious
	3.		
	4.		
	5.		
	6.		
	7.		
	8.		
	9.		
	10.		

TEST NO. 087

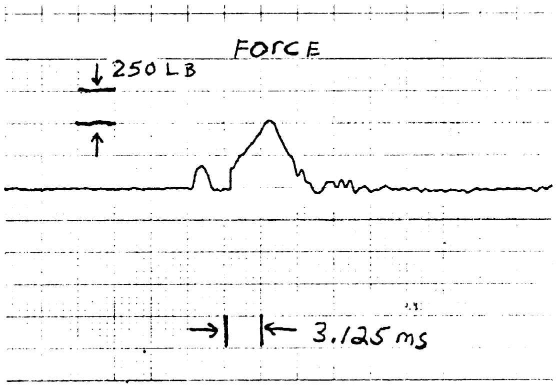
Autopsy Summary

1. Small bruises and hemorrhages due to collets
2. Highly localized contre-coup injury frontal lobe
3. Lesions near optic nerve (contre-coup)
4. Unconscious less than 15 min.
5.
6.
7.
8.
9.
10.
11.
12.
13.
14.
15.

Injuries Due to Impact only (not instrumentation)

		AIS
1.	Highly localized contre-coup injury Lt. frontal lobe	3
2.	Lesions near optic nerve (contre-coup)	3
3.	Unconscious less than 15 minutes	2
4.		
5.		
6.		
7.		
8.		
9.		
10.		

AIS Overall 4


FORCE
250 LB
3.125 ms

HEAD IMPACT TEST SUMMARY

TEST NO. 088 TEST DATE 8/11/75

TEST SUBJECT

SPECIES Cynomolgus

Body Weight 8.36 lb.

Sitting Height (Top of Head to bottom of Buttocks) 16.50 in.

Head Weight 1.09 lbs

Brain Weight 0.156 lbs

Brain Volume 4.27 in^3

Skull Inside Length A 2.379 in

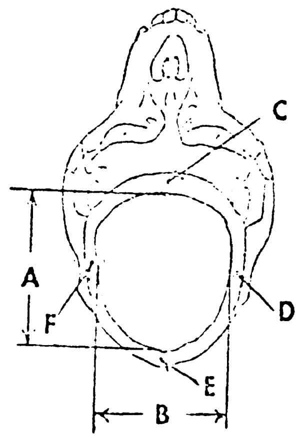
Skull Inside Width B 2.291 in

Skull Thickness at Pt. C 0.115 in

Skull Thickness at Pt. D 0.126 in

Skull Thickness at Pt. E 0.123 in

Skull Thickness at Pt. F 0.121 in



IMPACT CONDITIONS

Location of Impact Left side of head

Type of Impact 4" round rigid, with two inches of Ensolite

Impact Velocity 47.01 ft/sec

TEST NO. 088

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site __________

Opposite to Impact Site __________

Epidural Pressures in Direction of Impact:

At Impact Site __________

Opposite to Impact Site __________

Strain Gage Rosettes:

Right Parietal Gage __________

Left Parietal Gage __________

Frontal Gage __________

Force: __________

High Speed Motion Pictures:

Side Camera __________

Frame Rate __________

Type II

Accelerations in Direction of Impact:

At Impact Site No

Opposite to Impact Site No

Rigid Body Head Motion Analysis: Loss of one channel

EEG DATA: Pre-Impact No

Post Impact No

\- NOT ANALYZED -

Force: Good

TEST NO. 088

High Speed Motion Pictures:

Side Camera Good

Framing Rate 3000 fps

Front Camera Good

Framing Rate 1000 fps

INJURY:

Condition Prior to Impact Slight muscle tone, slight eye reflex, and some shivering

		Time After Impact	Condition
Consciousness	1.	0 min.	Unconscious
	2.	1 min.	Conscious
	3.	4 min.	Unconscious
	4.	8 min.	Conscious
	5.		
	6.		
	7.		
	8.		
	9.		
	10.		

TEST NO. 088

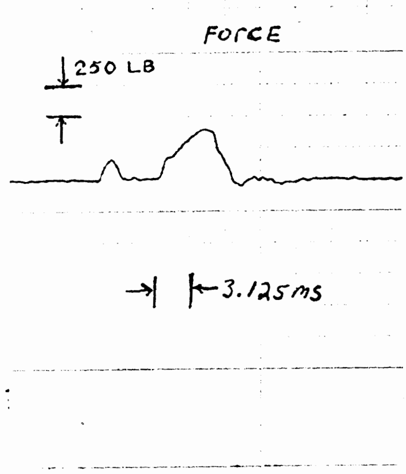
Autopsy Summary:

1. Small bruises and hemorrhage due to collets
2. Hemorrhaging on brain stem
3. Hemorrhaging on frontal mesulcus
4. Unconscious less than 15 min.
5.
6.
7.
8.
9.
10.
11.
12.
13.
14.
15.

Injuries Due to Impact only (not instrumentation)

	Injury	AIS
1.	Hemorrhage on brain stem	4
2.	Hemorrhage on frontal mesulcus	4
3.	Unconscious less than 15 min.	2
4.		
5.		
6.		
7.		
8.		
9.		
10.		

AIS Overall 5


FORCE
250 LB
3.125ms

HEAD IMPACT TEST SUMMARY

TEST NO. 089

TEST DATE 8/11/75

TEST SUBJECT

SPECIES Cynomolgus

Body Weight 10.78 **lb.**

Sitting Height (Top of Head to bottom of Buttocks) 16.50 **in.**

Head Weight 1.39 lbs

Brain Weight 0.125 lbs

Brain Volume 3.05 in^3

Skull Inside Length A 2.537 in

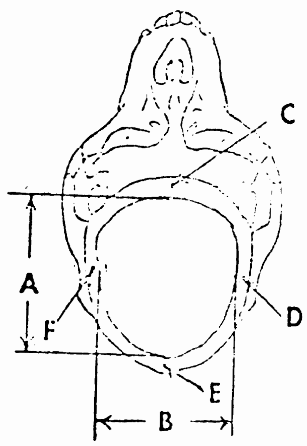
Skull Inside Width B 2.399 in

Skull Thickness at Pt. C 0.239 in

Skull Thickness at Pt. D 0.207 in

Skull Thickness at Pt. E 0.267 in

Skull Thickness at Pt. F 0.188 in



IMPACT CONDITIONS

Location of Impact Left side of head

Type of Impact 4 inch round rigid

Impact Velocity 38.67 ft/sec

TEST NO. 089

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site ______________

Opposite to Impact Site ______________

Epidural Pressures in Direction of Impact:

At Impact Site ______________

Opposite to Impact Site ______________

Strain Gage Rosettes:

Right Parietal Gage ______________

Left Parietal Gage ______________

Frontal Gage ______________

Force: ______________

High Speed Motion Pictures:

Side Camera ______________

Frame Rate ______________

Type II

Accelerations in Direction of Impact:

At Impact Site No

Opposite to Impact Site No

Rigid Body Head Motion Analysis: Good

EEG DATA: Pre-Impact No

Post Impact No

- NOT ANALYZED -

Force: Good

TEST NO. 089

High Speed Motion Picture:

Side Camera Good

Framing Rate 3000 fps

Front Camera Good

Framing Rate 1000 fps

INJURY:

Condition Prior to Impact Slight muscle tone, slight eye reflex, and some shivering

		Time After Impact	Condition
Consciousness	1.	0 min.	Unconscious
	2.	60 min.	Unconscious
	3.		
	4.		
	5.		
	6.		
	7.		
	8.		
	9.		
	10.		

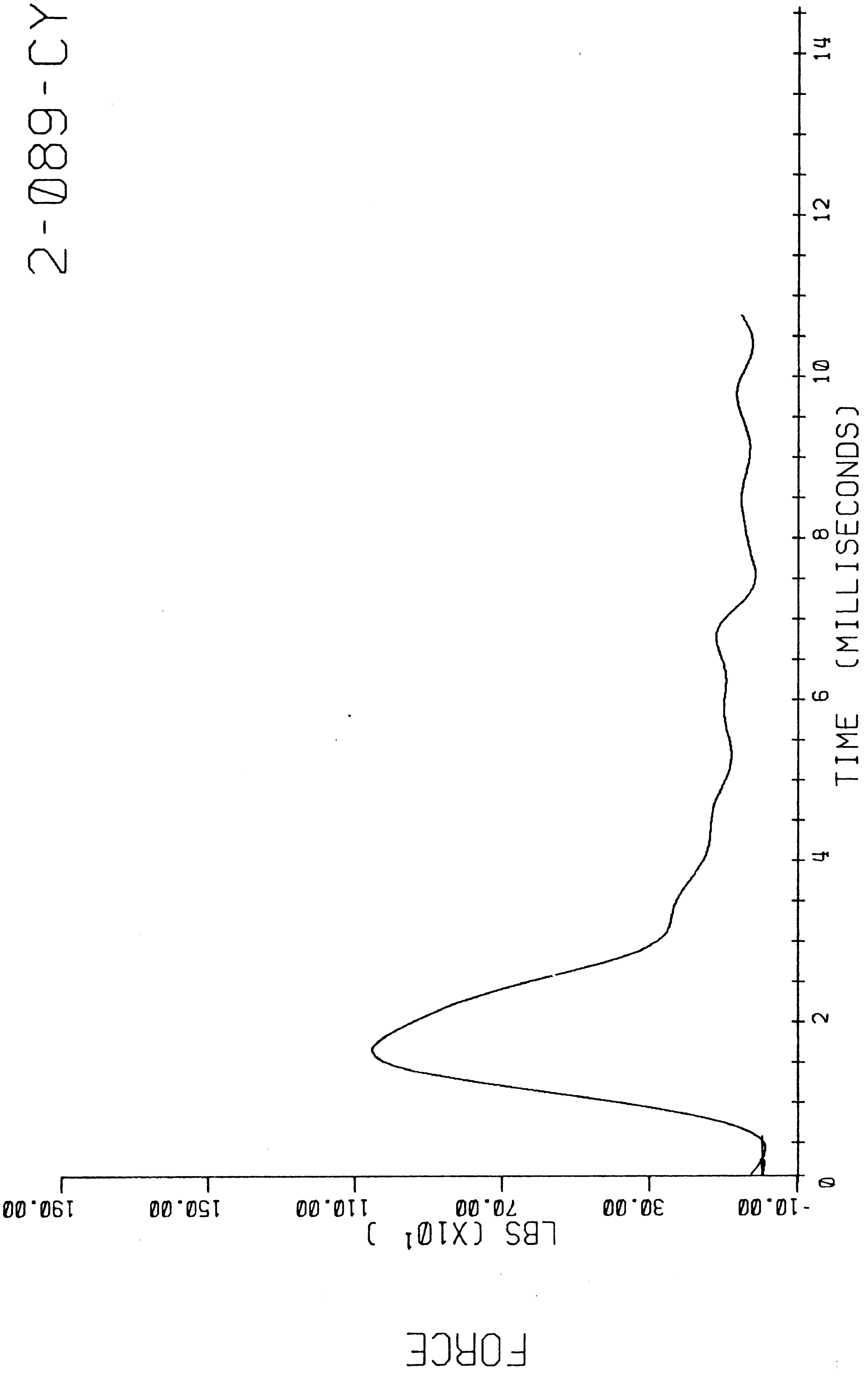
Autopsy Summary:

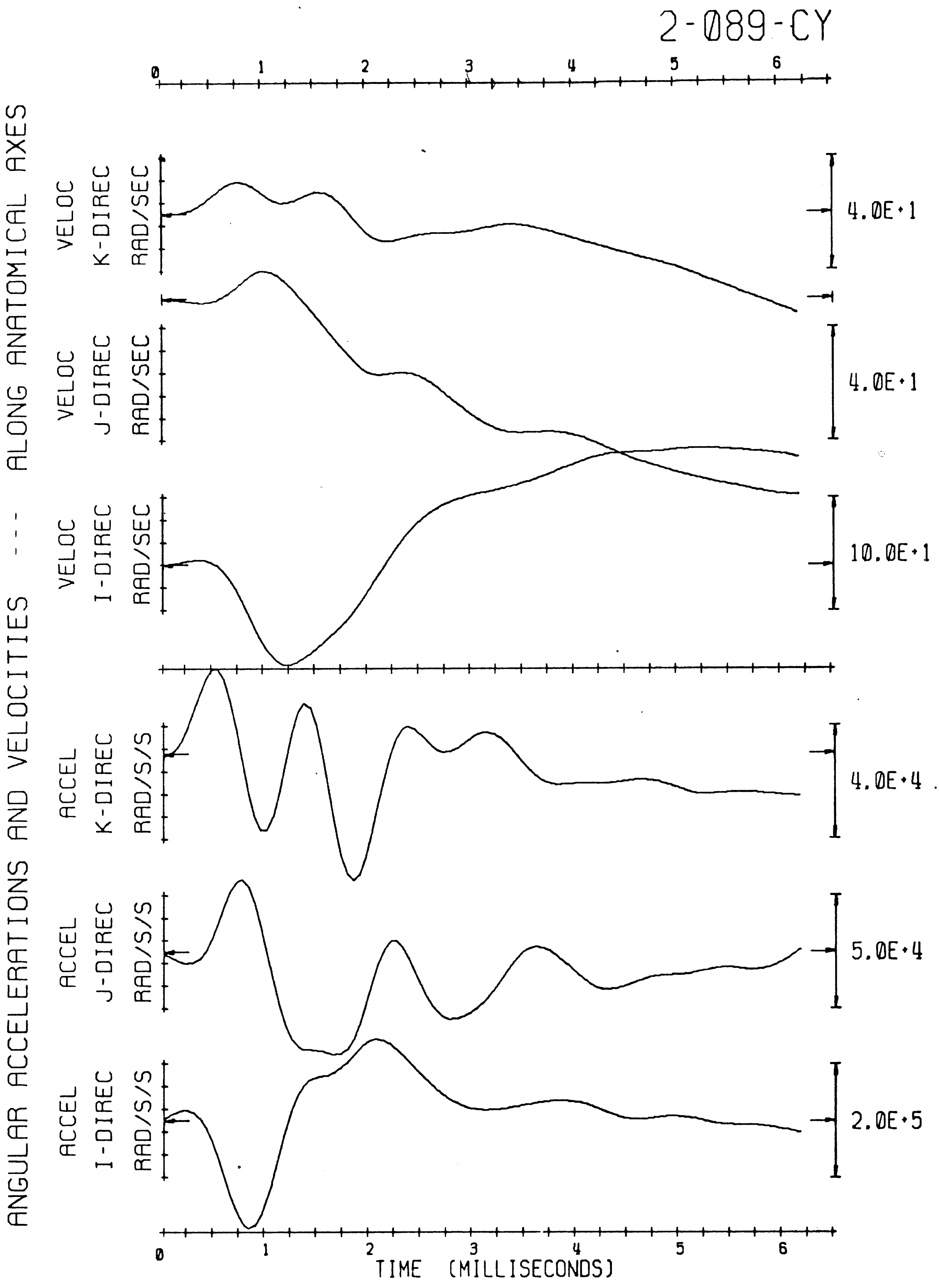
1. Deep bruising of muscle over Lt. zygomatic arch
2. Simple fracture of Lt. zygomatic arch
3. Small bruises and hemorrhage due to collets
4. Unconscious without severe neurological signs > 15 minutes
5. Tear to major vessels (Superior Sagittal Sinus)
6. Small hematoma on cerebellum
7.
8.
9.
10.
11.
12.
13.
14.
15.

Injuries Due to Impact only (not instrumentation)

	AIS
1. Deep bruising of muscle over Lt. zygomatic arch	2
2. Simple fracture of Lt. zygomatic arch	2
3. Unconscious without severe neuro. signs > 15 min.	3
4. Superior sagittal sinus tear	5
5. Small hematoma on cerebellum	4
6.	
7.	
8.	
9.	
10.	

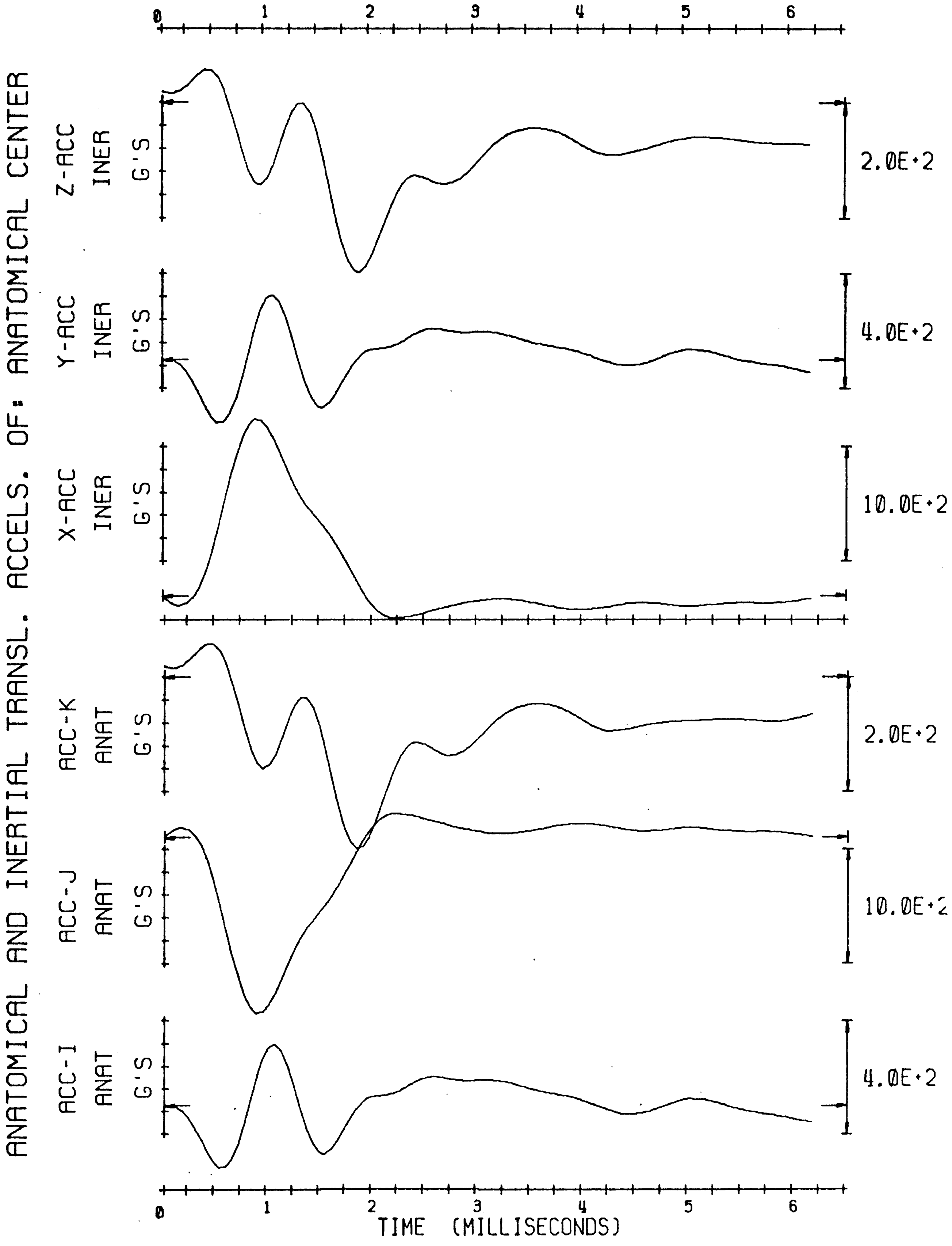
AIS Overall 6


2-Ø89-CY
TIME (MILLISECONDS)
Ø
2
4
6
8
1Ø
12
14
-1Ø.ØØ
3Ø.ØØ
7Ø.ØØ
11Ø.ØØ
15Ø.ØØ
19Ø.ØØ
LBS (X1Ø1)
FORCE



3-D RIGID BODY MOTION ANALYSIS

2-089-CY



3-D RIGID BODY MOTION ANALYSIS

HEAD IMPACT TEST SUMMARY

TEST NO. 090 TEST DATE 8/12/75

TEST SUBJECT

SPECIES Cynomolgus

Body Weight 9.02 lb.

Sitting Height (Top of Head to bottom of Buttocks) 17 in.

Head Weight 1.15 lbs

Brain Weight 0.125 lbs

Brain Volume 3.66 in^3

Skull Inside Length A 2.377 in

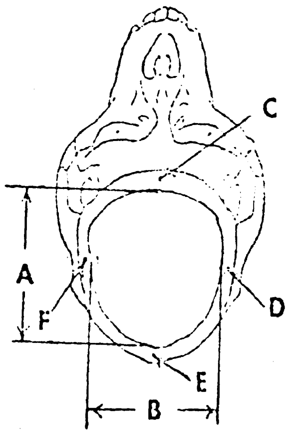
Skull Inside Width B 2.282 in

Skull Thickness at Pt. C 0.121 in

Skull Thickness at Pt. D 0.163 in

Skull Thickness at Pt. E 0.135 in

Skull Thickness at Pt. F 0.101 in



IMPACT CONDITIONS

Location of Impact Left Side of head

Type of Impact 4 inch round rigid

Impact Velocity 42.46 ft/sec

TEST NO. 090

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site __________

Opposite to Impact Site __________

Epidural Pressures in Direction of Impact:

At Impact Site __________

Opposite to Impact Site __________

Strain Gage Rosettes:

Right Parietal Gage __________

Left Parietal Gage __________

Frontal Gage __________

Force: __________

High Speed Motion Pictures:

Side Camera __________

Frame Rate __________

Type II

Accelerations in Direction of Impact:

At Impact Site No

Opposite to Impact Site No

Rigid Body Head Motion Analysis: Good

EEG DATA: Pre-Impact No

Post Impact No

\- NOT ANALYZED -

Force: Good

TEST NO. 090

High Speed Motion Pictures:

Side Camera: Good

Framing Rate: 3000 fps

Front Camera: Good

Framing Rate: 1000 fps

INJURY:

Condition Prior to Impact: Slight muscle tone, slight eye reflex, and some shivering

Consciousness		Time After Impact	Condition
	1.	0 min.	Unconscious
	2.	5 min.	Conscious
	3.		
	4.		
	5.		
	6.		
	7.		
	8.		
	9.		
	10.		

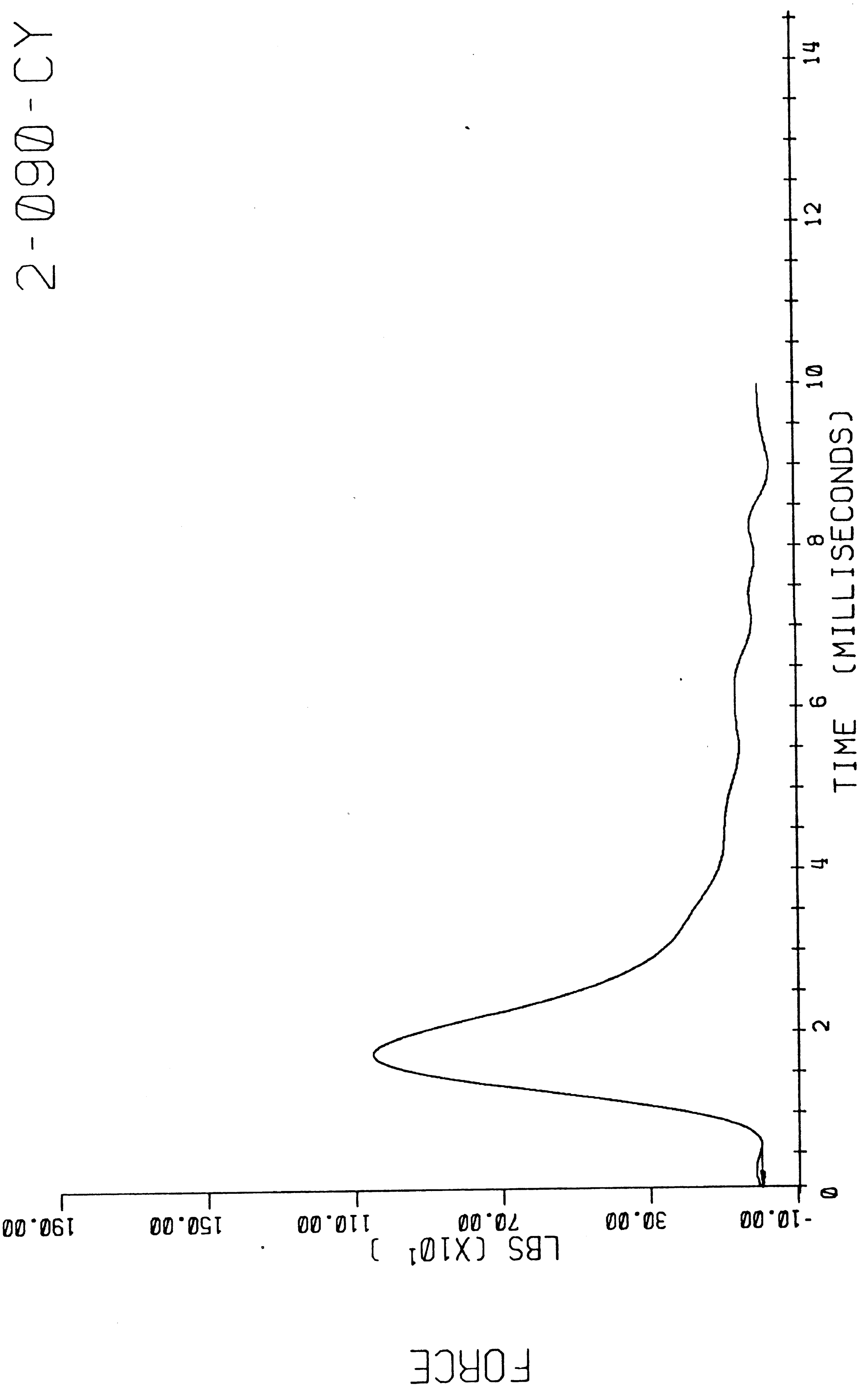
Autopsy Summary:

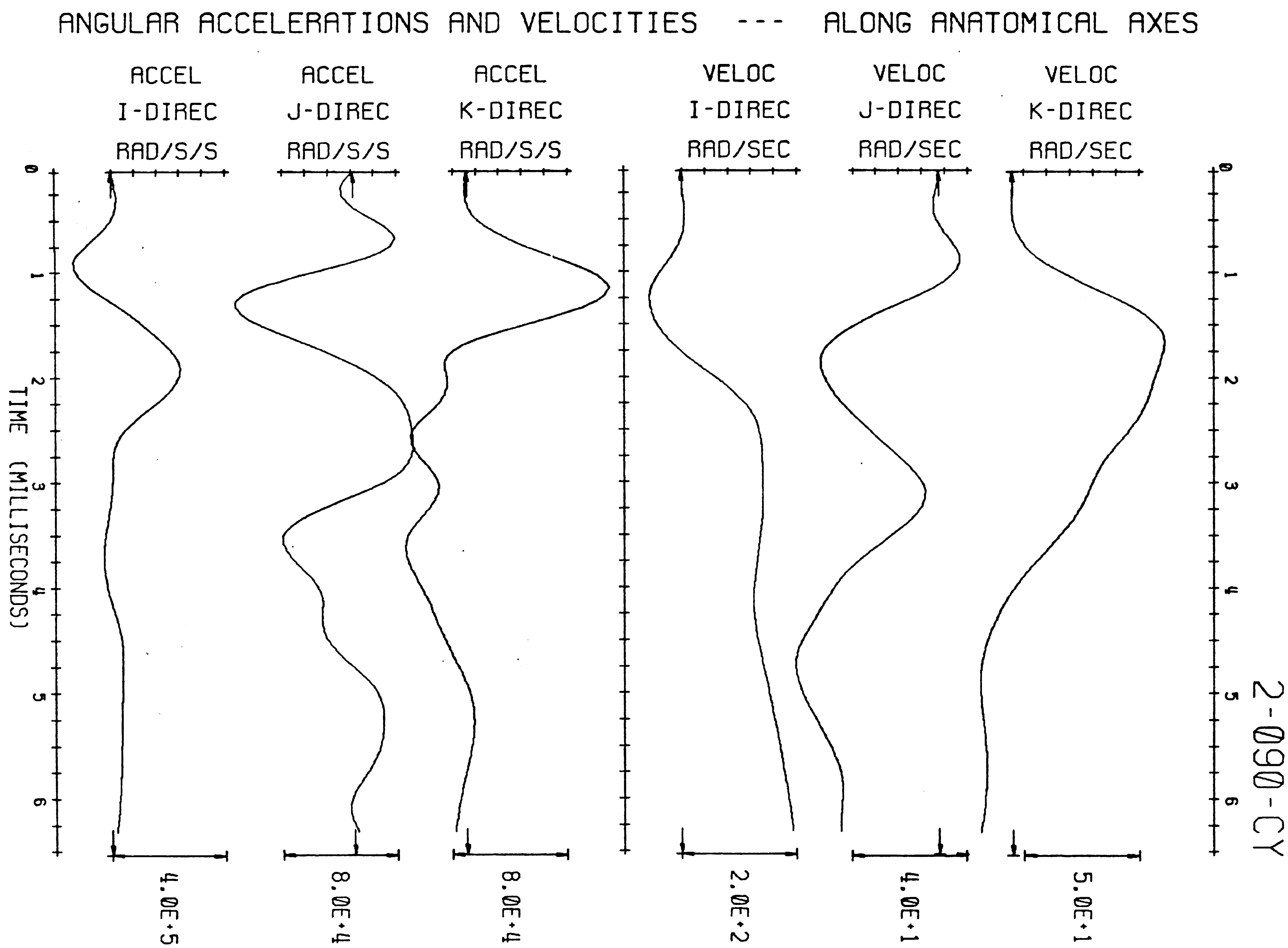
1. Small bruises and hemorrhage due to collets
2. Unconscious less than 15 min.
3. Severe hemorrhage over Lt. zygomatic arch
4. Slight hemorrhage over optic track
5. Simple fracture of Lt. zygomatic arch
6.
7.
8.
9.
10.
11.
12.
13.
14.
15.

Injuries Due to Impact only (not instrumentation)

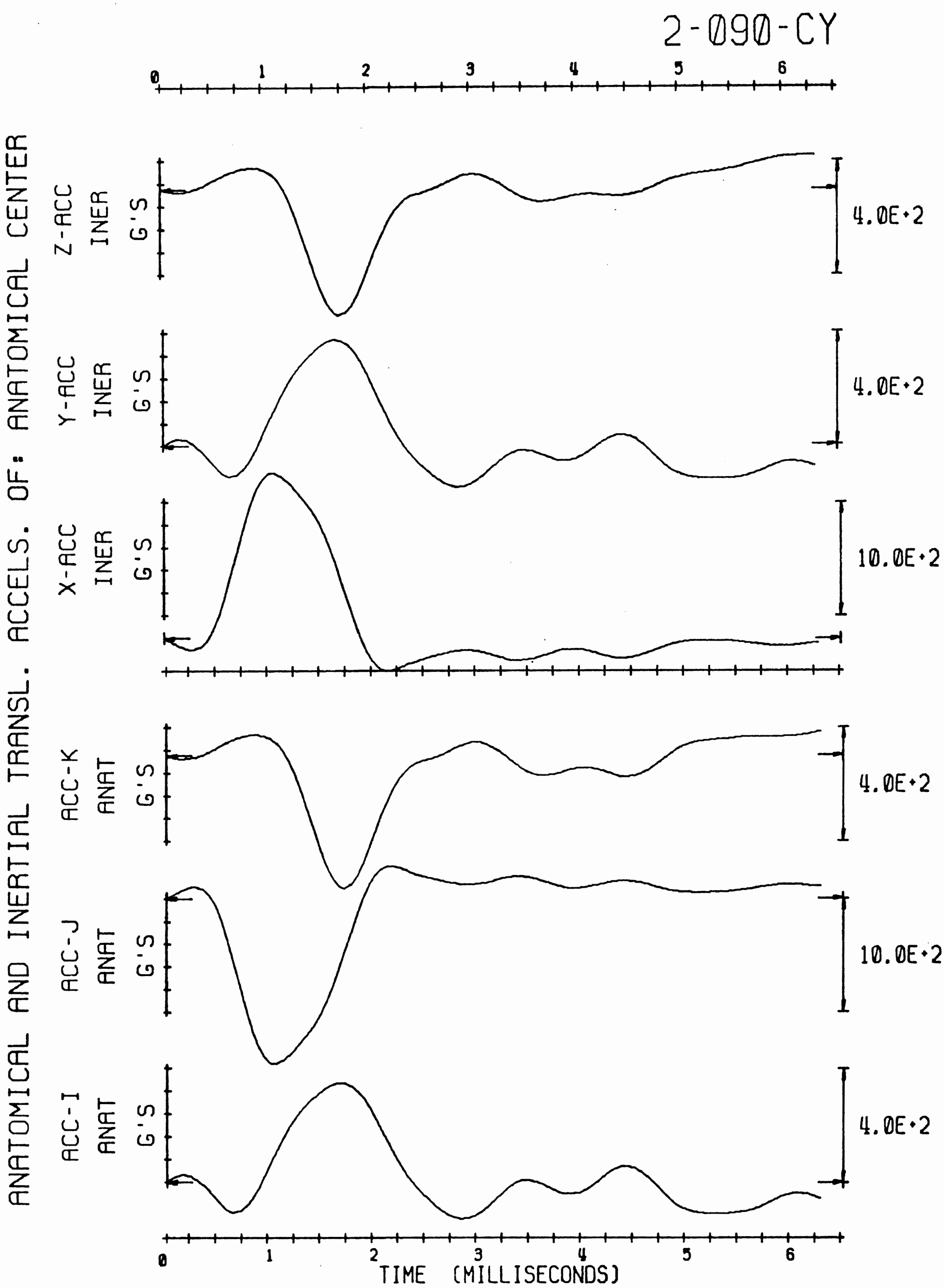
		AIS
1.	Unconscious less than 15 min.	2
2.	Severe hemorrhage over Lt. zygomatic arch	2
3.	Simple fracture of Lt. zygomatic arch	2
4.	Slight hemorrhage over optic track	3
5.		
6.		
7.		
8.		
9.		
10.		

AIS Overall 4


2-090-CY
FORCE
LBS (X10¹)
-10.00
30.00
70.00
110.00
150.00
190.00
TIME (MILLISECONDS)
0
2
4
6
8
10
12
14



3-D RIGID BODY MOTION ANALYSIS



3-D RIGID BODY MOTION ANALYSIS

HEAD IMPACT TEST SUMMARY

TEST NO. 091 TEST DATE 8/12/75

TEST SUBJECT

SPECIES Cynomolgus

Body Weight 8.58 lb.

Sitting Height (Top of Head to bottom of Buttocks) 16.25 in.

Head Weight 0.970 lbs

Brain Weight 0.133 lbs

Brain Volume 3.97 in^3

Skull Inside Length A 2.421 in

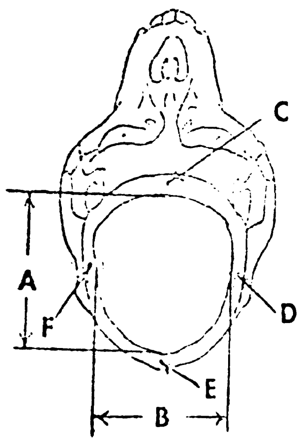
Skull Inside Width B 2.139 in

Skull Thickness at Pt. C 0.094 in

Skull Thickness at Pt. D 0.102 in

Skull Thickness at Pt. E 0.115 in

Skull Thickness at Pt. F 0.098 in



IMPACT CONDITIONS

Location of Impact Left side of head

Type of Impact 4" round rigid, with 2 inches of Ensolite.

Impact Velocity 48.17 ft/sec

TEST NO. 091

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site ______________

Opposite to Impact Site ______________

Epidural Pressures in Direction of Impact:

At Impact Site ______________

Opposite to Impact Site ______________

Strain Gage Rosettes:

Right Parietal Gage ______________

Left Parietal Gage ______________

Frontal Gage ______________

Force: ______________

High Speed Motion Pictures:

Side Camera ______________

Frame Rate ______________

Type II

Accelerations in Direction of Impact:

At Impact Site No

Opposite to Impact Site No

Rigid Body Head Motion Analysis: Good

EEG DATA: Pre-Impact No

Post Impact No

- NOT ANALYZED -

Force: Good

TEST NO. 091

High Speed Motion Picture

Side Camera: Good

Framing Rate: 3000 fps

Front Camera: Good

Framing Rate: 1000 fps

INJURY:

Condition Prior to Impact: Slight muscle tone, slight eye reflex, and some shivering

		Time After Impact	Condition
Consciousness	1.	0 min.	Unconscious
	2.	7 min.	Conscious
	3.		
	4.		
	5.		
	6.		
	7.		
	8.		
	9.		
	10.		

TEST NO. 091

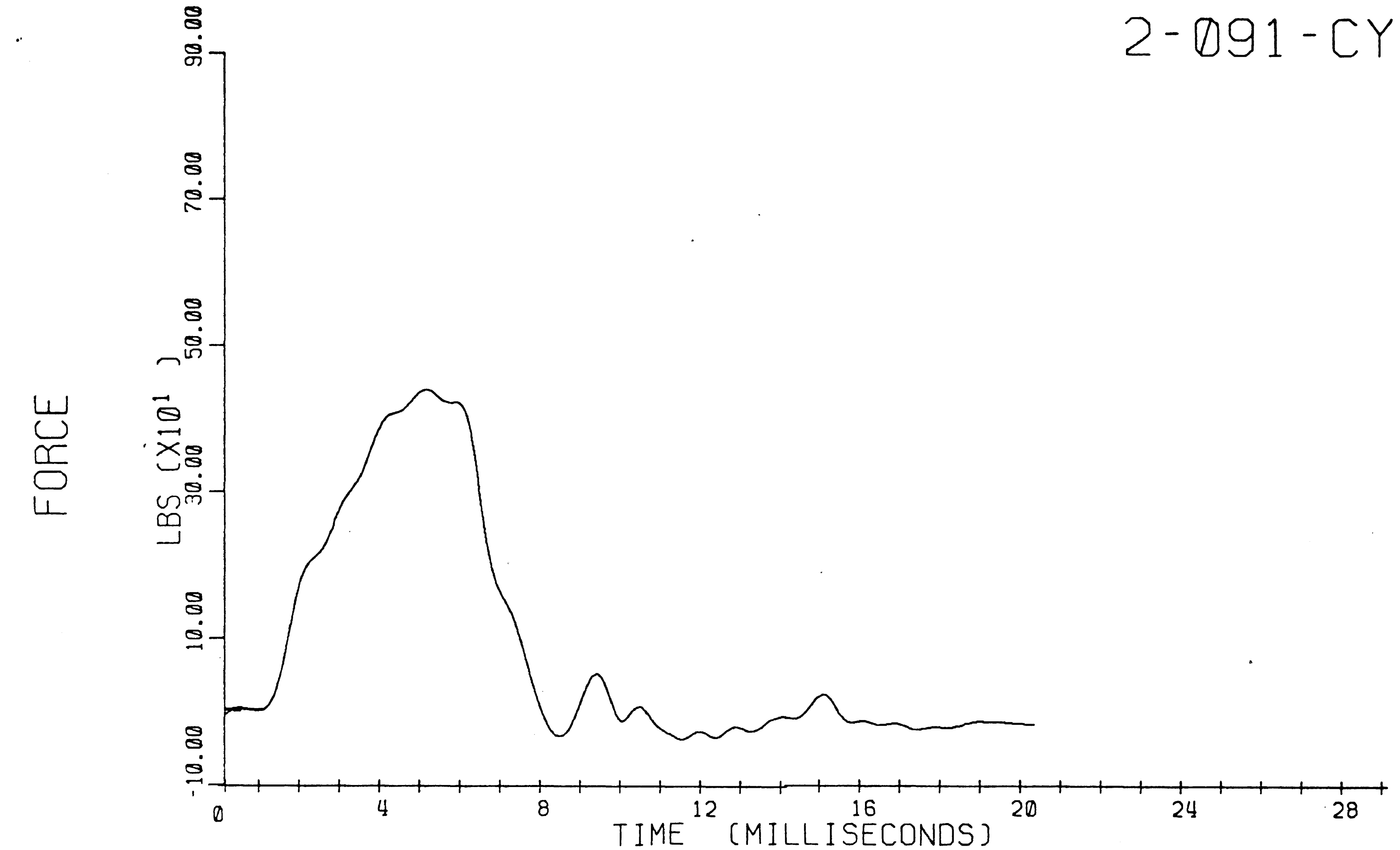
Autopsy Summary:

1. Small bruises and hemorrhage due to collets
2. Unconscious less than 15 min.
3. Superior sagittal sinus tear
4.
5.
6.
7.
8.
9.
10.
11.
12.
13.
14.
15.

Injuries Due to Impact only (not instrumentation)

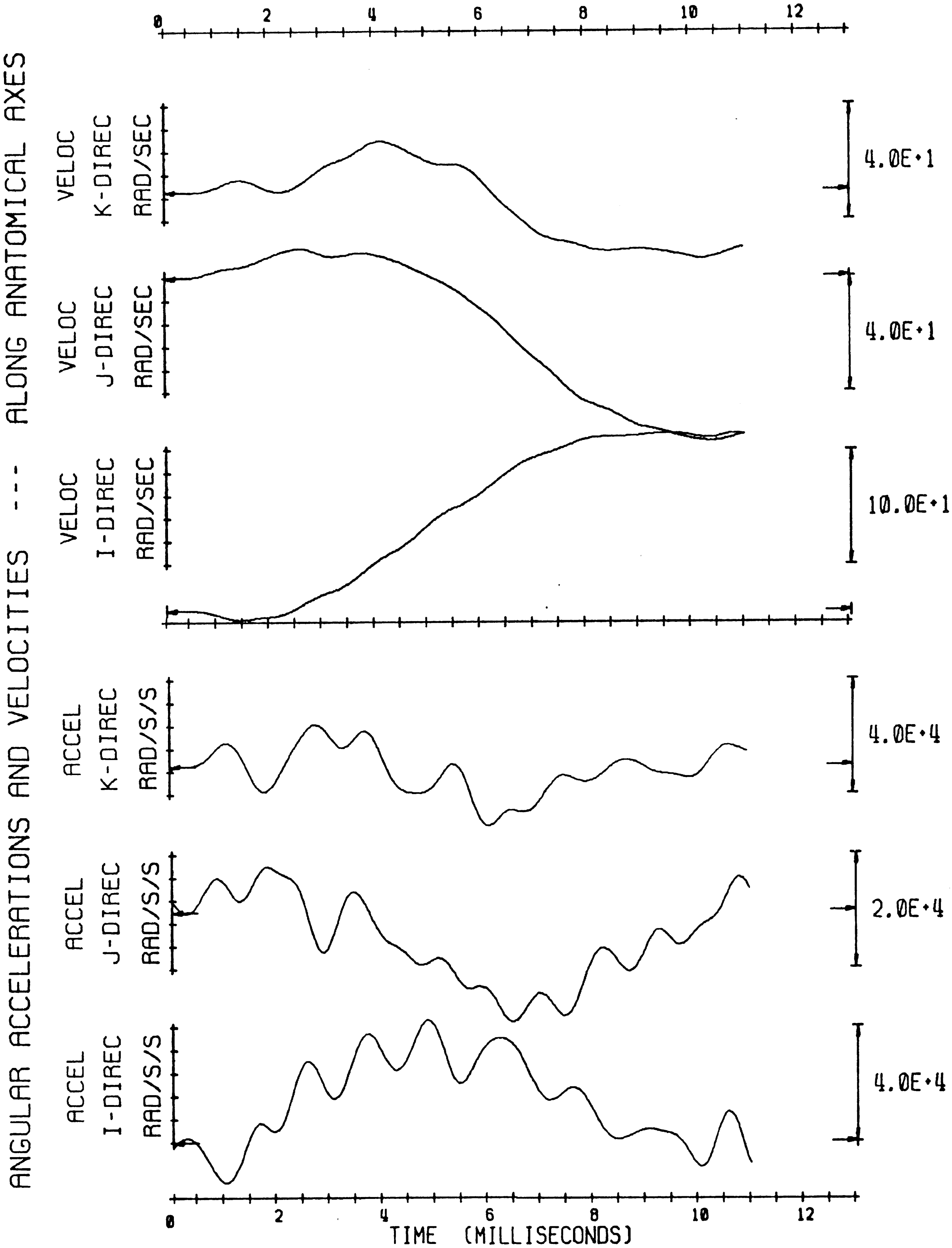
		AIS
1.	Unconscious less than 15 min.	2
2.	Superior sagittal sinus tear	4
3.		
4.		
5.		
6.		
7.		
8.		
9.		
10.		

AIS Overall 4

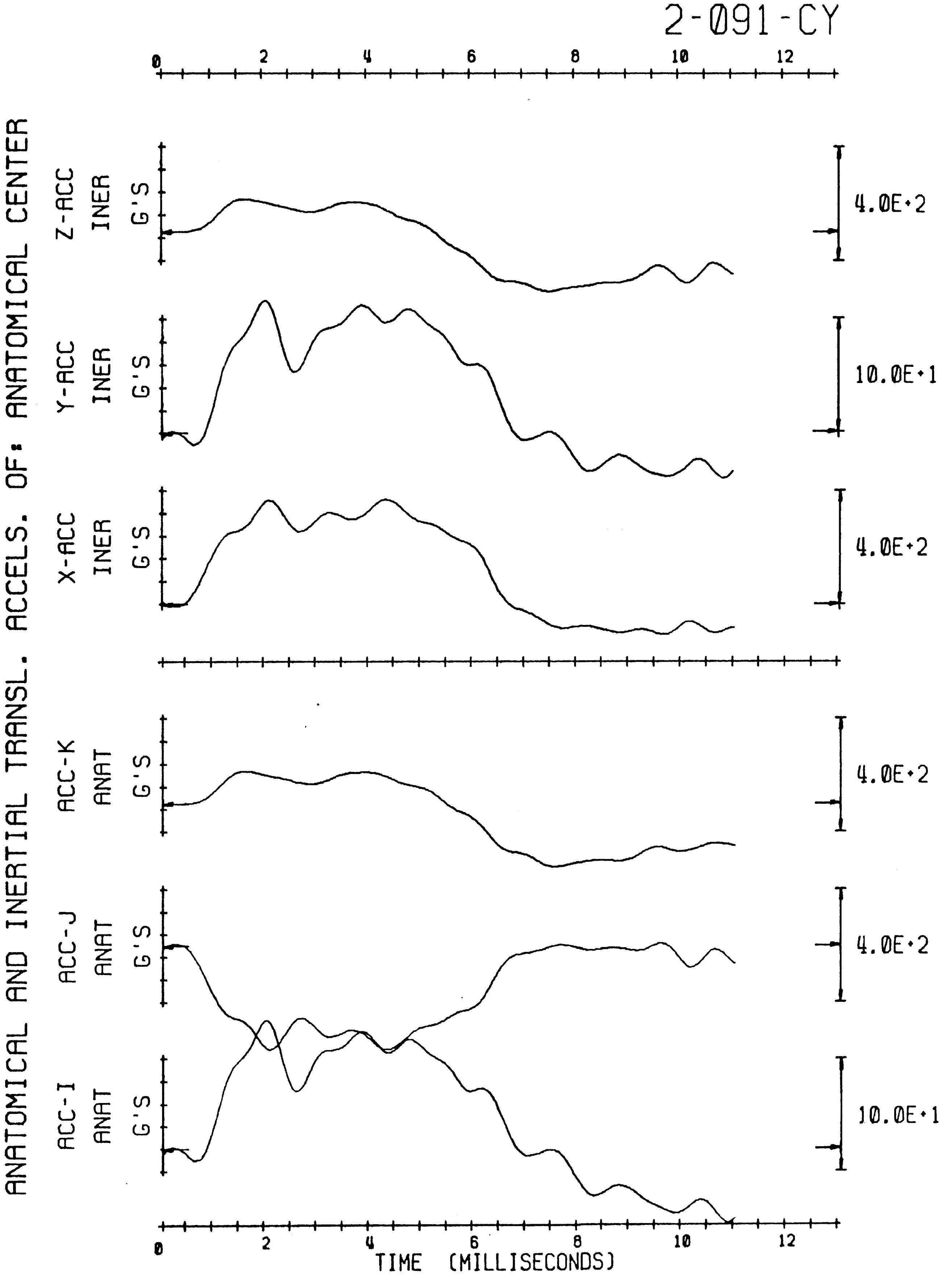


2-Ø91-CY
FORCE
LBS (X1Ø1)
-10.00
10.00
30.00
50.00
70.00
90.00
TIME (MILLISECONDS)
Ø
4
8
12
16
20
24
28

2-091-CY



3-D RIGID BODY MOTION ANALYSIS



3-D RIGID BODY MOTION ANALYSIS

HEAD IMPACT TEST SUMMARY

TEST NO. 092

TEST DATE 8/13/75

TEST SUBJECT

SPECIES Cynomolgus

Body Weight 10.34 lb.

Sitting Height (Top of Head to bottom of Buttocks) 16.75 in.

Head Weight 1.13 lbs

Brain Weight 0.148 lbs

Brain Volume 3.35 in^3

Skull Inside Length A 2.51 in

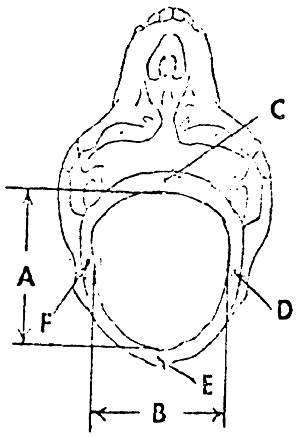
Skull Inside Width B 2.01 in

Skull Thickness at Pt. C 0.173 in

Skull Thickness at Pt. D 0.086 in

Skull Thickness at Pt. E 0.105 in

Skull Thickness at Pt. F 0.070 in



IMPACT CONDITIONS

Location of Impact Left side of head

Type of Impact 4 inch round rigid, with 2 inches of Ensolite.

Impact Velocity 51.31 ft/sec

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site ____________

Opposite to Impact Site ____________

Epidural Pressures in Direction of Impact:

At Impact Site ____________

Opposite to Impact Site ____________

Strain Gage Rosettes:

Right Parietal Gage ____________

Left Parietal Gage ____________

Frontal Gage ____________

Force: ____________

High Speed Motion Pictures:

Side Camera ____________

Frame Rate ____________

Type II

Accelerations in Direction of Impact:

At Impact Site No

Opposite to Impact Site No

Rigid Body Head Motion Analysis: Good

EEG DATA: Pre-Impact No

Post Impact No

- NOT ANALYZED -

Force: Good

TEST NO. 092

High Speed Motion Pictures:

Side Camera Good

Framing Rate 3000 fps

Front Camera Good

Framing Rate 1000 fps

INJURY:

Condition Prior to Impact Slight muscle tone, slight eye reflex, and some shivering

		Time After Impact	Condition
Consciousness	1.	0 min.	Unconscious
	2.	2 min.	Conscious
	3.		
	4.		
	5.		
	6.		
	7.		
	8.		
	9.		
	10.		

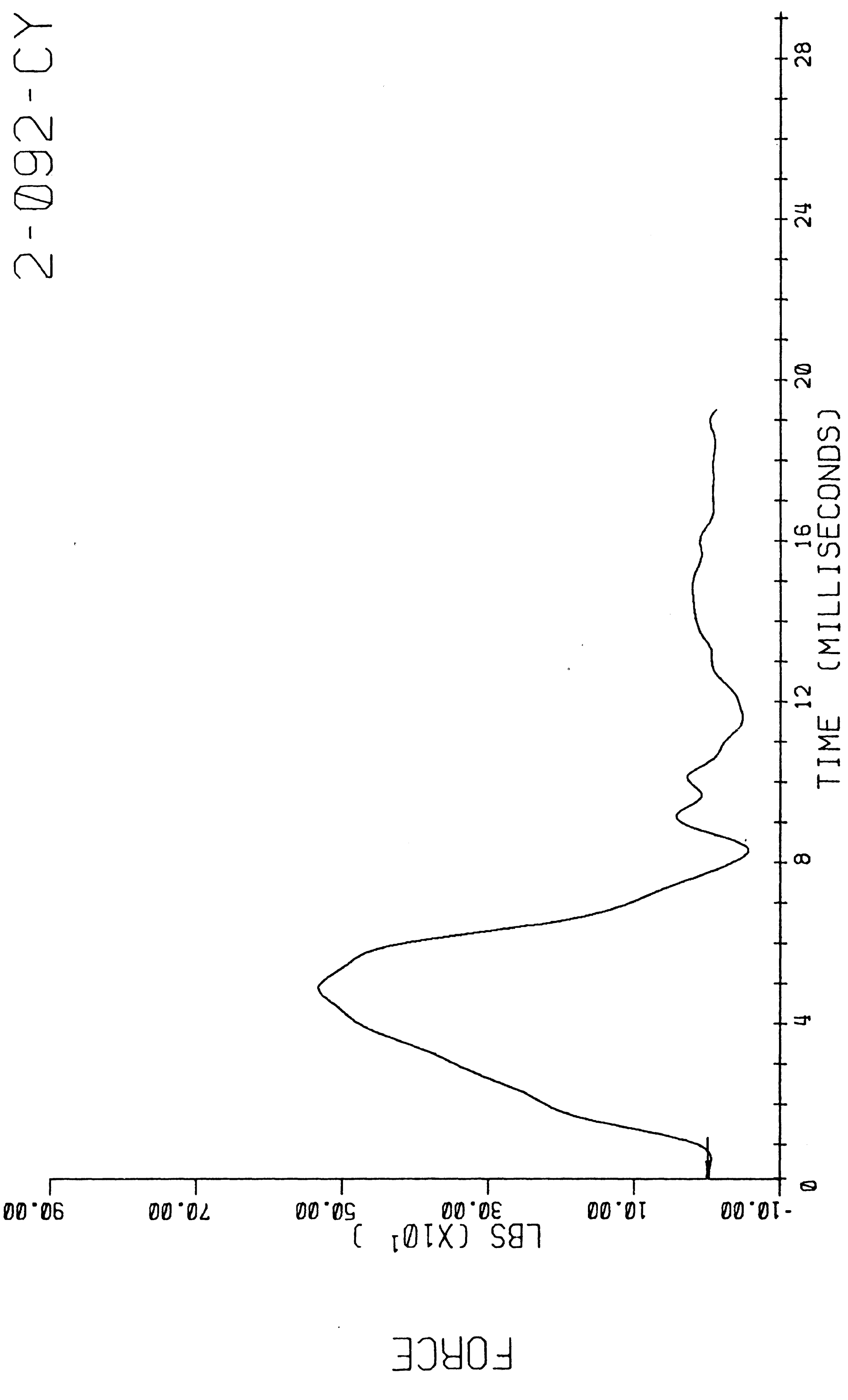
Autopsy Summary

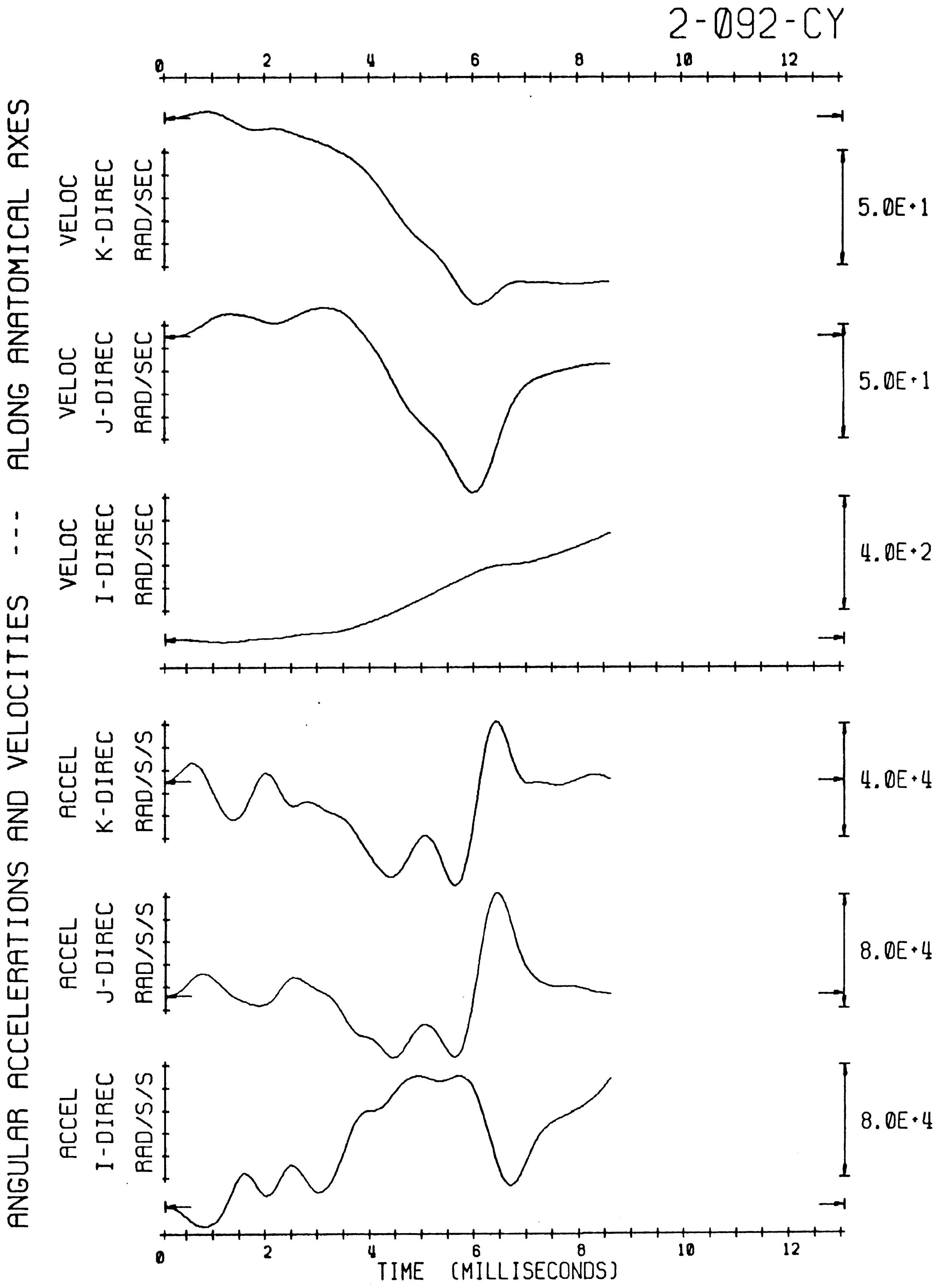
1. Small bruises and hemorrhage due to collets
2. Hematoma on cerebellum
3. Unconscious less than 15 min.
4.
5.
6.
7.
8.
9.
10.
11.
12.
13.
14.
15.

Injuries Due to Impact only (not instrumentation)

	Injury	AIS
1.	Hematoma on cerebellum	4
2.	Unconscious less than 15 min.	2
3.		
4.		
5.		
6.		
7.		
8.		
9.		
10.		

AIS Overall 4

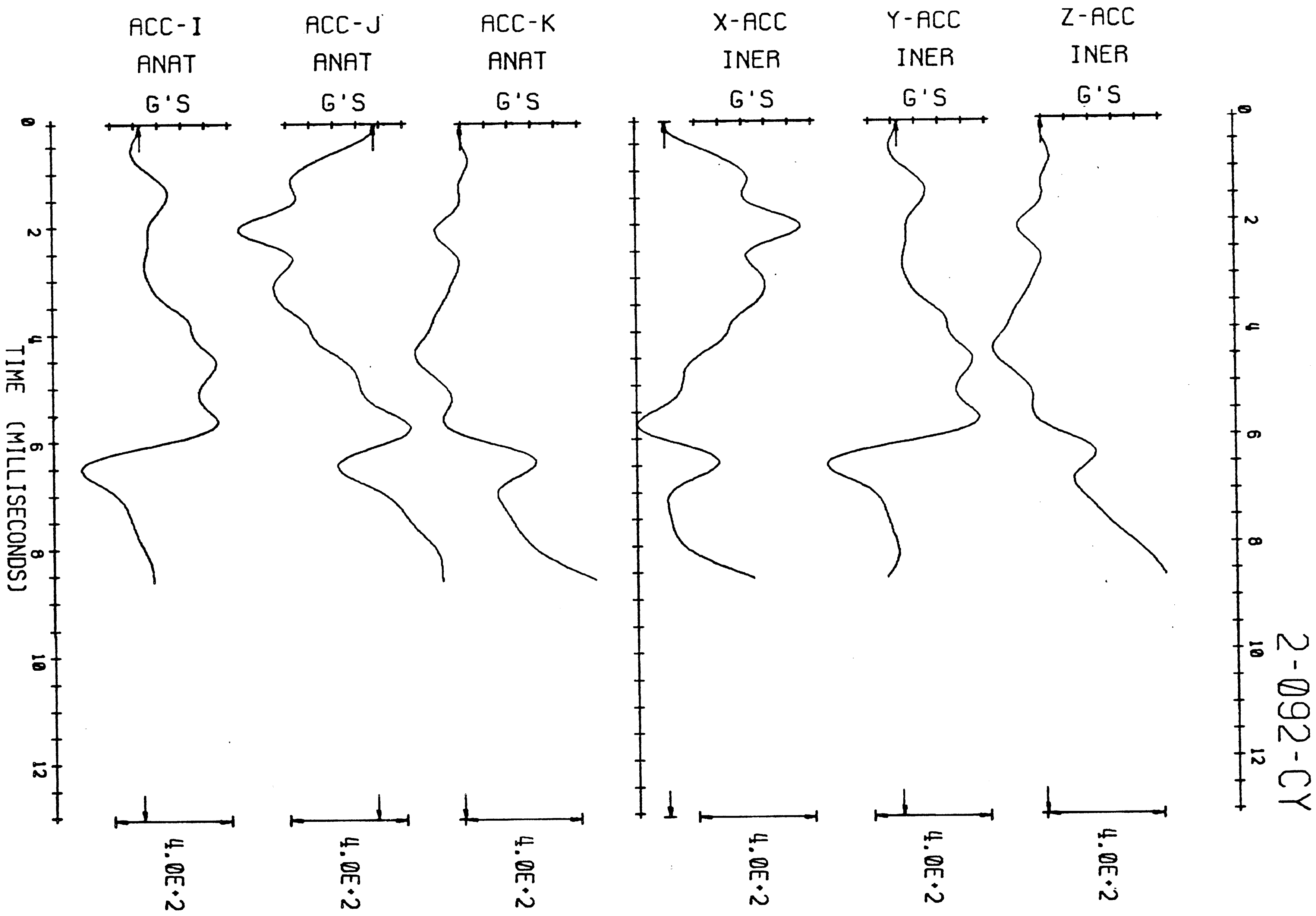

2-Ø92-CY
FORCE
LBS (X1Ø1)
-10.00
10.00
30.00
50.00
70.00
90.00
TIME (MILLISECONDS)
0
4
8
12
16
20
24
28



3-D RIGID BODY MOTION ANALYSIS

3-D RIGID BODY MOTION ANALYSIS

ANATOMICAL AND INERTIAL TRANSL. ACCELS. OF: ANATOMICAL CENTER



2-092-CY

HEAD IMPACT TEST SUMMARY

TEST NO. 093

TEST DATE 8/13/75

TEST SUBJECT

SPECIES Cynomolgus

Body Weight 8.36 lb.

Sitting Height (Top of Head to bottom of Buttocks) 16.50 in.

Head Weight 1.02 lbs

Brain Weight 0.172 lbs

Brain Volume 3.35 in^3

Skull Inside Length A 2.260 in

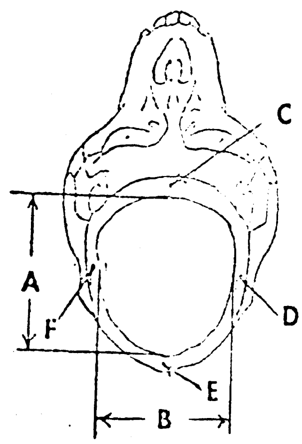
Skull Inside Width B 2.019 in

Skull Thickness at Pt. C 0.101 in

Skull Thickness at Pt. D 0.111 in

Skull Thickness at Pt. E 0.118 in

Skull Thickness at Pt. F 0.101 in



IMPACT CONDITIONS

Location of Impact Left side of head

Type of Impact 4 inch round rigid

Impact Velocity 40.53 ft/sec

TEST NO. 093

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site ______________

Opposite to Impact Site ______________

Epidural Pressures in Direction of Impact:

At Impact Site ______________

Opposite to Impact Site ______________

Strain Gage Rosettes:

Right Parietal Gage ______________

Left Parietal Gage ______________

Frontal Gage ______________

Force: ______________

High Speed Motion Pictures:

Side Camera ______________

Frame Rate ______________

Type II

Accelerations in Direction of Impact:

At Impact Site No

Opposite to Impact Site No

Rigid Body Head Motion Analysis: Fair

EEG DATA: Pre-Impact No

Post Impact No

\- NOT ANALYZED -

Force: Good

TEST NO. 093

High Speed Motion Pictures:

Side Camera: Good

Framing Rate: 3000 fps

Front Camera: Good

Framing Rate: 1000 fps

INJURY:

Condition Prior to Impact: Slight muscle tone, slight eye reflex, and some shivering

		Time After Impact	Condition
Consciousness	1.	0 min.	Unconscious
	2.	10 min.	Conscious
	3.		
	4.		
	5.		
	6.		
	7.		
	8.		
	9.		
	10.		

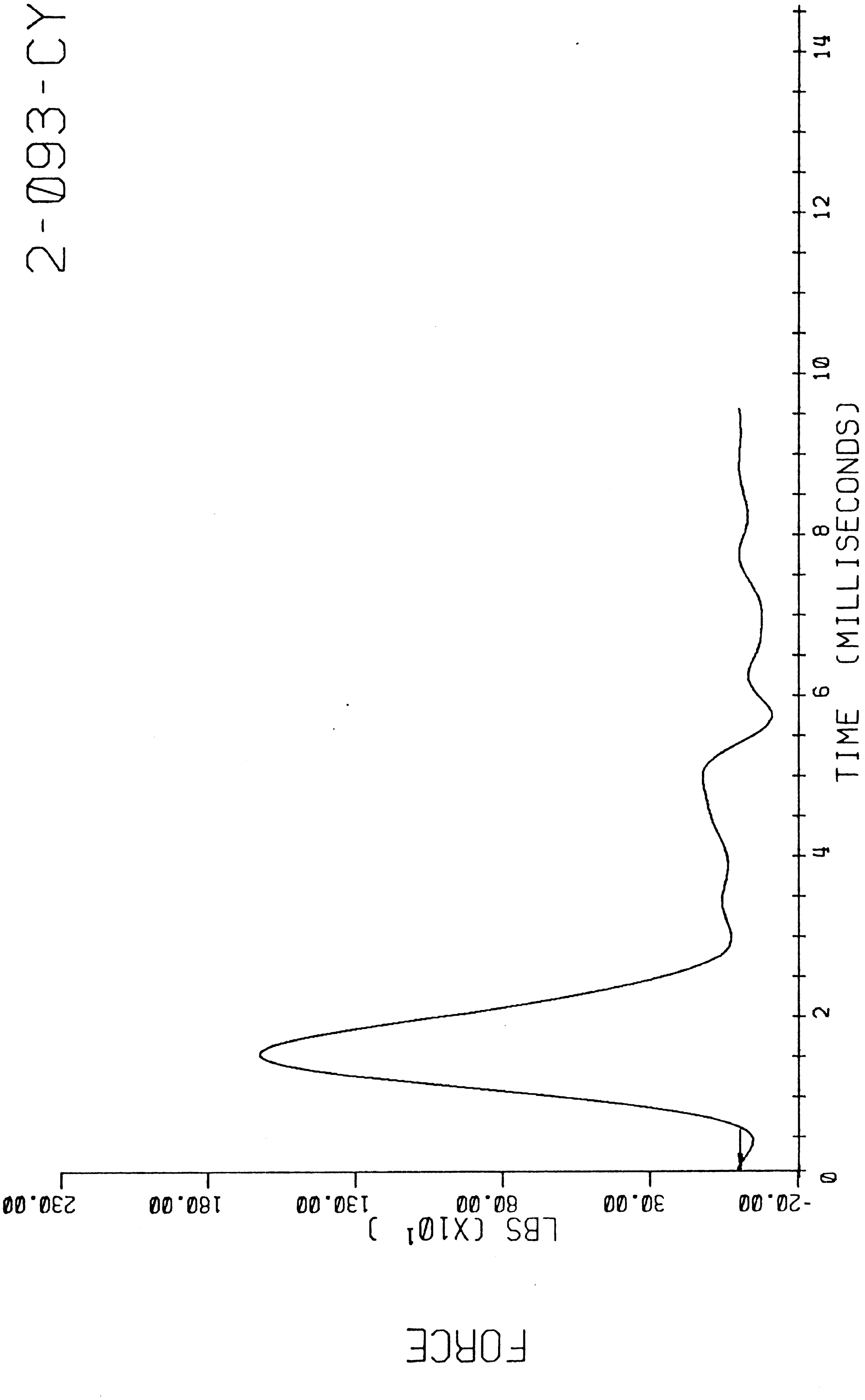
Autopsy Summary:

1. Minor hemorrhage over Lt. zygomatic arch
2. Comminuted fracture of Lt. zygomatic arch
3. Unconscious less than 15 min.
4. Brain stem hemorrhage
5. Small bruises and hemorrhage due to collets
6.
7.
8.
9.
10.
11.
12.
13.
14.
15.

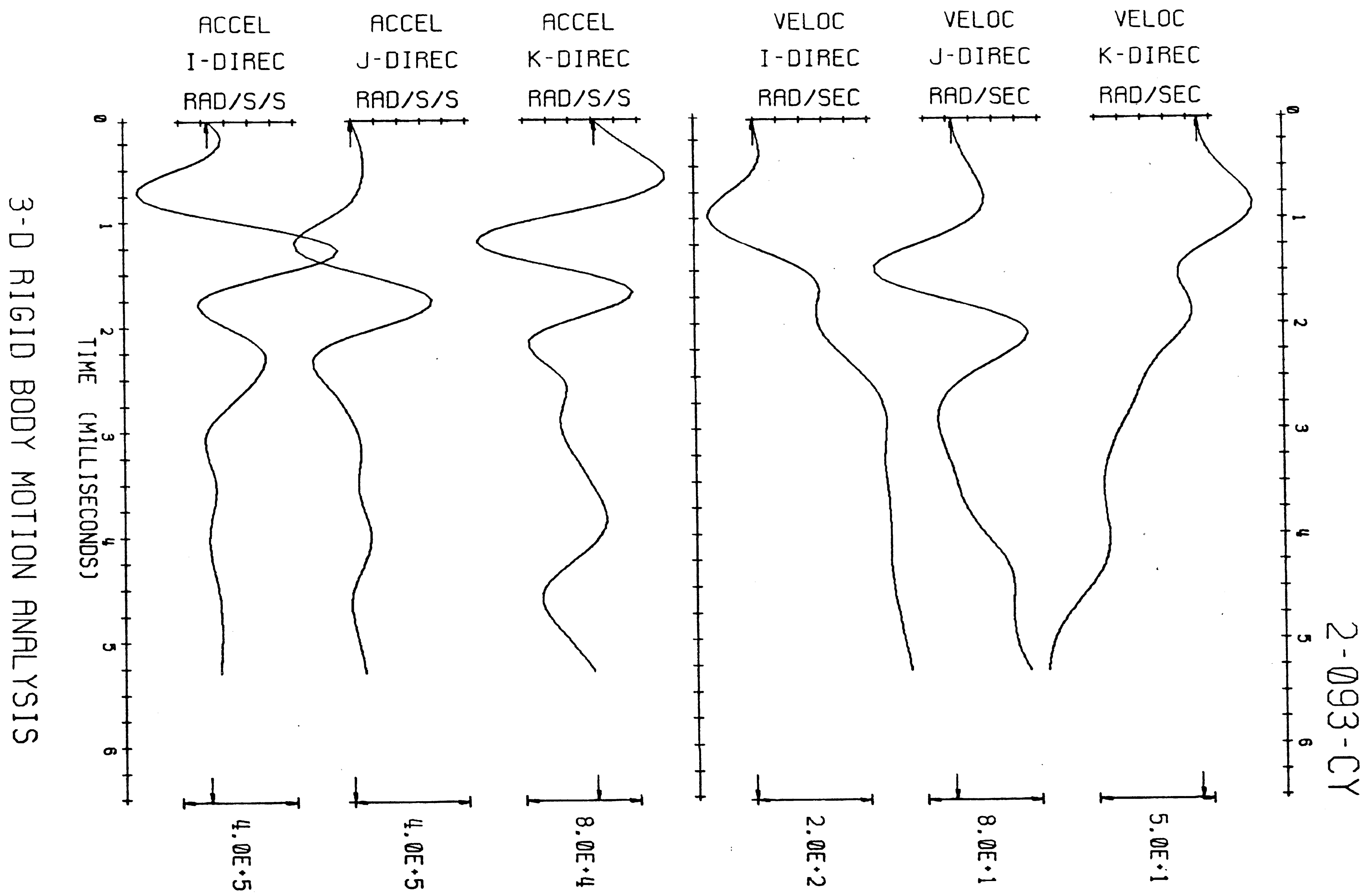
Injuries Due to Impact only (not instrumentation)

	Injury	AIS
1.	Minor hemorrhage over Lt. zygomatic arch	1
2.	Comminuted fracture of Lt. zygomatic arch	3
3.	Unconscious less than 15 min.	2
4.	Brain stem hemorrhage	4 + 1
5.		
6.		
7.		
8.		
9.		
10.		

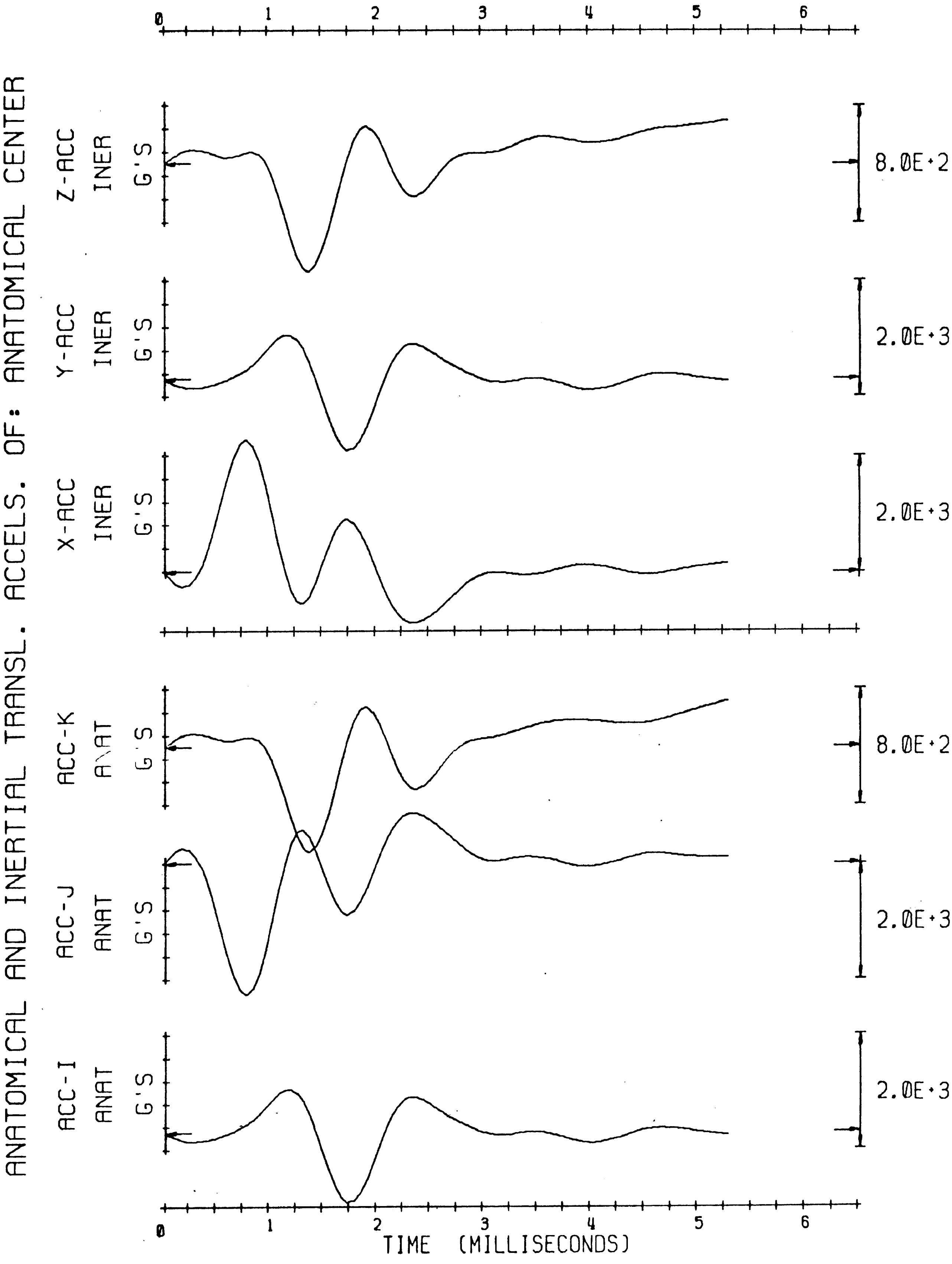
AIS Overall 5


2-Ø93-CY
FORCE
LBS (X1Ø1)
-20.ØØ
30.ØØ
80.ØØ
130.ØØ
180.ØØ
230.ØØ
TIME (MILLISECONDS)
Ø
2
4
6
8
1Ø
12
14

ANGULAR ACCELERATIONS AND VELOCITIES --- ALONG ANATOMICAL AXES



2-093-CY



3-D RIGID BODY MOTION ANALYSIS

HEAD IMPACT TEST SUMMARY

TEST NO. 094 TEST DATE 8/14/75

TEST SUBJECT

SPECIES Baboon

Body Weight 22.88 lb.

Sitting Height (Top of Head to bottom of Buttocks) 22.00 in.

Head Weight 2.41 lbs

Brain Weight 0.328 lbs

Brain Volume 7.93 in^3

Skull Inside Length A 5.33 in

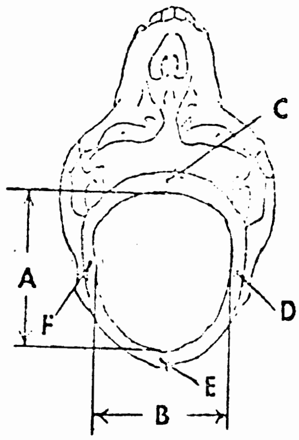
Skull Inside Width B 2.98 in

Skull Thickness at Pt. C 0.146 in

Skull Thickness at Pt. D 0.170 in

Skull Thickness at Pt. E 0.148 in

Skull Thickness at Pt. F 0.120 in



IMPACT CONDITIONS

Location of Impact Back of Head

Type of Impact 4 inch round rigid

Impact Velocity 37.91 ft/sec

TEST NO. 094

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site ______________

Opposite to Impact Site ______________

Epidural Pressures in Direction of Impact:

At Impact Site ______________

Opposite to Impact Site ______________

Strain Gage Rosettes:

Right Parietal Gage ______________

Left Parietal Gage ______________

Frontal Gage ______________

Force: ______________

High Speed Motion Pictures:

Side Camera ______________

Frame Rate ______________

Type II

Accelerations in Direction of Impact:

At Impact Site No

Opposite to Impact Site No

Rigid Body Head Motion Analysis: Good

EEG DATA: Pre-Impact No

Post Impact No

- NOT ANALYZED -

Force: Good

TEST NO. 094

High Speed Motion Pictures:

Side Camera Good

Framing Rate 3000 fps

Front Camera Good

Framing Rate 1000 fps

INJURY:

Condition Prior to Impact Slight muscle tone, slight eye reflex, and some shivering

		Time After Impact	Condition
Consciousness	1.	0 min.	Unconscious
	2.	23 min	Unconscious
	3.	40 min	Conscious
	4.	79 min.	Conscious
	5.		
	6.		
	7.		
	8.		
	9.		
	10.		

TEST NO. 094

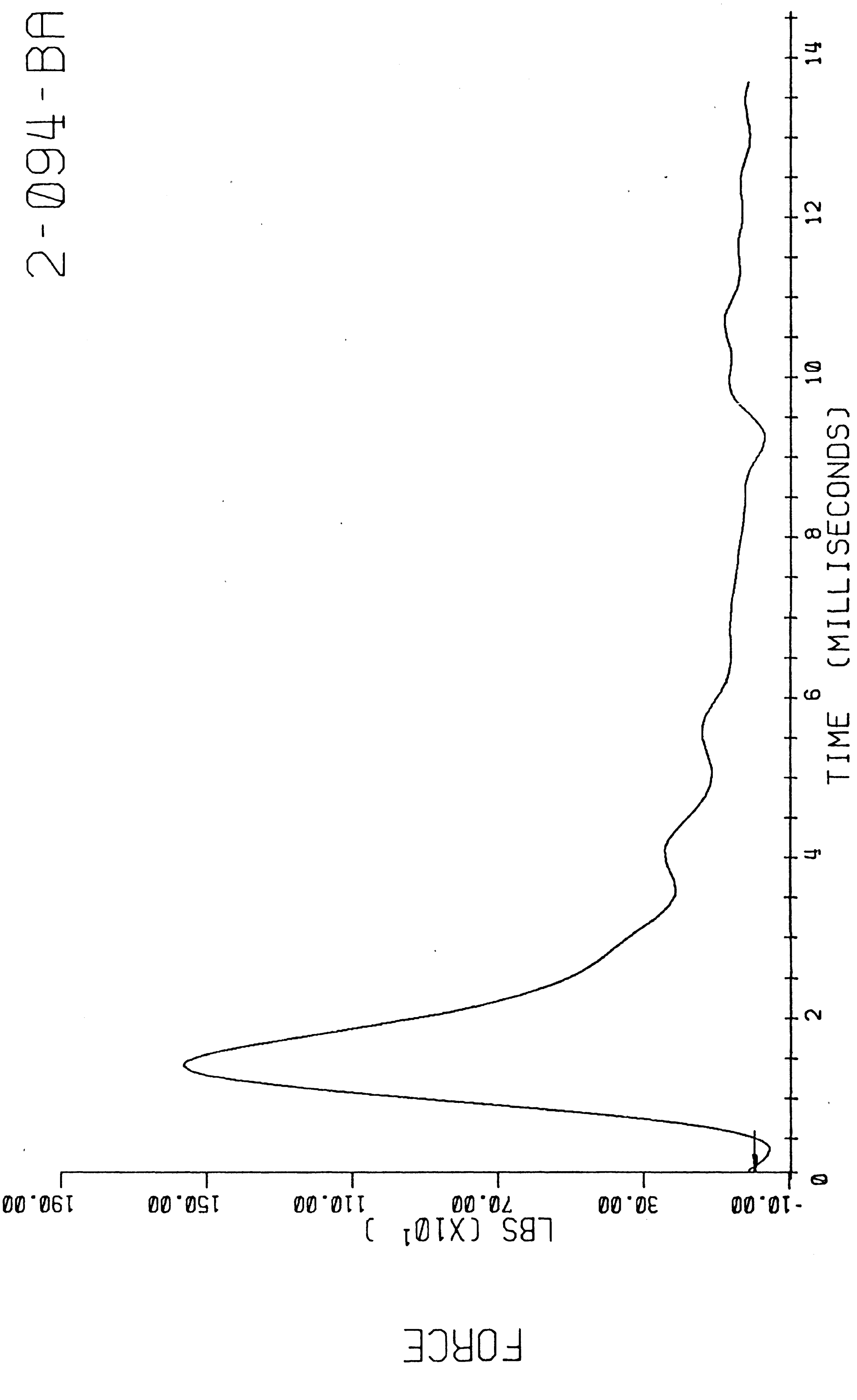
Autopsy Summary:

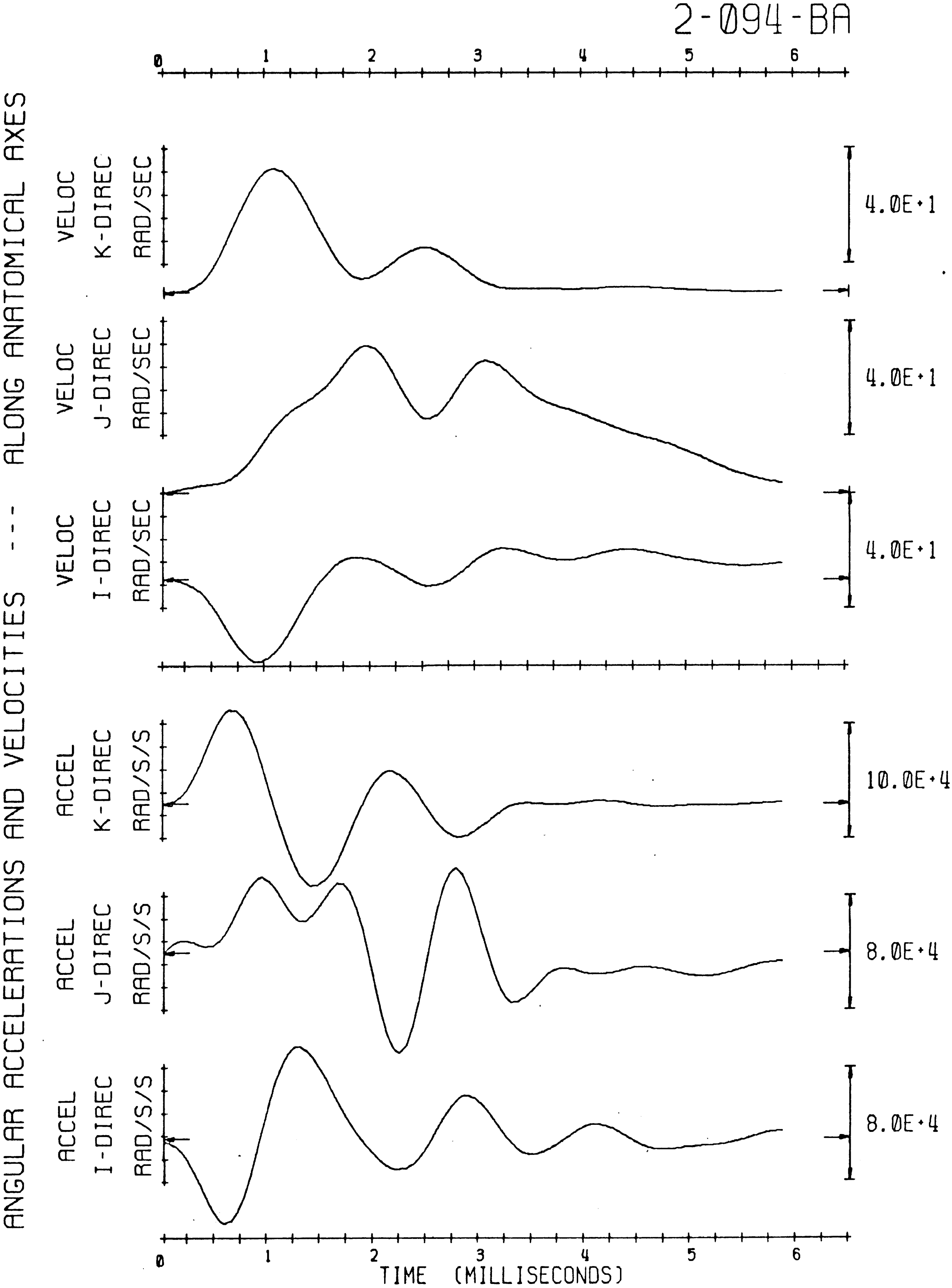
1. Large hematoma on back of head
2. Extensive hemorrhage Rt. parietal lobe
3. Subdural hemorrhage over Lt. parietal lobe
4. Localized injury Rt. top frontal lobe (contre-coup)
5. Localized injury Rt. bottom frontal lobe (contre-coup)
6. Small bruise and hemorrhage due to collets
7. Unconscious without severe neurological signs > 15 min.
8.
9.
10.
11.
12.
13.
14.
15.

Injuries Due to Impact only (not instrumentation)

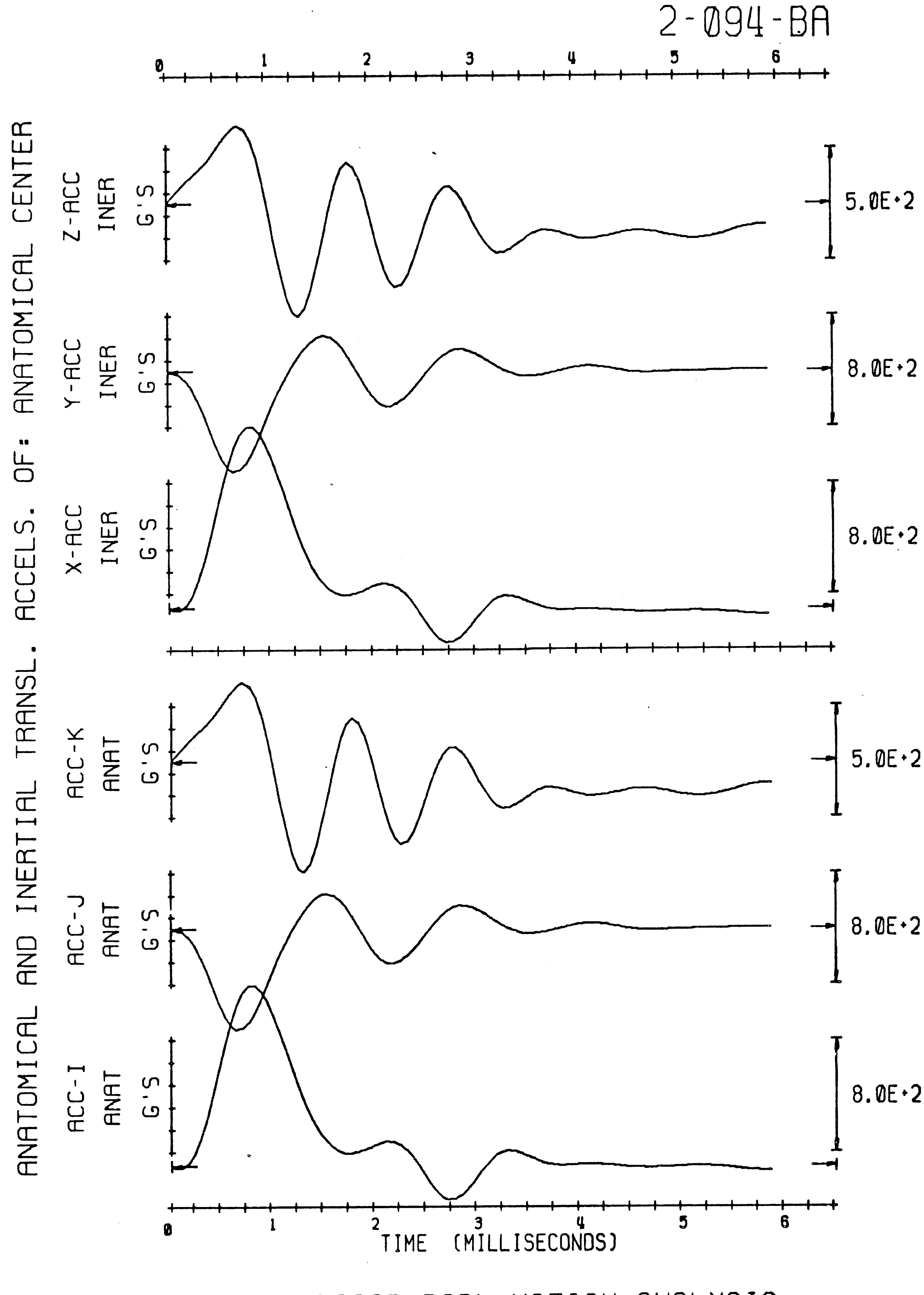
	Injury	AIS
1.	Large hematoma on back of head	2
2.	Extensive hemorrhage Rt parietal lobe	5
3.	Subdural hemorrhage over Lt. parietal lobe	4
4.	Localized injury Rt. top frontal lobe (contre-coup)	3
5.	Localized injury Rt. bottom frontal lobe (contre-coup)	3
6.	Unconscious > 15 min.	3
7.		
8.		
9.		
10.		

AIS Overall 6


2-094-BA
TIME (MILLISECONDS)
0
2
4
6
8
10
12
14
FORCE
LBS (X10¹)
-10.00
30.00
70.00
110.00
150.00
190.00



3-D RIGID BODY MOTION ANALYSIS



3-D R'GID BODY MOTION ANALYSIS

HEAD IMPACT TEST SUMMARY

TEST NO. 095 TEST DATE 8/14/75

TEST SUBJECT

SPECIES Baboon

Body Weight 26.18 lb.

Sitting Height (Top of Head to bottom of Buttocks) 23.00 in.

Head Weight 2.41 lbs

Brain Weight 0.343 lbs

Brain Volume 9.15 in^3

Skull Inside Length A 3.38 in

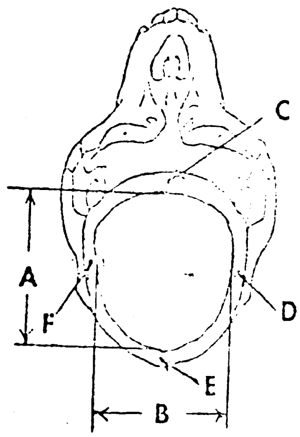
Skull Inside Width B 2.87 in

Skull Thickness at Pt. C 0.241 in

Skull Thickness at Pt. D 0.142 in

Skull Thickness at Pt. E 0.146 in

Skull Thickness at Pt. F 0.154 in



IMPACT CONDITIONS

Location of Impact Back of head

Type of Impact 4 inch round, rigid, with 2 inches of Ensolite

Impact Velocity 53.08 ft/sec

TEST NO. 095

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site ______________

Opposite to Impact Site ______________

Epidural Pressures in Direction of Impact:

At Impact Site ______________

Opposite to Impact Site ______________

Strain Gage Rosettes:

Right Parietal Gage ______________

Left Parietal Gage ______________

Frontal Gage ______________

Force: ______________

High Speed Motion Pictures:

Side Camera ______________

Frame Rate ______________

Type II

Accelerations in Direction of Impact:

At Impact Site No

Opposite to Impact Site No

Rigid Body Head Motion Analysis: Good

EEG DATA: Pre-Impact No

Post Impact No

- NOT ANALYZED -

Force: Good

TEST NO. 095

High Speed Motion Pictures:

Side Camera Good

Framing Rate 3000 fps

Front Camera Good

Framing Rate 1000 fps

INJURY:

Condition Prior to Impact Slight muscle tone, slight eye reflex, and some shivering

		Time After Impact	Condition
Consciousness	1.	0 min.	Unconscious
	2.	3 min.	Conscious
	3.		
	4.		
	5.		
	6.		
	7.		
	8.		
	9.		
	10.		

TEST NO. 095

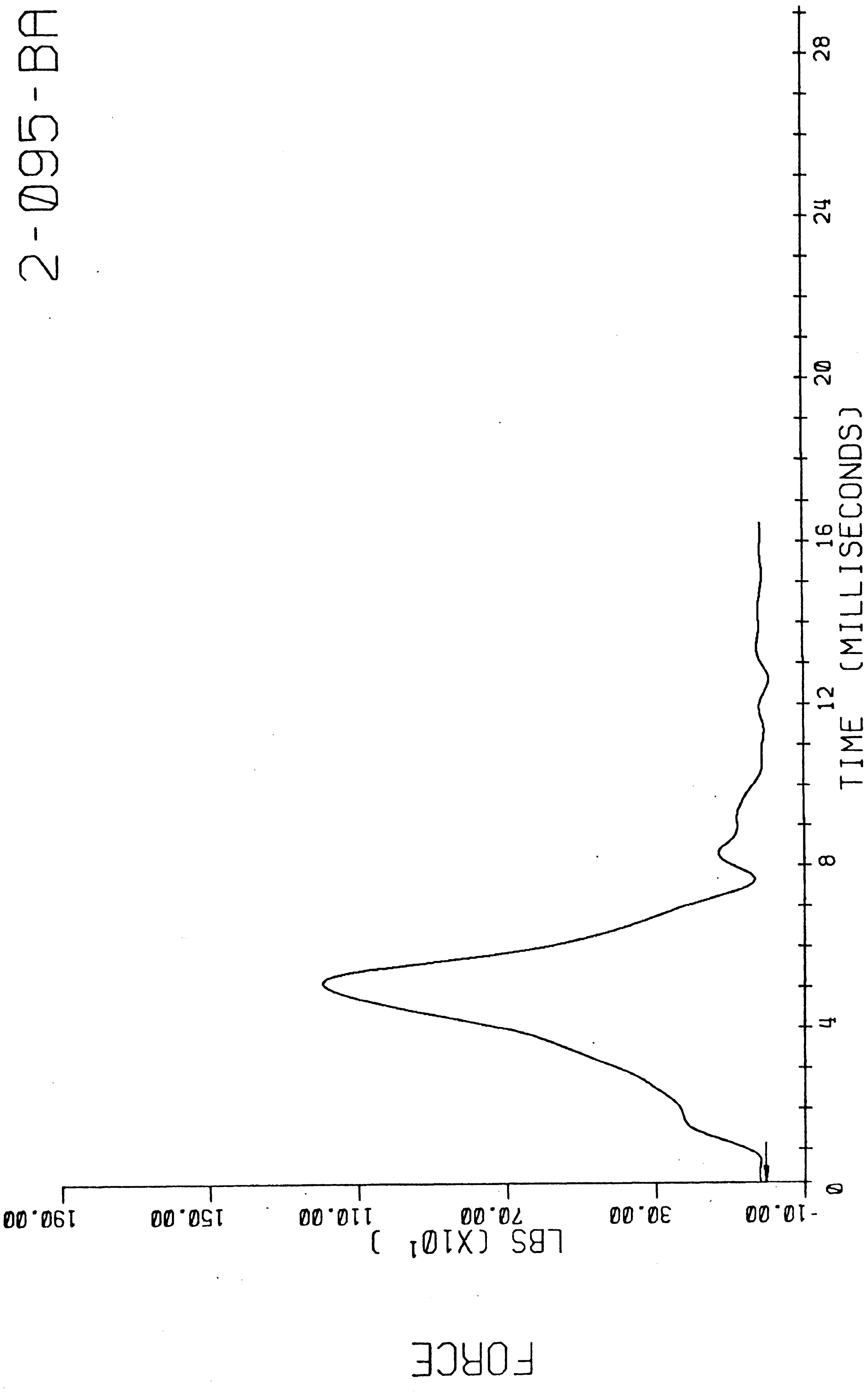
Autopsy Summary:

1. Unconscious less than 15 minutes
2. Epidural hemorrhage over occipital lobe
3. Small bruises and hemorrhage due to collets
4.
5.
6.
7.
8.
9.
10.
11.
12.
13.
14.
15.

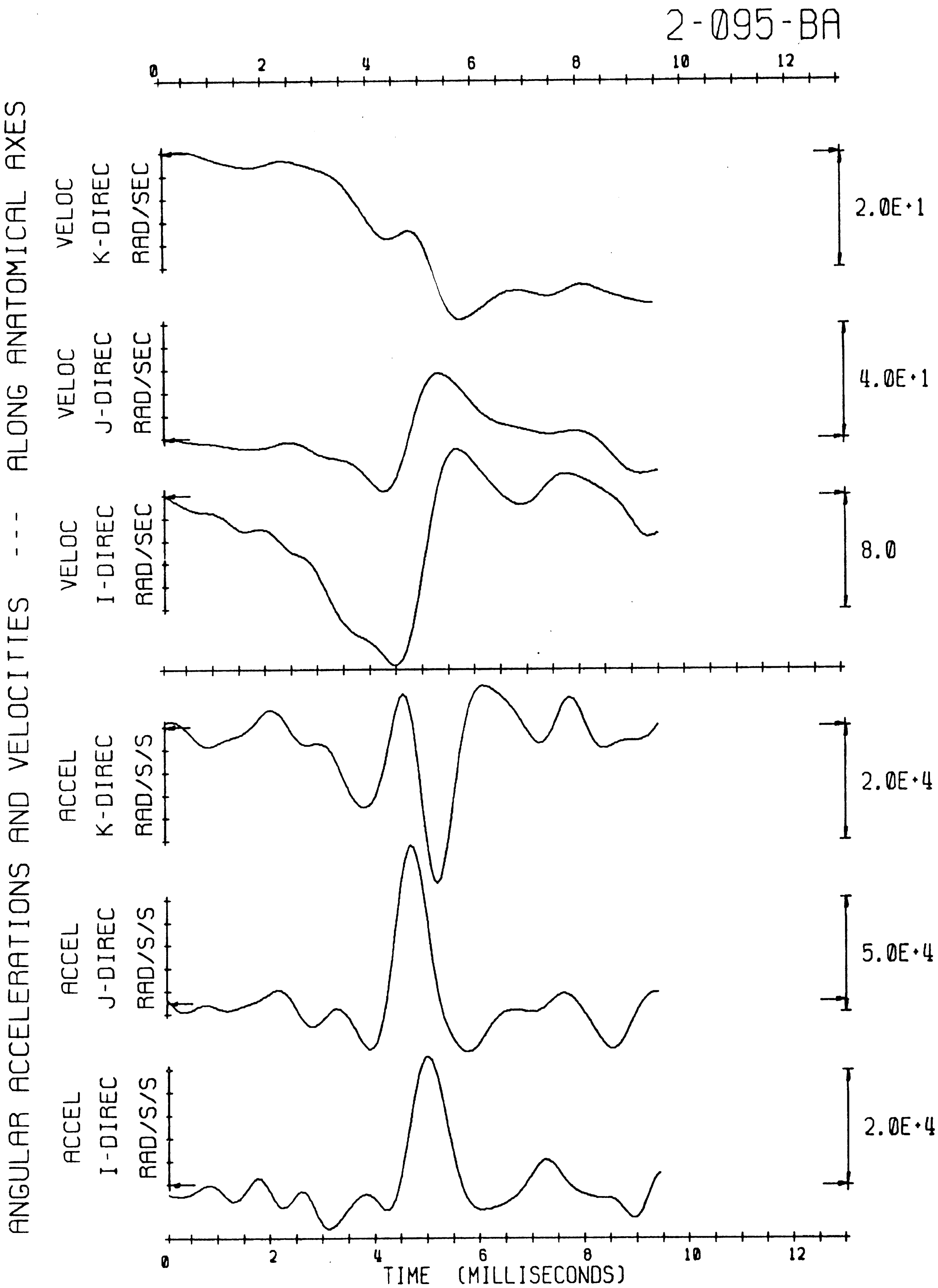
Injuries Due to Impact only (not instrumentation)

		AIS
1.	Unconscious less than 15 minutes	2
2.	Epidural hemorrhage over occipital lobe	3
3.		
4.		
5.		
6.		
7.		
8.		
9.		
10.		

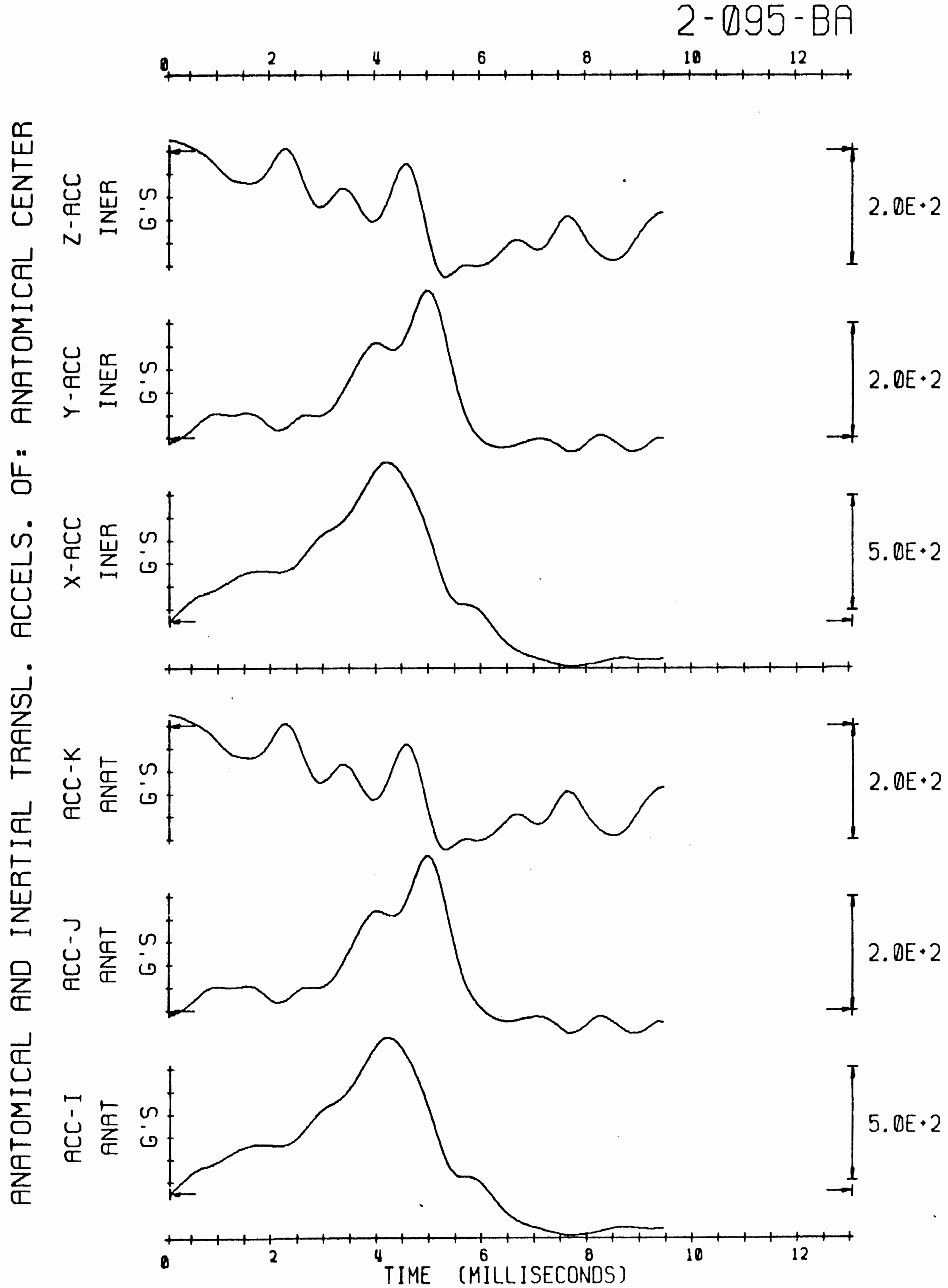
AIS Overall 3



2-Ø95-BA
TIME (MILLISECONDS)
Ø
4
8
12
16
20
24
28
LBS (X1Ø1)
-10.00
30.00
70.00
110.00
150.00
190.00
FORCE



3-D RIGID BODY MOTION ANALYSIS



3-D RIGID BODY MOTION ANALYSIS

HEAD IMPACT TEST SUMMARY

TEST NO. 096

TEST DATE 8/14/75

TEST SUBJECT

SPECIES Baboon

Body Weight 24.88 lb.

Sitting Height (Top of Head to bottom of Buttocks) 22.50 in.

Head Weight 2.78 lbs

Brain Weight 0.359 lbs

Brain Volume 9.15 in^3

Skull Inside Length A 3.19 in

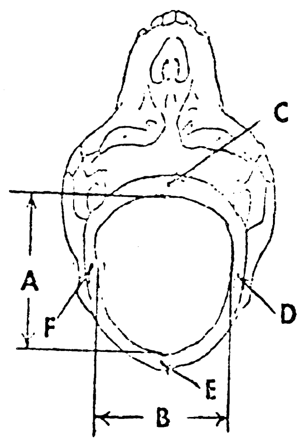
Skull Inside Width B 2.94 in

Skull Thickness at Pt. C 0.160 in

Skull Thickness at Pt. D 0.165 in

Skull Thickness at Pt. E 0.178 in

Skull Thickness at Pt. F 0.151 in



IMPACT CONDITIONS

Location of Impact Left side of head

Type of Impact 4inch round rigid

Impact Velocity 41.70 ft/sec

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site ______

Opposite to Impact Site ______

Epidural Pressures in Direction of Impact:

At Impact Site ______

Opposite to Impact Site ______

Strain Gage Rosettes:

Right Parietal Gage ______

Left Parietal Gage ______

Frontal Gage ______

Force: ______

High Speed Motion Pictures:

Side Camera ______

Frame Rate ______

Type II

Accelerations in Direction of Impact:

At Impact Site No

Opposite to Impact Site No

Rigid Body Head Motion Analysis: Good

EEG DATA: Pre-Impact No

Post Impact No

- NOT ANALYZED -

Force: Good

High Speed Motion Pictures:

Side Camera Good

Framing Rate 3000 fps

Front Camera Good

Framing Rate 1000 fps

INJURY:

Condition Prior to Impact Slight muscle tone, slight eye reflex, and some shivering

		Time After Impact	Condition
Consciousness	1.	0 min.	Unconscious
	2.	9 min.	Unconscious
	3.	55 min.	Slight pupillary response only
	4.	65 min.	Unconscious
	5.		
	6.		
	7.		
	8.		
	9.		
	10.		

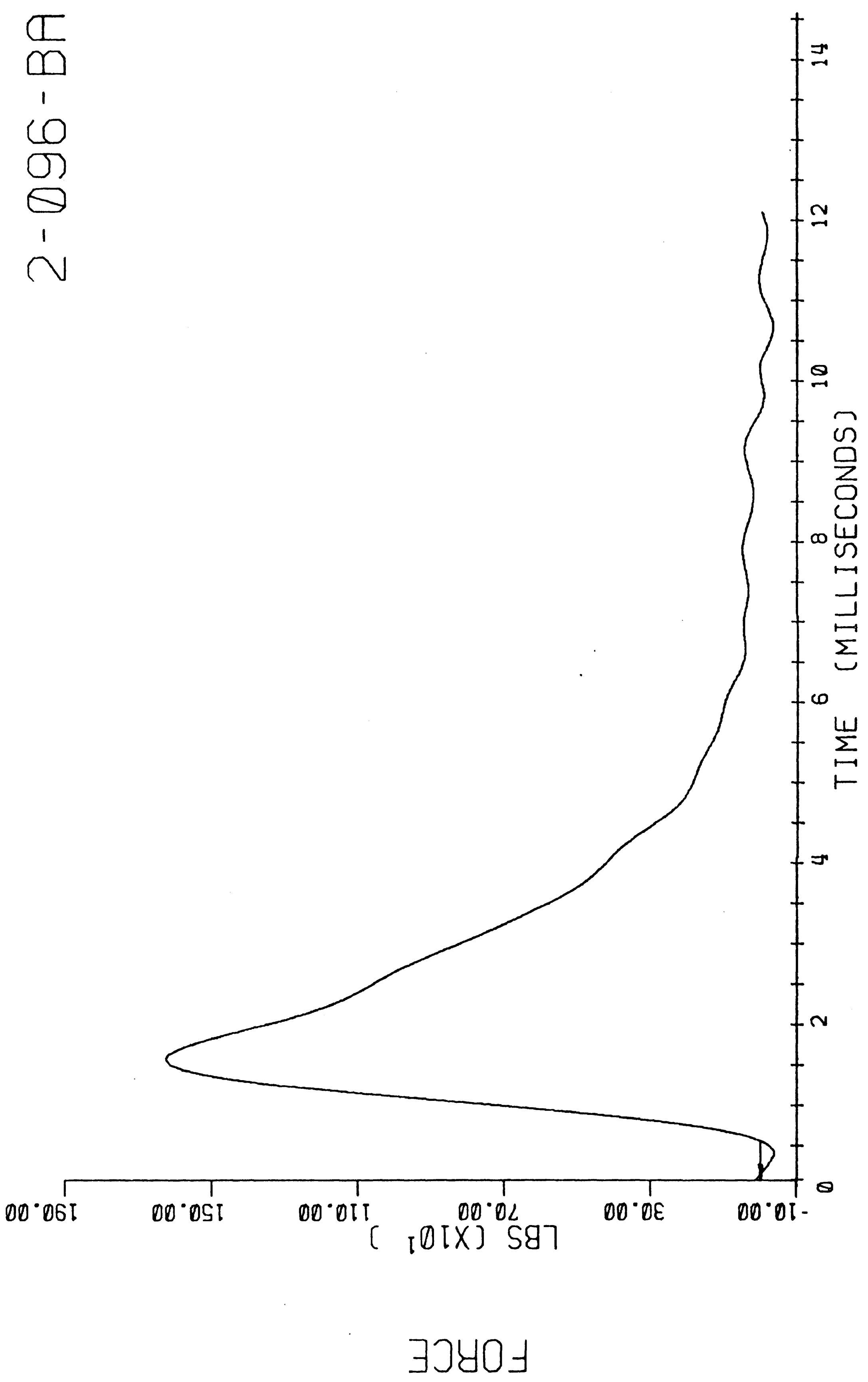
Autopsy Summary:

1. Unconscious with severe neurological signs > 15 min.
2. Deep bruising of muscle over Lt. zygomatic arch
3. Comminuted fracture Lt. zygomatic arch (multiple)
4. Tear of superior sagittal sinus
5. Small bruises and hemorrhage due to collets
6. Subdural hemorrhage Rt. parietal lobe
7.
8.
9.
10.
11.
12.
13.
14.
15.

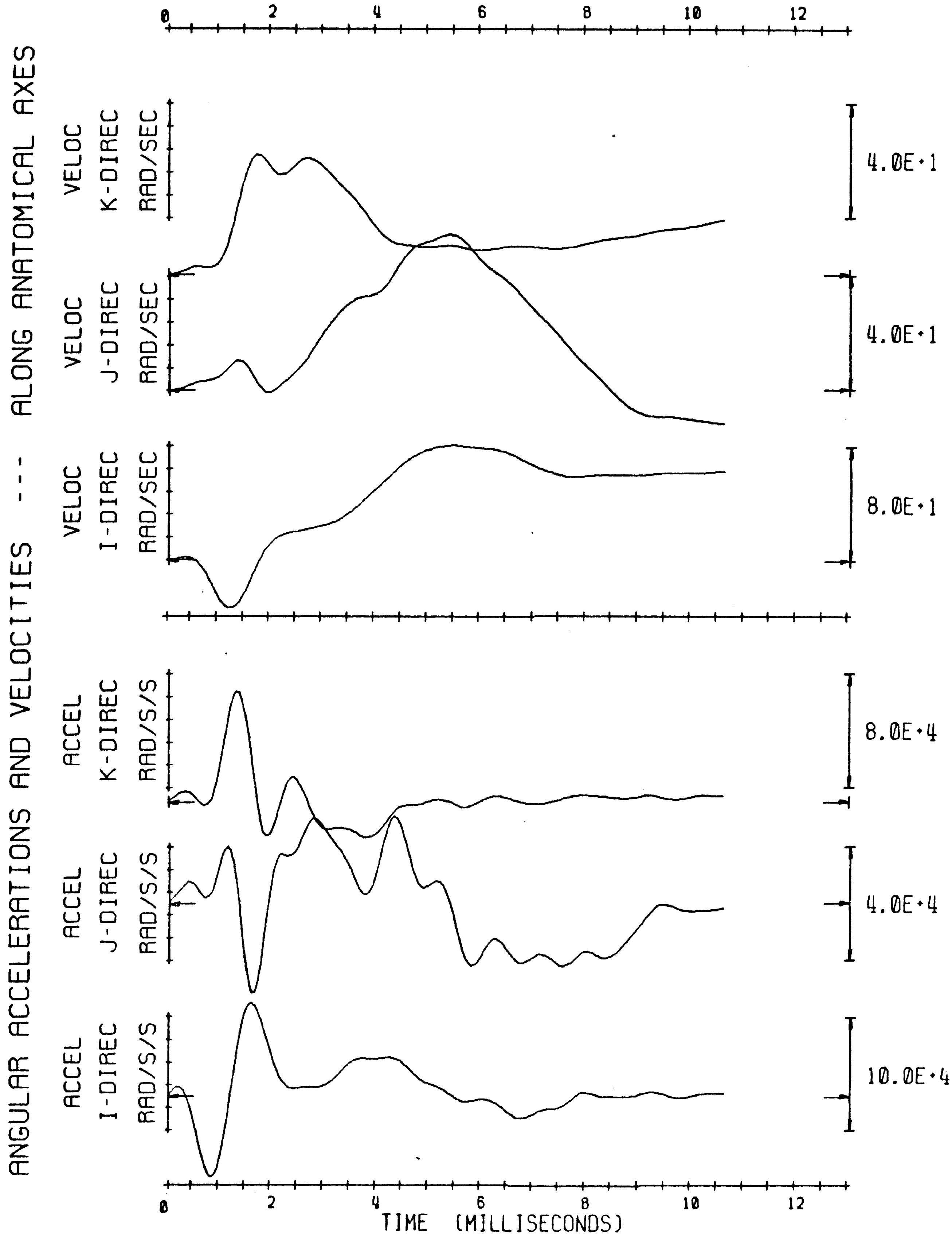
Injuries Due to Impact only (not instrumentation)

	Injury	AIS
1.	Unconscious > 15 min.	4
2.	Deep bruising of muscle over Lt. zygomatic arch	2
3.	Communited fracture left zygomatic arch (multiple)	3
4.	Tear of superior sagittal sinus	5
5.	Subdural hemorrhage Rt. parietal lobe	4
6.		
7.		
8.		
9.		
10.		

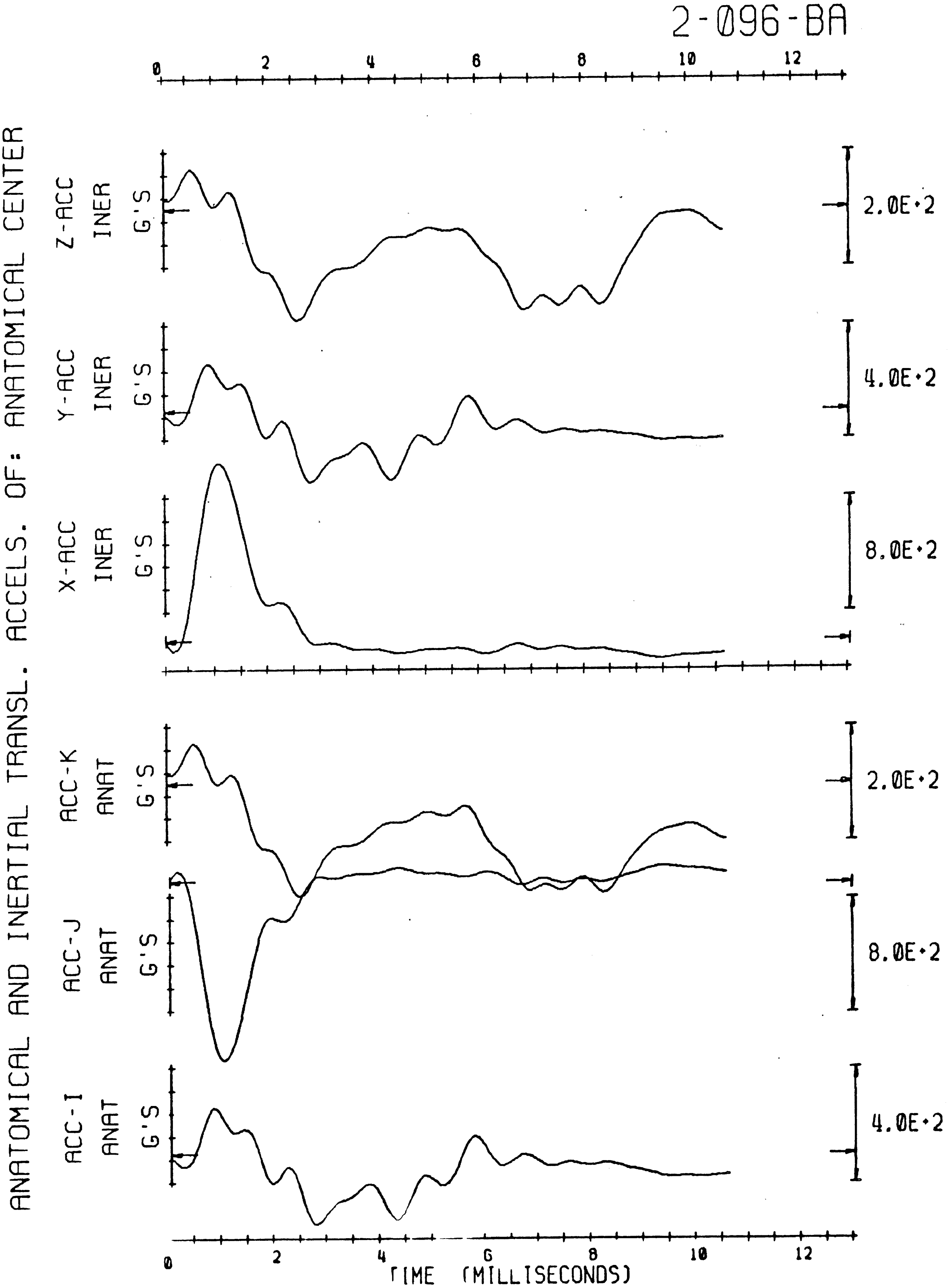
AIS Overall 6


2-096-BA
FORCE
LBS (X10¹)
-10.00
30.00
70.00
110.00
150.00
190.00
TIME (MILLISECONDS)
0
2
4
6
8
10
12
14

2-096-BA



3-D RIGID BODY MOTION ANALYSIS



3-D RIGID BODY MOTION ANALYSIS

APPENDIX B-4

HUMAN CADAVER TYPE III

HEAD IMPACT TEST SUMMARY

TEST NO. 011 TEST DATE 1/17/75

TEST SUBJECT

SPECIES Human (20089)

Body Weight 176 lb.

Sitting Height (Top of Head to bottom of Buttocks) --- in.

Head Weight 10.7 lbs

Brain Weight 0.71 lbs

Brain Volume 61.0 in^3

Skull Inside Length A 6.35 in

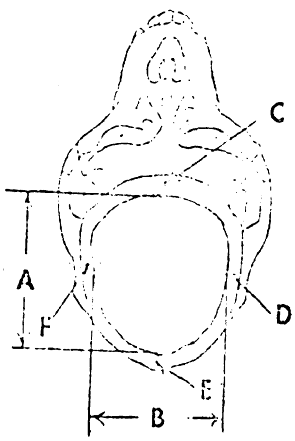
Skull Inside Width B 5.54 in

Skull Thickness at Pt. C .28 in

Skull Thickness at Pt. D .24 in

Skull Thickness at Pt. E .40 in

Skull Thickness at Pt. F .23 in



IMPACT CONDITIONS

Location of Impact Back of head

Type of Impact Four inch diameter rigid impactor

Impact Velocity 19.6 ft/sec

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site ---

Opposite to Impact Site Loss of Data

Epidural Pressures in Direction of Impact:

At Impact Site ---

Opposite to Impact Site ---

Strain Gage Rosettes:

Right Parietal Gage Good

Left Parietal Gage Good

Frontal Gage Good

Force: Good

High Speed Motion Pictures:

Side Camera Good

Frame Rate 3000 fps

Type II

Accelerations in Direction of Impact:

At Impact Site ________

Opposite to Impact Site ________

Rigid Body Head Motion Analysis: ________

EEG DATA: Pre-Impact ________

Post Impact ________

- NOT ANALYZED -

TEST NO. 011

High Speed Motion Pictures:

Side Camera ______________________

Framing Rate ______________________

Front Camera ______________________

Framing Rate ______________________

INJURY:

Condition Prior to Impact Cadaver

____

	Time After Impact	Condition
Consciousness 1.		
2.		
3.		
4.		
5.		
6.		
7.		
8.		
9.		
10.		

TEST NO. 011

Autopsy Summary:

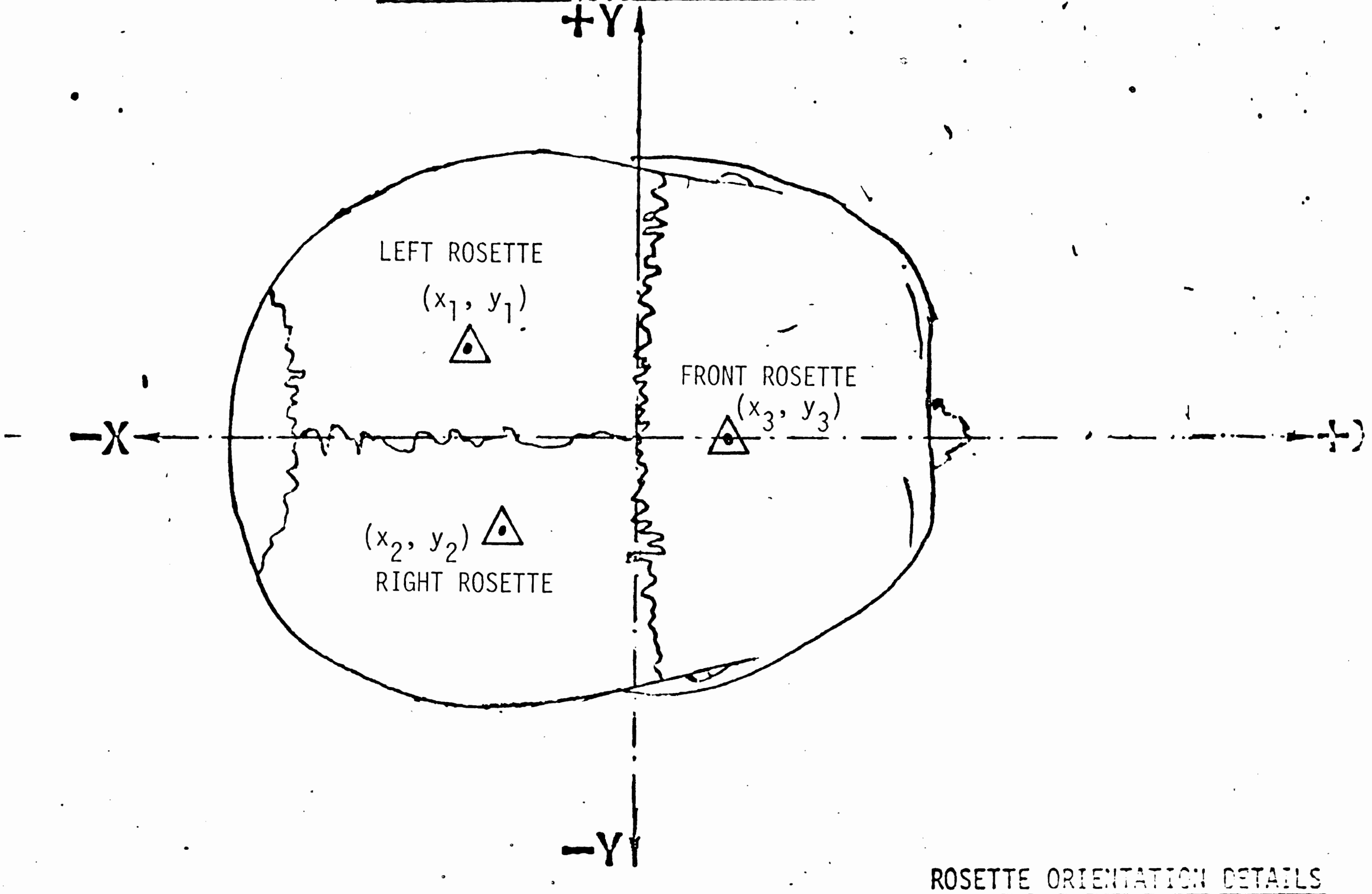
1. No injury
2.
3.
4.
5.
6.
7.
8.
9.
10.
11.
12.
13.
14.
15.

Injuries Due to Impact only (not instrumentation)

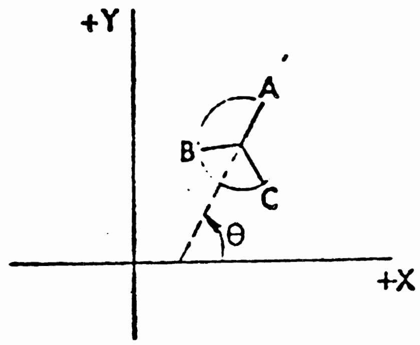
		AIS
1.	No injury	0
2.		
3.		
4.		
5.		
6.		
7.		
8.		
9.		
10.		

AIS Overall 0

HSRI STRAIN ROSETTE DATA SHEET TEST 011



ROSETTE ORIENTATION DETAILS



a. △ -- Location of strain rosettes.

b. R -- Right L -- Left T -- Top

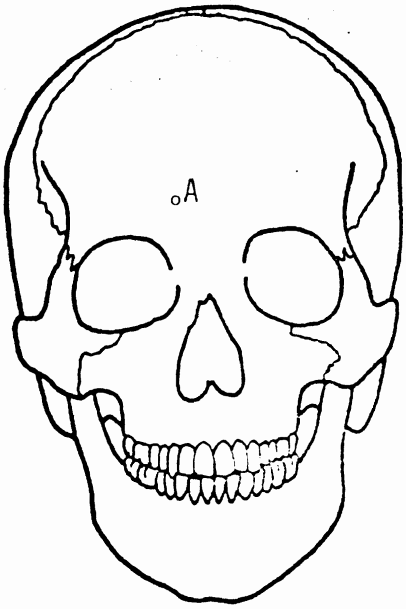
c. θ is the angle (measured anti-clockwise) arm 'A' of the rosette makes with the positive direction of the X-axis.

Note: Arm 'A' corresponds to arm '1' as printed on rosette.

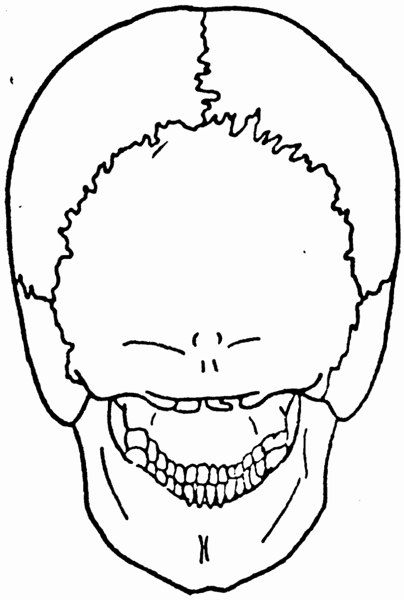
d. All distances are measured along the surface of the skull.

LEFT ROSETTE	RIGHT ROSETTE	FRONT ROSETTE
x_1 = -0.9 in	x_2 = -1.3 in.	x_3 = 1.45 in.
y_1 = 2.0 in	y_2 = -2.1 in.	y_3 = 0
θ_1 = 174.5°	θ_2 = 171°	θ_3 = 177°

RUN NO. 011

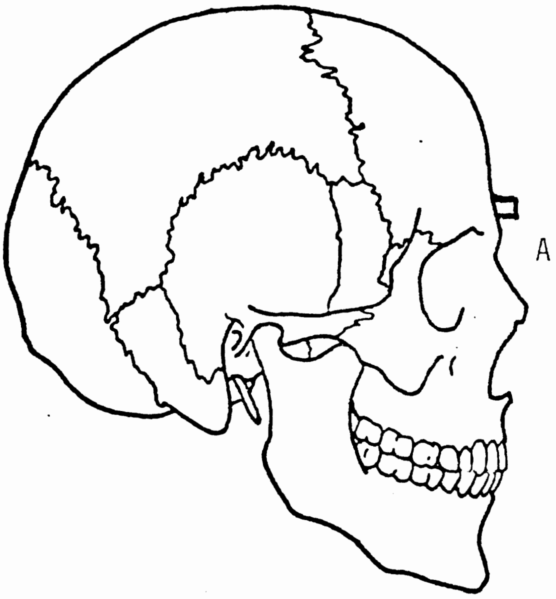


Anterior View

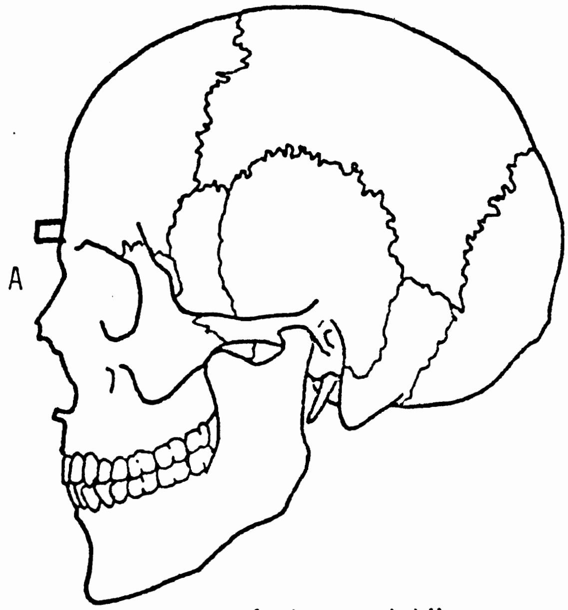


Posterior View

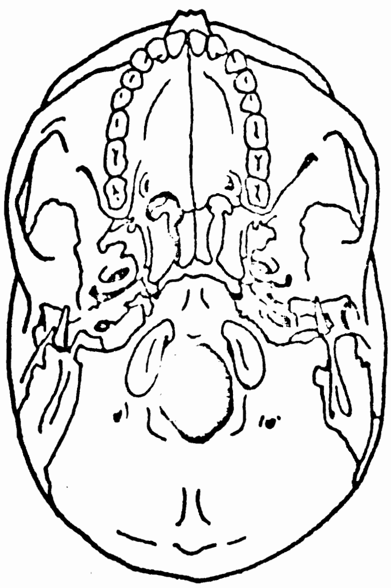
A - Accelerometer



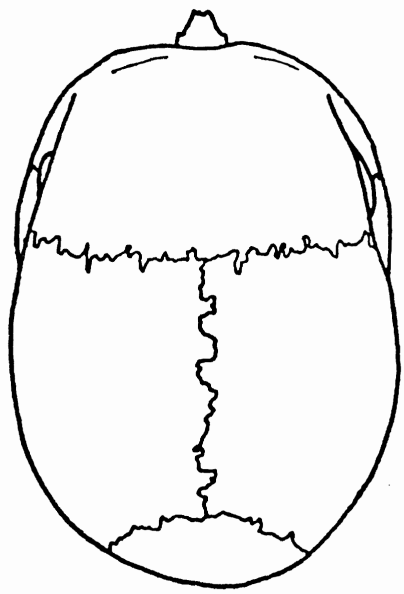
Right Lateral View



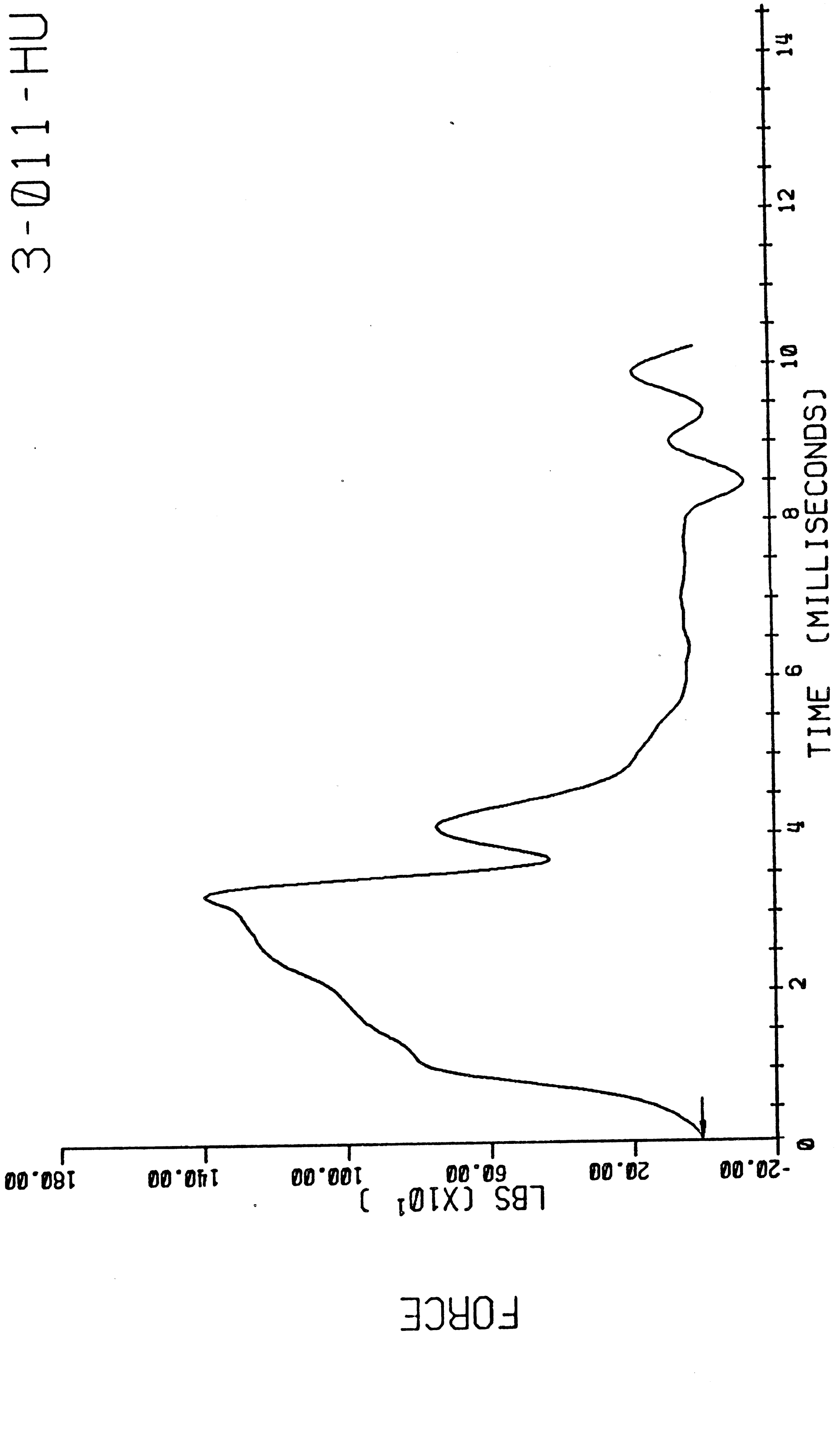
Left Lateral View



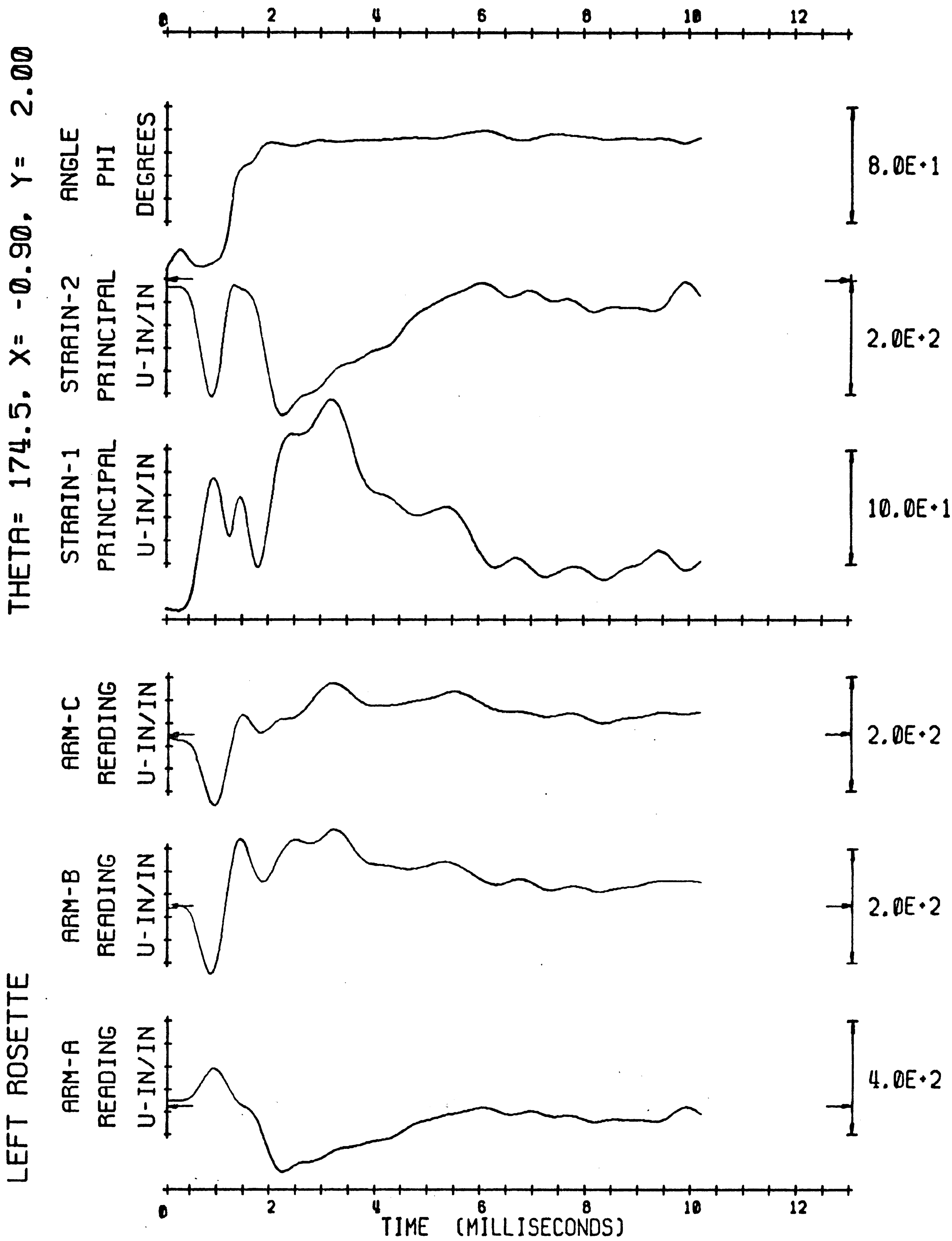
Inferior View



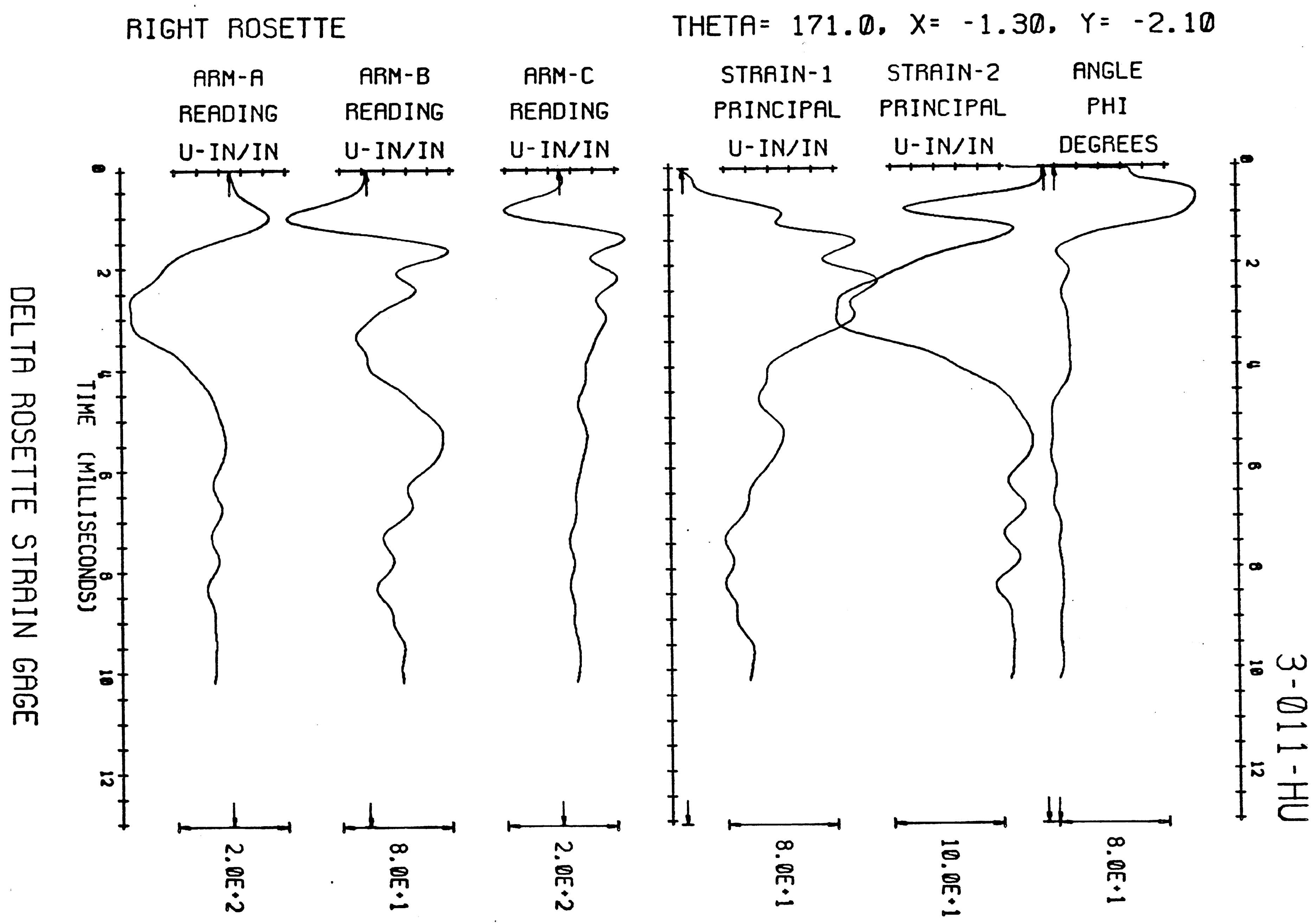
Superior View

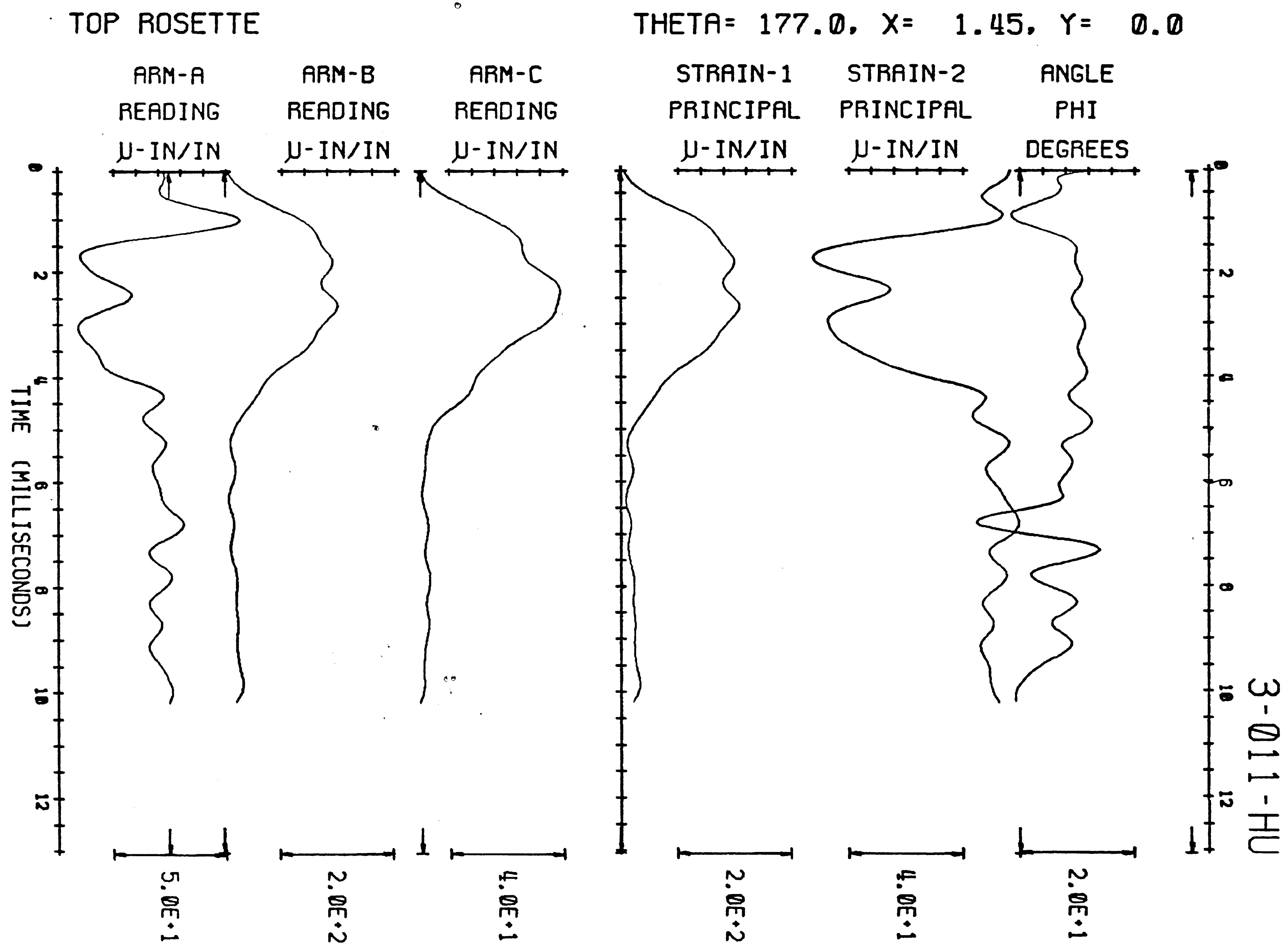

3-Ø11-HU
FORCE
LBS (X1Ø1)
-20.00
20.00
60.00
100.00
140.00
180.00
TIME (MILLISECONDS)
0
2
4
6
8
10
12
14

3-Ø11-HU



DELTA ROSETTE STRAIN GAGE


RIGHT ROSETTE
THETA= 171.0, X= -1.30, Y= -2.10
ARM-A READING U-IN/IN
ARM-B READING U-IN/IN
ARM-C READING U-IN/IN
STRAIN-1 PRINCIPAL U-IN/IN
STRAIN-2 PRINCIPAL U-IN/IN
ANGLE PHI DEGREES
TIME (MILLISECONDS)
0
2
4
6
8
10
12
2.0E+2
8.0E+1
2.0E+2
8.0E+1
10.0E+1
8.0E+1
3-011-HU
DELTA ROSETTE STRAIN GAGE



DELTA ROSETTE STRAIN GAGE

HEAD IMPACT TEST SUMMARY

TEST NO. 032 TEST DATE 2/19/75

TEST SUBJECT

SPECIES Human (20122)

Body Weight 150 lb.

Sitting Height (Top of Head to bottom of Buttocks) --- in.

Head Weight 9.7 lbs

Brain Weight 0.74 lbs

Brain Volume 59.0 in^3

Skull Inside Length A 6.13 in

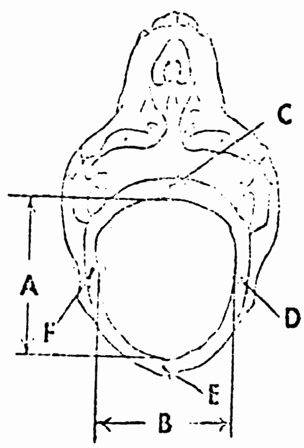
Skull Inside Width B 5.47 in

Skull Thickness at Pt. C .25 in

Skull Thickness at Pt. D .24 in

Skull Thickness at Pt. E .39 in

Skull Thickness at Pt. F .21 in



IMPACT CONDITIONS

Location of Impact Left Side of head

Type of Impact Four inch diameter rigid impactor

Impact Velocity 25.0 ft/sec

Test No. 032

DATA MEASURED

Type I

Accelerations in Direction of Impact:

At Impact Site ---

Opposite to Impact Site ---

Epidural Pressures in Direction of Impact:

At Impact Site Good

Opposite to Impact Site Fair

Strain Gage Rosettes:

Right Parietal Gage Lost

Left Parietal Gage Good

Frontal Gage Good

Force: Good

High Speed Motion Pictures:

Side Camera Good

Frame Rate 3000 fps

Type II

Accelerations in Direction of Impact:

At Impact Site ______

Opposite to Impact Site ______

Rigid Body Head Motion Analysis: ______

EEG DATA: Pre-Impact ______

Post Impact ______

- NOT ANALYZED -

TEST NO. 032

High Speed Motion Pictures:

Side Camera __________

Framing Rate __________

Front Camera __________

Framing Rate __________

INJURY:

Condition Prior to Impact Cadaver

		Time After Impact	Condition
Consciousness	1.		
	2.		
	3.		
	4.		
	5.		
	6.		
	7.		
	8.		
	9.		
	10.		

TEST NO. 032

Autopsy Summary:

1. Brain slightly softer than normal
2. Some hemorrhage in spinal column fluid
3. A few black particles from pressurization fluid noticed in brain
4.
5.
6.
7.
8.
9.
10.
11.
12.
13.
14.
15.

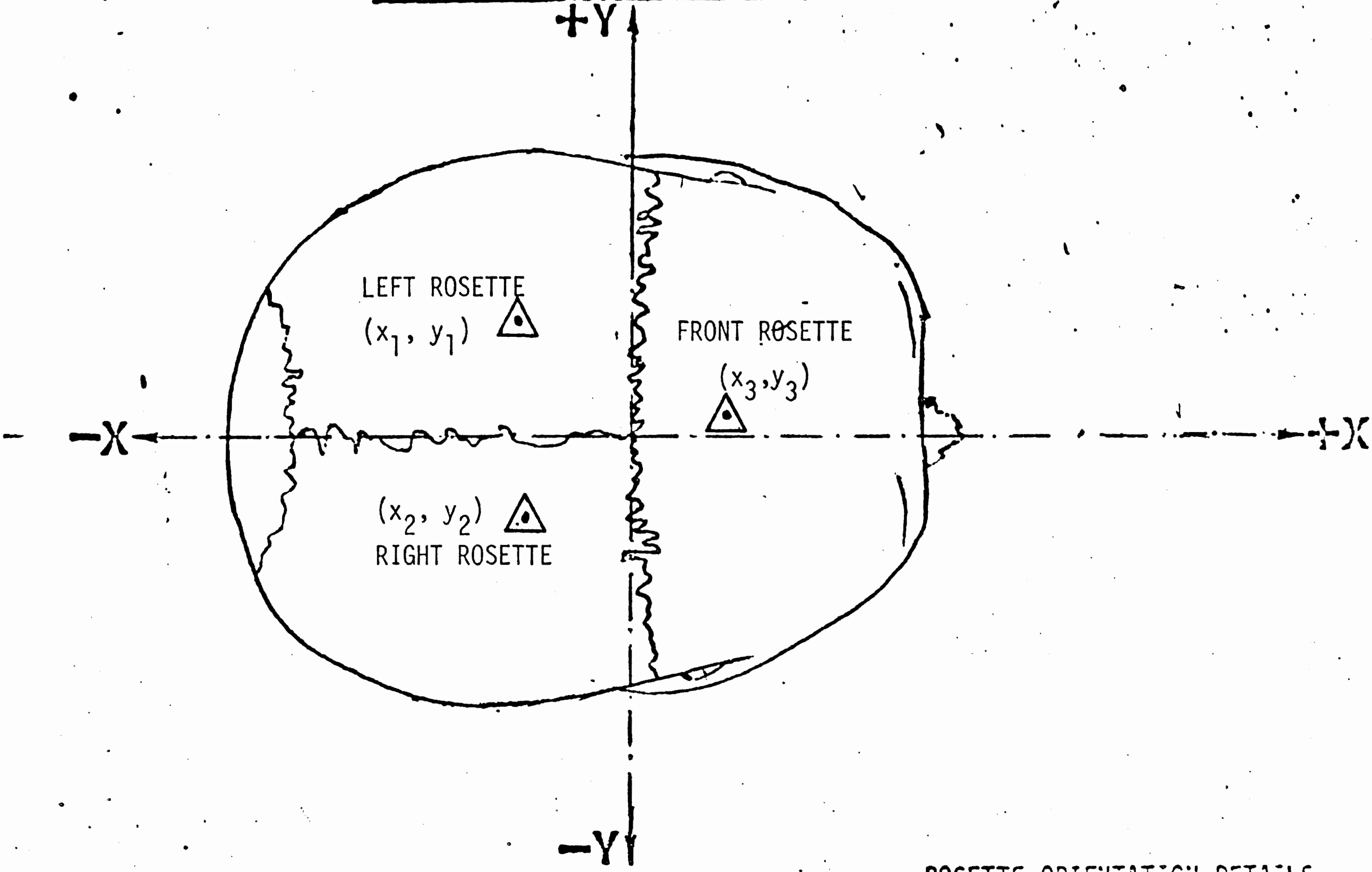
Injuries Due to Impact only (not instrumentation)

	Injury	AIS
1.	Hemorrhage in spinal column fluid	3
2.		
3.		
4.		
5.		
6.		
7.		
8.		
9.		
10.		

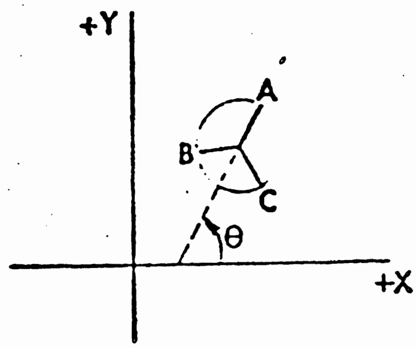
AIS Overall 3

HSRI STRAIN ROSETTE DATA SHEET

TEST 032



ROSETTE ORIENTATION DETAILS



a. △ -- Location of strain rosettes.

b. R -- Right L -- Left T -- Top

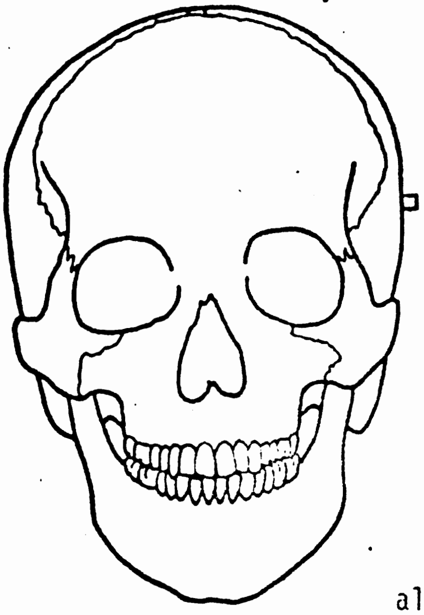
c. θ is the angle (measured anti-clockwise) arm 'A' of the rosette makes with the positive direction of the X-axis.

Note: Arm 'A' corresponds to arm '1' as printed on rosette.

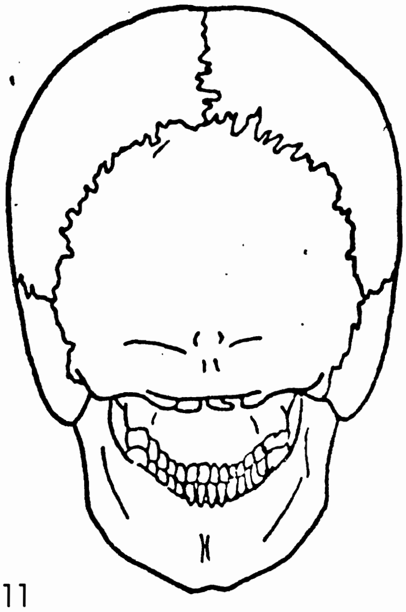
d. All distances are measured along the surface of the skull.

LEFT ROSETTE	RIGHT ROSETTE	FRONT ROSETTE
x_1 = -2.5 in.	x_2 = -2.2 in.	x_3 = 1.0 in.
y_1 = 2.2 in.	y_2 = -2.0 in.	y_3 = 0.2 in.
θ_1 = 4°	θ_2 = 177°	θ_3 = 3°

RUN NO. 032



Anterior View

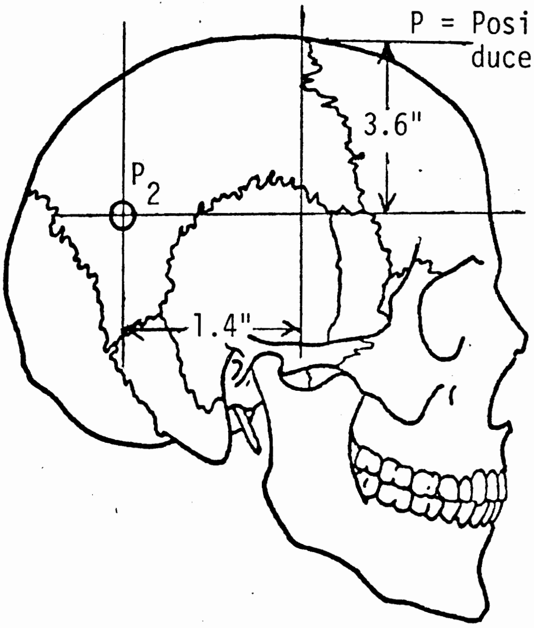


Posterior View

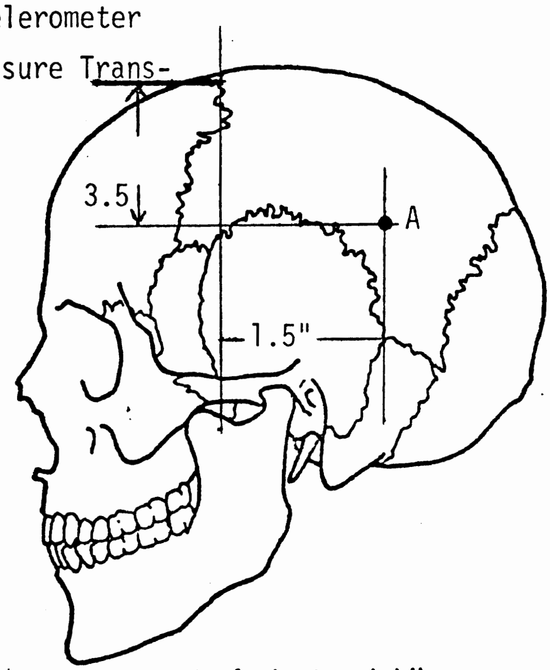
All measurements along surface of skull

A = Position of Accelerometer

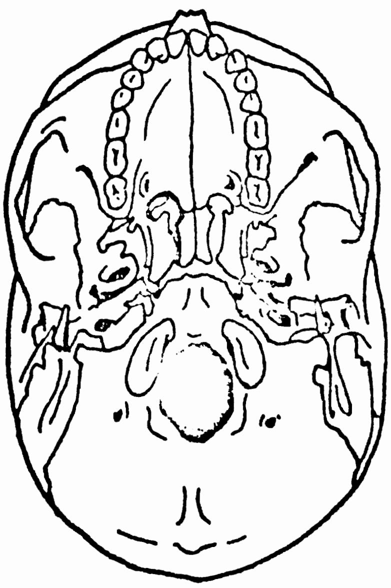
P = Position of Pressure Transducers.



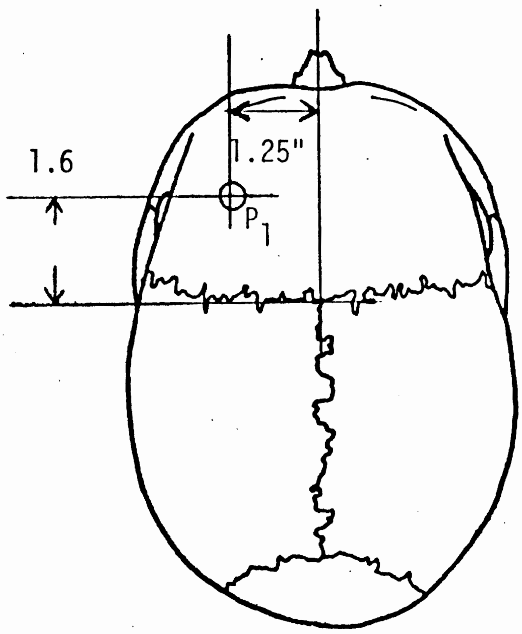
Right Lateral View



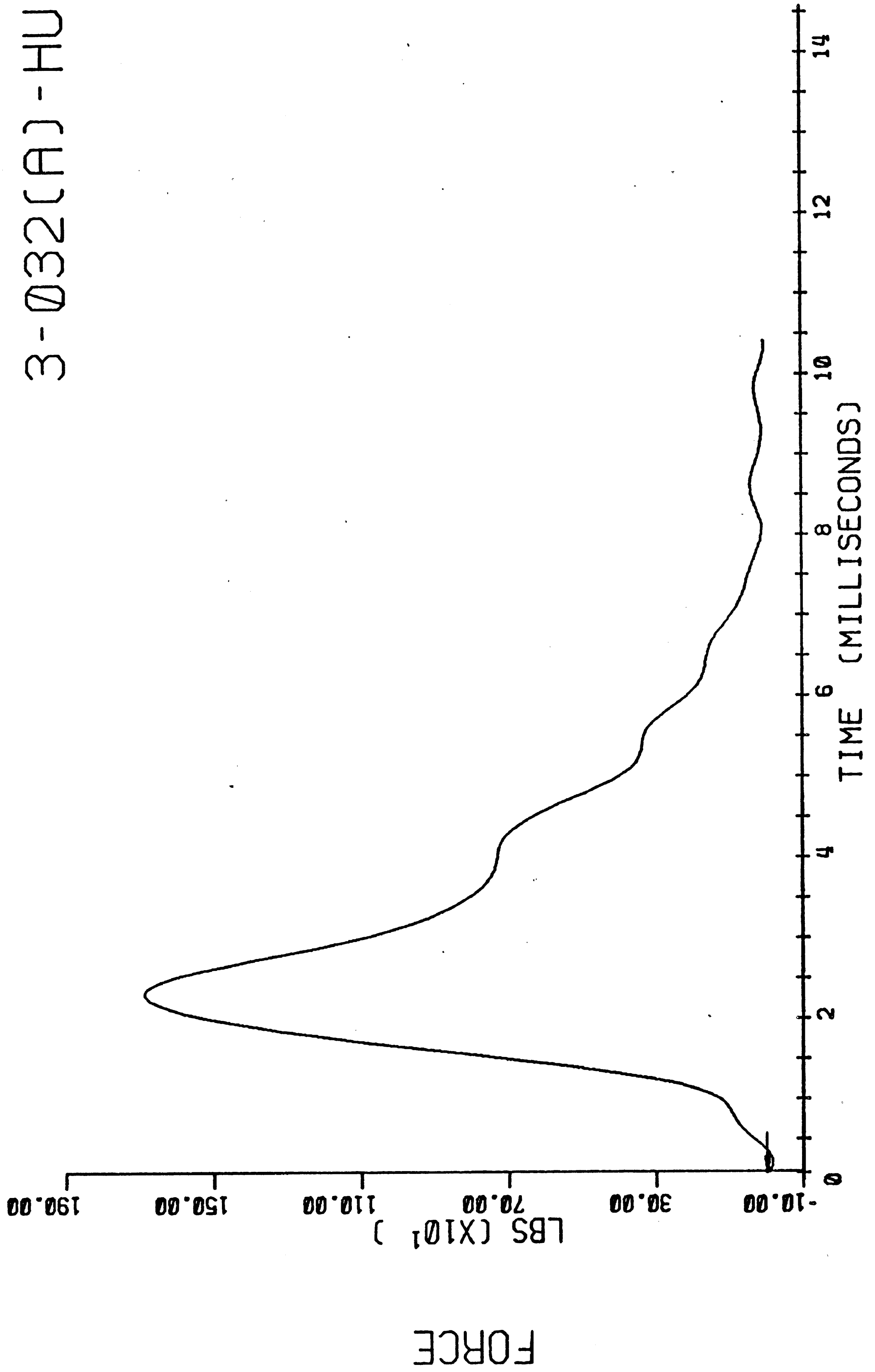
Left Lateral View

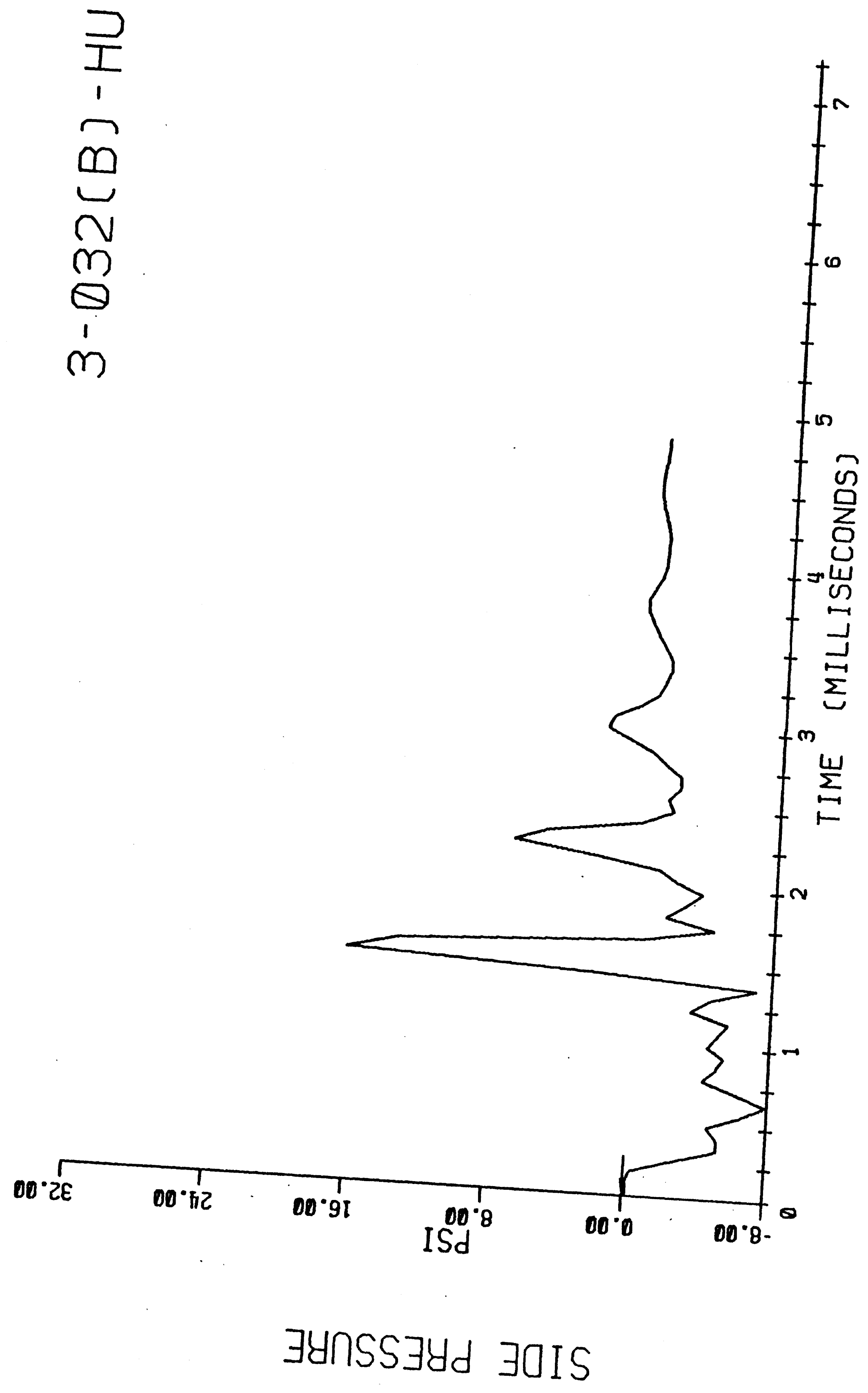


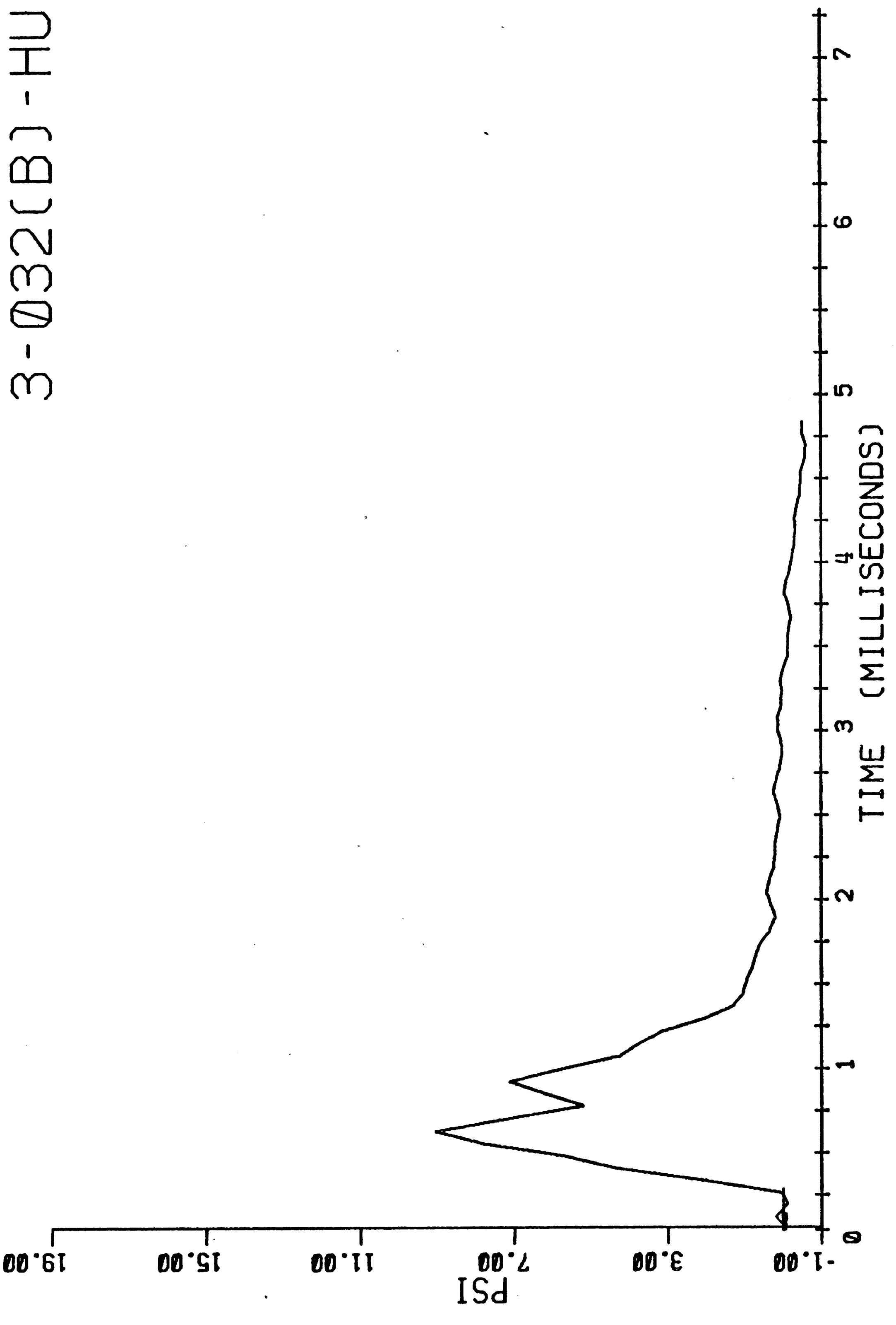
Inferior View



Superior View

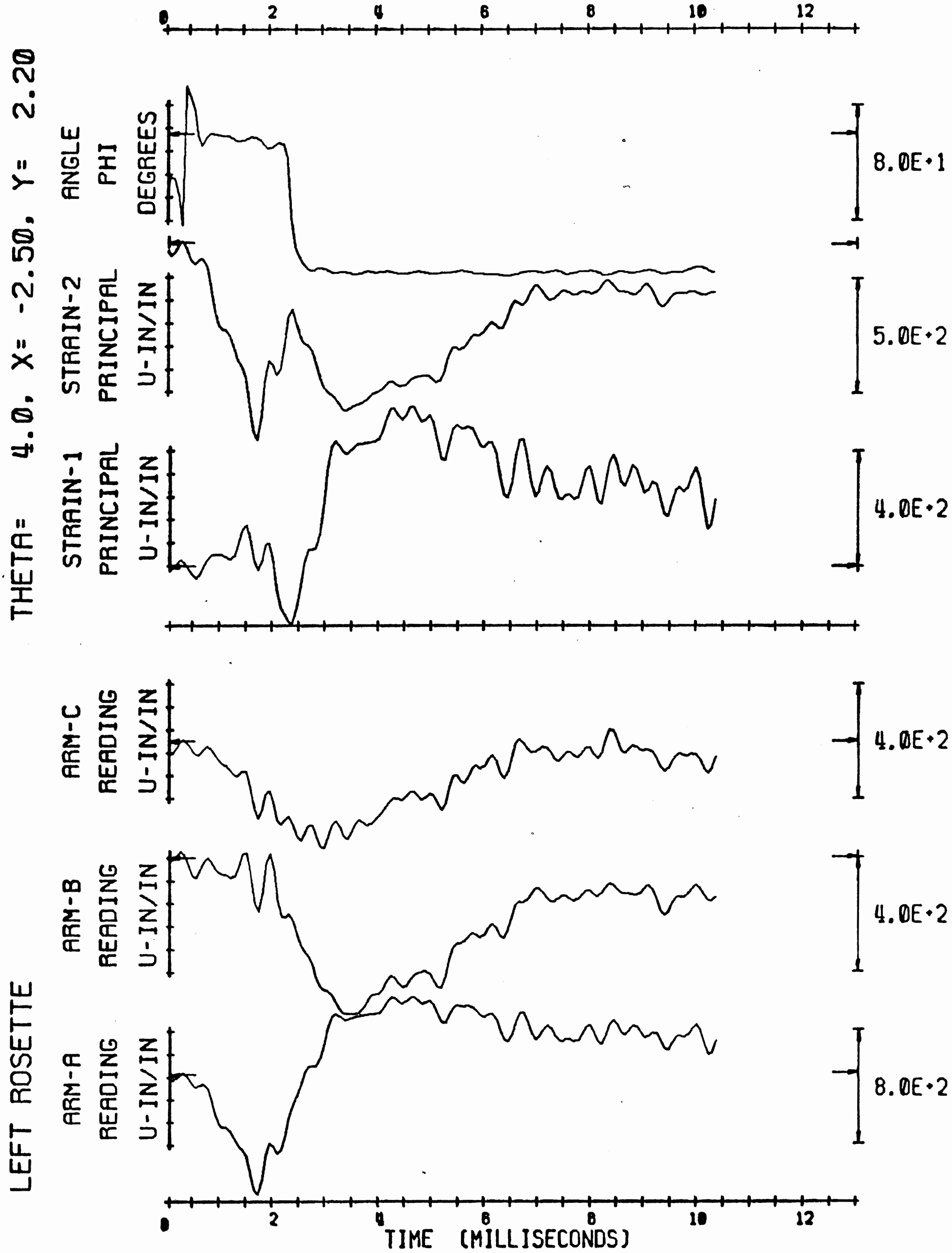

3-Ø32(A)-HU
TIME (MILLISECONDS)
0
2
4
6
8
10
12
14
FORCE
LBS (X1Ø1)
-10.00
30.00
70.00
110.00
150.00
190.00


3-Ø32(B)-HU
SIDE PRESSURE
PSI
32.00
24.00
16.00
8.00
0.00
-8.00
TIME (MILLISECONDS)
0
1
2
3
4
5
6
7

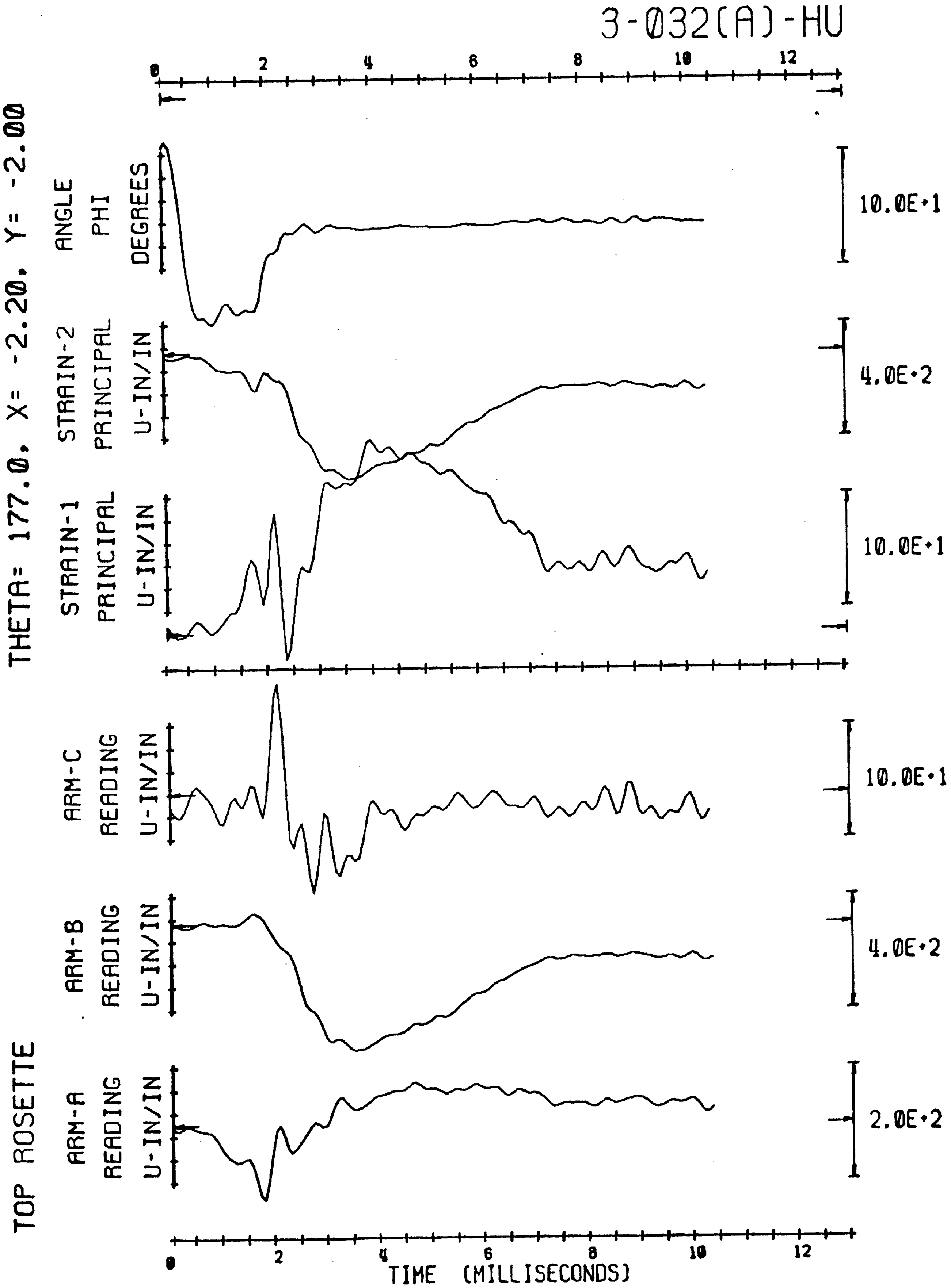


FRONT PRESSURE

3-032(A)-HU



DELTA ROSETTE STRAIN GAGE



DELTA ROSETTE STRAIN GAGE

APPENDIX C

INSTRUMENTATION SPECIFICATIONS

APPENDIX C-1

SKULL: STATIC COMPRESSION

C-1. SKULL: STATIC COMPRESSION

INSTRUMENT	NAME AND MODEL NUMBER	MANUFACTURER	SPECIFICATIONS
I. Strain Gage	EA- -015YD-120 Option SE	Micro-Measurements	Strain Range: ±3% to ±5% Strain Level: ±1500 to -120 με Resistance: 120 ± .6% Ω
Ia. Strain Gage Amplifier	Accudata 105 Gage Control Unit	Honeywell	Frequency Response: 0-10 kHz within ± 0.5% Bridge Balance: Compensate for a ± 5% unbalance in one leg of a 350 Ω gage with limiting resistor supplied. Output Voltage with No Load: 12 volts dc ± 7% Output Current: 0 to 40 ma. Load Regulation: 2%, no load to full load. Line Regulation: ± 0.1% for a ± 1% change in supply voltage (44 volt dc). DC Drift: 0.05% per degree F. Output Ripple: < 1 v p-p. Power Requirements: 44 volt dc at 50 ma.
Ib. Strain Gage DC Amplifier	Accudata 120	Honeywell	Input Impedance: 10 MΩ minimum at dc. Frequency Response: (a) R_{load} > 36Ω and C_{load} < 0.1μ fd: for < 10 kHz, ±2%dc Full scale output (F.S.O.) for < 20 kHz, ±5%dc (80% F.S.O.) (b) R_{load} > 1000Ω and C_{load} < 0.01μ fd for < 10 kHz, ±2%dc F.S.O. for < 40 kHz, ±5%dc F.S.O for < 100 kHz, ±3db dc (30% F.S.O.)

INSTRUMENT	NAME AND MODEL NUMBER	MANUFACTURER	SPECIFICATIONS
(cont.) Strain Gage D.C. Amplifier	Accudata 120	Honeywell	Gain: 10-1000 max. DC gain linearity better than ±0.2% F.S.O. (±5 mv) up to F.S.O. Phase Shift: < 10° from dc to 10 kHz. Noise: (a) Full B.W.: < 5μv rms RTI + 500μv rms at output. (b) D-C to kHz B.W.: < 2μv rms RTI + 100μv rms at output.
2. Static Load Cell	Tension-Compression Model TTC	Instron Corp.	Crosshead Speeds: .02 to 20 ipm. Load Cell Ranges: (b) maximum 0-10,000 lbs Recorder System: High Speed Graphic. Min. Speed Response= 1 sec. F.S. Max. Speed Response with 1% accuracy = 3 sec F.S.
2a Load Cell Amplifier	Accudata 105 Gage Control Unit	Honeywell	see Strain Gage Amplifier (1a under Skull: Static Compression)
2b Load Cell DC Amplifier	Accudata 120	Honeywell	see Strain Gage DC Amplifier (1b under Skull: Static Compression)
3. Extensiometer Transducer	PCA 117-100	Schaevitz	Range: ±.100
3a Extensiometer Signal Conditioner	MLMPL-201	Shaevitz	Excitation Frequency: 2500 H Excitation: 3v Linearity: .05 Power Requirements: 105/130 v rms, 50/400 Hz, 15 w, 220v rms/50 Hz. Frequency Response: dc to 100 Hz within ±1 db.

INSTRUMENT	NAME AND MODEL NUMBER	MANUFACTURER	SPECIFICATION
(cont.)			
Extensiometer Signal Conditioner	MLMPL-201	Schaevitz	Sensitivity: 0.5v rms in, 5v dc out. Non-Linearity: < 0.1% F.S.
4. Visicorder Oscillograph	Model 1612	Honeywell	Recording Frequency Range: DC to 5000 cycles per sec. Writing Speed: In excess of 50,000 ips spot velocity. Time Line System: Four-in-val Timeline System. Timing intervals of 0.01, 0.1, 1.0 and 10 seconds; accuracy of ±1% over $\geq$ 10 counts or ±1.25% between adjacent timelines. Recording Channels: 36 active channels plus 6 static reference channels. Recording Lamp: 100 watt high pressure mercury vapor arc, 2-electrode, vertically mounted. Record Capacity: Accepts all available light sensitive direct print and certain develop out types of recording papers; 12" wide. Thick base paper to 200 ft. and thin base paper to 450 ft. Chart Speeds: 15 forward (recording) speeds of 1,2,4,8 or 16 in/sec times 0.1, 1.0 or 10, up to 160 in./sec. max.
4a Galvanometer for Visicorder Oscillograph	M3300	Honeywell	Nominal Undamped Natural Freq.: 3300 cps Flat (±5%) Frequency Response: 0-2000 cps Required External Damping Resistance: effective damping essentially unchanged with variations in source resistance throughout the range of 3 to 100Ω.

INSTRUMENT	NAME AND MODEL NUMBER	MANUFACTURER	SPECIFICATIONS
(cont.)			
Galvanometer	M3300	Honeywell	Max. p-to-p Deflection with ±2% linearity: 6 inches

APPENDIX C-2

HEAD IMPACTS

C-2 HEAD IMPACTS

INSTRUMENT	NAME AND MODEL NUMBER	MANUFACTURER	SPECIFICATIONS
1. Air Cannon Load Cell	Load Washer Model 904A	Kistler Instrument Co.	Min. Resonant Freq.: 50 kHz. Linearity: 1% F.S. Shock & Vibration Limit: 10,000 g's. Overload Capacity: 10% F.S. F.S. Range: 0-20,000 lbs. Sensitivity: 10 pCb/lb. Resolution: 0.05 lb. Rigidity: 2.5 x 10^{-8} in/lb. Capacitance: 100 pF.
1a Load Cell Charge Amplifier	Dial Calibration Charge Amplifier Model 503	Kistler Instrument Co.	Input Range: 0.1 to 1000 pCb/psi, g, lb. Full Scale Sensitivity: (a) for min. sensitivity 1.0v min. (b) for max. sensitivity: 10v min. Output Voltage to High Impedance Load: ±10v peak. Output Current to Low Impedance Load: ±20 amp peak. Output Impedance = 100Ω. Frequency Response: 2-3 x 1C Hz (for range > 100). Input Impedance: 10^9Ω.
2. Air Cannon Accelerometer	Model 805-A	Kistler Instrument Co.	Range: 0-10^5 g's. Acceleration Limit: 20,000 g's. Resolution: 0.05 g's Overload: 10% Charge Sensitivity: 0.29 pCb/g. Freq. Response (±5%): near D.C. to 12,000 Hz. Resonant Freq.: 53.5 kHz. Capacity: 59 pF. Transverse Sensitivity: 4.6%

INSTRUMENT	NAME AND MODEL NUMBER	MANUFACTURER	SPECIFICATION
2a Accelerometer Charge Amplifier	Dial Calibration Charge Amplifier Model 503	Kistler Instrument Co.	see Load Cell Charge Amplifier (1a under Head Impact).
3. Accelerometers rigid body (head)	Miniature Piezoresistive Accelerometer Model 2264-2000	Endevco Dynamic Instrument Division	Nominal Resonant Freq.: 4700 Hz. Sensitivity: (a) at rated excitation: .2 mv/g (b) transverse: <2%. Acceleration Range: -2000 g to +2000 g. Linearity: ±2% of reading max., 0 to 150 g ±2.5% of reading. max., 0 to 200 g. Resistance: 1700Ω ±20%, at 75°F. Freq. Response (reference 100 Hz): ±10% max., 0 to 1200 Hz at +75°F.
3a Accelerometer DC Amplifier	Accudata 120	Honeywell	see Strain Gage DC Amplifier Accudata 120 (1b under Skull: Static Compression).
4. Accelerometers rigid body (head)	Miniature Piezoelectric Accelerometer Model 96	Wilcoxon Research	Nominal Capacity: 250 pf. Nominal Resonant Freq.: 75 kHz. Sensitivity: (a) Nominal transverse: 5% of axial. (b) Maximum transverse: 10% of axial. (c) Nominal accoustic: 0.2 g equiv. at 155 dB. (d) Nominal magnetic: 10^{-4} g/gauss equiv. Acceleration Range: 10^{-2} to 10^{-4} g. Linearity: 1.5%. Resistance: 10^3 MΩ min at 70° F. Freq. Response: 10 kHz.
4a Impedance Converter	Impedance Converter Model 558	Kistler Instrument Co.	Output Voltage: ±5v. Output Impedance: 100Ω.

INSTRUMENT	NAME AND MODEL NUMBER	MANUFACTURER	SPECIFICATIONS
(cont.)			
4a Impedance Converter	Impedance Converter Model 558	Kistler Instrument Co.	Output Current: 2 mA. Non-linearity: 1% Noise: 60 µv rms.
4b Coupler	Piezotron Coupler Model 549	Kistler Instrument Co.	Input Current: 3.9 ±0.5 mA. Freq. Response: (1 msi load ±5%) (10v pp output) (a) AC mode: 0.6 to 150 kHz. Full Scale Input: 10v pp.
5. Epidural Pressure Transducer	U. of M. Bi-75	U. of M. Bio-mechanics	Freq. Response: at least 400 Hz. Shock Limit: 44.1 psi. Sensitivity: Resolution: 0.1 psi.
5a Transducer Amplifier	Accudata 105 Gage Control Unit	Honeywell	see Strain Gage Amplifier (1a under Skull: Static Compression).
5b Transducer DC Amplifier	Accudata 120	Honeywell	see Strain Gage DC Amplifier (1b under Skull: Static Compression).
6. Tape Recorder	Model 7600 Magnetic	Honeywell	Input Impedance: 10 kΩ. Speed Range: 1 7/8 ips to 120 ips (ex: for 30 ips, freq. response < 10 kHz). (a) Tape Speed: 120 ips Center Freq.: 216 kHz. Data Bandwidth within 1.0 db: 0-40,000 Hz. RMS S/N: 48 db. (b) Tape Speed: 30 ips Center Freq.: 54 kHz. Data Bandwidth within 1.0 db: 0-10,000 Hz. RMS S/N: 47 db. 3v Input: 40% deviation = 3v out.

INSTRUMENT	NAME AND MODEL NUMBER	MANUFACTURER	SPECIFICATIONS
7. High Speed Motion Picture Camera	Hycam	Redlake	Framing Rate: 0-10,000 frames/sec. Servo: to 5000 frames. Film: 16 mm. Lens: 25 mm.
8. Rotary Prism Recording Camera	Model-1B	Photo-Sonics, Inc.	Framing Rate: 0-1000 frames/sec. Film: 16 mm. Lens: 25 mm. Servo: Full
9a. Ektachrome Film	7242	Kodak	ASA: 125 16 mm.
9b. 4-X Reversal Film	7277	Kodak	ASA: 320 16 mm.