SIX MONTH MAIN REPORT

Volume I of IV

Interim Report on Contract PH-43-67-1136

by D. H. Robbins, Project Engineer
V. L. Roberts, Project Director

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INTRODUCTION

This report is concerned with the first six months of progress in determining the physical properties of the head. This volume, entitled "Main Report", describes the objectives of the research program which have been met and the outline of research for the next six months. In addition, it includes a brief description of the literature surveys, experiments, and analyses which have been carried out.

The stated objective of the project is the characterization of the physical properties of tissues of scalp, skull, dura, fluid-filled sub-arachnoid space, brain, and fluid-filled ventricles. Human biopsy and fresh autopsy material were to be used. "In vivo" test procedures were to be developed and used insofar as possible and compared with "in vitro" results.

The progress which has been made thus far has occurred in a series of evolutionary steps. The first question posed was, "What has been done in the past?" This resulted in bibliographies entitled "Bibliography on the Properties of Soft Tissues" and "Bibliography on the Physical Properties of Skeletal System." These are described briefly in the State of the Art section of this volume of the report and completely in Appendices A and B.

Next it was necessary to establish sources for materials. This was accomplished by organizing a collection program at The University of Michigan Medical Center and the Veterans Administration Hospital in Ann Arbor both of which are within five minutes of the Biomechanics Laboratories. Bone plugs which are either 0.75 in. or 1.25 in. in diameter have been obtained from the temporal, parietal, and frontal bones of the skull. Cerebral brain tissue has been removed at four human autopsies. Procedures for obtaining cerebrospinal fluid have been established but tests have not yet been carried out. Dura is readily available and fresh skin is available in more limited quantities. Embalmed calvariums have been obtained from the University's Department of Anatomy.

The next step was development of testing procedures. This work is essentially complete and to this date a total of about 600 tests (tension, compression, shear, puncture, dynamic shear, bulk modulus) have been carried out on human skull bone, human and primate brain, and human skin. These tests are described briefly in this main report and in detail in Appendices C through G.

The remainder of the first year of the project will be concerned primarily with carrying out additional tests and evaluating results both statistically and physically. Particular emphasis will be placed on histology as a means of relating the measured properties to the microscopic structure of the tissue in question.

The primary new tests which will be carried out are dynamic property tests. Experiments on bone and skin will be carried out on a new high speed Plas-Tech testing machine. In addition, some "in vivo" test techniques now under development will be used to gain further information on brain tissue. These tests will be carried out both "in vivo" and "in vitro" on monkeys.

Analytical work has been underway during the contract period to date. An impact problem for a spherical shell has been solved (Appendix H) preparatory for a fluid-filled shell analysis and the solution is currently being numerically studied on a digital computer. In addition, a technique for generating constitutive equations is being developed. This technique will allow stress at a point to be expressed in terms of a set of functions of strain and strain rate. The first year of research will culminate with a set of first generation constitutive equations.

All this work is guided by the following concerns: 1. What are the physical properties of the skull and its contents?; 2. What injuries should be modeled? (a head injury bibliography will be included in the next report); 3. What materials and techniques should be used in fabricating models? (the subcontractor, Dow-Corning Corporation, is conducting a survey); and 4. What mathematical models are tractable and most pertinent? A progress schedule showing the first six months of activity as well as the next six months is shown in Figure 1.

STATE OF THE ART

Many papers, treatises, and notes have been written on the topic of physical properties of the various tissues of the body. In the beginning of this project it was decided to determine the current state of the art particularly with respect to the tissues of the head. This resulted in the bone bibliography in Appendix B and the soft tissue bibliography in Appendix A.

The bone bibliography is an extension of one compiled by F. Gaynor Evans in connection with his research and writing in the area. This bibliography is a listing by authors of several hundred references to publications. Noticeably absent are references to the bones of the skull. Only a very few studies have been carried out on topics such as the split-line technique as a means of determining skull "grain structure" and growth patterns. Only one paper is known concerning basic physical properties of parietal bone. On

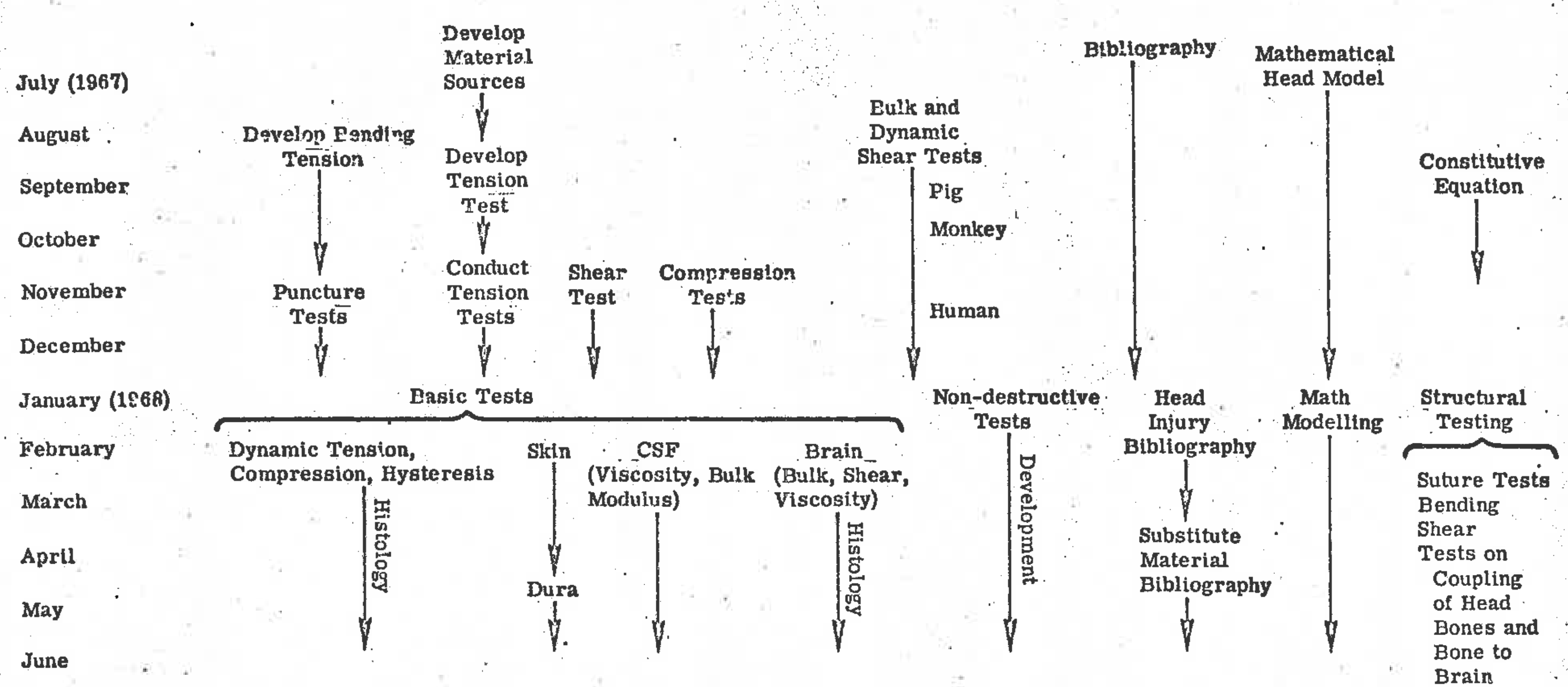

FIGURE 1. SCHEDULE OF WORK

the other hand there are a number of papers concerning structural failure of whole skulls.

A part of the effort was directed toward evaluation of hardness testing as a technique. At present there does not seem to be any evidence implying that useful information could be obtained from macroscopic hardness testing especially in view of the sandwich nature of the bones of the skull. Sugryama has found an age variation; no one else has. Evans has found an insignificant regional variation. As for microhardness testing, it appears as if there is enough conflicting evidence in the published literature so that a major effort would have to be undertaken to get any meaningful data at all. In this sense the bibliographic effort has helped to shape the research program.

A bibliography on soft tissue properties has also been compiled and at present includes 240 references. It is estimated that 400 references will be included when the current searching is completed. This is designed to be a self-perpetuating source of information in that all references have been abstracted and coded in the keysort card system described in Appendix A. A deck of punched cards will be included in the year end report.

An important aspect of this bibliography is an evaluation of the frequency of the various coding categories shown in Figure 2. The low frequency of references to the soft tissues of the head, the dynamic properties of soft tissues in general, review articles, and dynamic test procedures substantiates again the importance of the current research program.

Figure 2

SPECIMEN ORIGIN

1 Man
2 Primates (apes,monkeys)
3 Rodents (rats,mice,guinea pigs)
4 Uniguiculate (cats,dogs,rabbits)
5 Ungulate (horse,swine,cow,goat,deer,elephants)
6 Birds (chicken,ducks,fowls)
7 Cold blooded vertebrate (reptile,fish,amphibians)
8 Metals
9 Fibrous (wood)
10 Polymers
11 Other

ANATOMY

12 Lower extremities
13 Upper extremities
14 Skull
15 Torso (ribs,spine,pelvis,shoulder)
16 Viscera
17 Joints
18 Cartilage
19 Muscle
20 Ligaments & Tendon
21 Bone
22 Integument (skin & subcutaneous tissue)
23 Nerves & Nervous Tissue
24 Cardiovascular system & lungs
25 Microstructural Components (osteons, collagen,hair)
26 Blood
27 Body Fluids (CSF, synovial, serum)

SPECIMEN CONDITION

28 Living Tissue (in vivo)
29 Fresh
30 Refrigerated (unfrozen)
31 Frozen & Thawed
32 Embalmed
33 Solution
34 Dried
35 Other

MODE OF ANALYSIS

R1 Tension
R2 Compression
R3 Flexure
R4 Torsion,shear, tearing,puncture,penetration
R5 Combined Stress
R6 Pressure
R7 Chemical
R8 Optical (X-ray, photography,polaroid)
R9 Acoustical
R10 Electrical (Piezoresistance, etc.)

TYPE OF PAPER

R11 Theoretical work
R12 Experimental work
R13 Histological
R14 Pathological
R15 Review
R16 Technique Description
R17 Apparatus Description
R18 Property Correlation
R19 Statistical Validity
R20 On file, no punch for R20 indicates comment.

Figure 2. Continued

RECORDED PARAMETERS

B1	Age of Source
B2	Time after death
B3	Specimen Geometry
B4	Temperature
B5	Moisture content
B6	Density
B7	Viscosity
B8	Elasticity
B9	Hardness
B10	Ductility, extensibility
B11	Inhomogeneity
B12	Anisotropy
B13	Energy Absorbtion
B14	Strength
B15	Frequency
B16	Amplitude
B17	Rate of Variable Change
B18	Stress
B19	Strain
B20	Strain Rate
B21	Failure
B22	Other
B23	Radiation
B24	Wounds & Healing
B25	Velocity
B26	Electrical Properties
B27	Ionic Properties
B28	
B29	
B30	
B31	
B32	
B33	
B34	
B35	

AUTHOR

L1	A	N
L2	B	O
L3	C	P
L4	D	Q
L5	E	R
L6	F	S
L7	G	T
L8	H	U
L9	I	V
L10	J	W
L11	K	X
L12	L	Y
L13	M	Z
L14	Index	

RATE

L15	Creep-Stress Relaxation
L16	Quasi-static
L17	Impact
L18	High Speed
L19	Cyclic
L20	Pulse

One additional bibliography will be compiled during the next six months of the contract. The causes, types, and pathology of head injury are not included in the current surveys. It is felt that a complete knowledge of this subject is necessary in order to further shape the program for finding physical properties. In addition, it is imperative that this information be known in order that meaningful models can be fabricated and subjected to realistic loadings which simulate real injuries of the various types.

EXPERIMENTAL RESEARCH PROGRAM

A. Sources of Biological Specimens

Before any extensive experimental program could be started it was necessary to define sources for material. It was found that human material at autopsy was readily available from The University of Michigan Medical Center and from the Veterans Administration Hospital in Ann Arbor both of which are close to the Biomechanics Laboratories. Embalmed human material was available from the Department of Anatomy at the University. A number of monkeys have been supplied at sacrifice by the Parke-Davis Laboratories in Ann Arbor and by the University. The subcontractor, Dow-Corning Corporation, has a small source of living and sacrificed monkeys within the Corporation. Besides this, slaughterhouses in the area provide a source of material for preliminary test development.

The skull bones which have been used are primarily from two sources, human autopsy and embalmed cadavers. The Biomechanics staff is on call for all autopsies at the two hospitals. There are over 500 autopsies at the two hospitals each year so the source is quite adequate at present.

Specimens are removed with a 3/4 inch or a 1-1/4 inch diameter Stryker bone plug cutter mounted in a Stryker autopsy saw. As many as four plugs have been taken from a single skull using the smaller cutter and more are feasible. In the cases of parietal, temporal, and occipital bones, the space left by the bone plug is not filled. There have been no objections to this procedure by hospital staffs, funeral directors, or family. It has been decided that holes in frontal bone will be filled with dental acrylic. These human autopsy specimens have been used primarily for the tension and compression tests thus far. A collection of suture specimens is being made for structural tests which will begin shortly.

Calvariums are available from the gross lab of the Department of Anatomy. The supply is more than adequate for any testing. Several calvariums have been used in the shear tests. It is expected that this source of material will be useful in determining regional differences in skull physical properties.

Primate material has not been found useful for skull tests. The inner and outer tables are too thin and the structural curvature too high for designing a tensile specimen. Certain structural tests such as shear and bending will be carried out using both human and primate material in an effort at correlating properties.

Brain material has been obtained from ungulates, primates, and man. Most testing has been done on human brain material obtained at autopsy. In these cases at least one-third of a cerebrum has been obtained at each autopsy. It is necessary to have these relatively large quantities available for the structural bulk modulus tests and for the dynamic shear tests.

Although extensive testing has not yet begun, sources have been established for skin, dura, and cerebrospinal fluid. Small strips of skin can be obtained from the autopsy cut across the surface of the skull.

Also larger strips of skin can be obtained from cadavers delivered to the University's Department of Anatomy before embalming has been carried out. Dura is available at autopsy in large quantities.

Cerebrospinal fluid will be obtained from the freshest autopsies. The University's Department of Pathology has agreed to assist us in drawing the fluid directly from the head before the body is opened.

B. Anatomical Identification and Storage of Material.

When material is obtained a complete specimen record is made. The location of a specimen of bone is specified by measuring the distances of the specimen from standard anatomical features such as suture lines. In addition, a record of skull length, width, and circumference is being initiated to define more clearly specimen location in light of the variety of head shapes and sizes which occur in the population. An example data sheet is included as Figure 3. This typical specimen is identified as follows: 1. UM or VA refers to the hospital; 2. a number such as 14 defines the chronology; and 3. symbols such as P, F, T, or O refer to parietal, frontal, temporal, or occipital while L and R refer to left and right. Other tags are added when necessary. Orientation of a specimen in the skull, posterier-anterior and right-left, is indicated by making a cross directly on the skull before the specimen is removed. In addition a circular paper spot representing each bone plug is placed on a reference skull kept in the laboratory to serve as a tally and also to indicate location for future specimens.

In the case of brain material a similar procedure is followed. The location of a specimen is recorded on a sketch of a brain.

A summary of all autopsy specimens is shown in Figure 4. The various bone specimen numbers used in this report refer back to this chart.

FIGURE 3. HEAD INJURY PROJECT - DATA SHEET

DATE: 12/7/67

TIME OF DEATH: 11:23 P.M. 12/6/67

AGE: 63

SEX: Male

RACE: Caucasian

CAUSE OF DEATH: Severe closed head injury

SPECIMEN NO:
UM-14-PL
UM-14-PR

TIME SPECIMEN REMOVED: 9:00 A.M.

STORAGE OF SPECIMEN:

FRESH

SALINE

FROZEN ✓

LOCATION OF SPECIMEN:

Right - 4.0 cm posterior of coronal suture

2.0 cm right of saggital suture

Left - 4.5 cm posterior of coronal suture

2.0 cm left of saggital suture

NOTES:

FIGURE 4. SUMMARY OF HUMAN MATERIAL

Bone Specimen	Age	Race	Sex	Cause of Death
UM 1 TLTR PL PR	64	C	F	Abdomen neoplasim,pneumonia, cancer
UM 2 PL PR	70	C	M	Carcinoma of lung
UM 3 PL PR	49	C	M	Pneuomia,Hodgkin's disease
UM 4 PL PR	61	N	M	
UM 5 PL PR	69	C	M	Mycosis Fungoides, GI bleeding
UM 6 2 PR	60	C	M	Carcimona of lung and pulmonary edema
UM 7 PL PR	61	C	F	Post-rundil-cirrhosis
UM 8 PL PR	42	C	M	Bleeding gastritis, ulcer
UM 9 PL PR	63	C	F	Hemangiosarcoma of the lung
UM 10 PL PR	31	C	M	Auto Accident
UM 11 PL PR	77	C	F	Metastatic malignant melanona
UM 12 PL PR	63	C	M	Auto accident,frontal craniotomy
UM 13 PL PR	24	C	M	Chronic renal failure
UM 14 PL PR	63	C	M	Severe closed head injury
UM 15 PL PR	44	C	F	Mitoial insuffficency and Acotic insufficency
UM 16 PL PR	60	C	M	Renal insufficency and hyperkalima
UM 17 PL PR	37	C	M	Severe body traumas
VA 1 PL	33	C	M	Kidney failure
VA 2 PL	53	C	M	Post operation bleeding
VA 3 PL		C	M	
VA 4 PL	57	C	M	Carcimona of colon
VA 5 PL	55	C	M	Carcinoma of lung

Figure 4. Continued

Bone Specimen	Age	Race	Sex	Cause of Death
VA 6 PL	75	C	M	Cardio vascular collapse
VA 7 TR	45	C	M	Stroke-diabetes
VA 8 PL	56	N	M	Stroke
VA 10 TK	41	C	M	Lymphatic leukemia
VA 11 F	51	C	M	Carcinoma of lung
VA 12 PL	71	C	M	Cirrhosis of Liver
VA 13 FL	50	C	M	GI bleed, cirrhosis of liver, mild heart attack
VA 14 PL	66	C	M	Carcinoma of lung
VA 15 PL	45	C	M	Recurrent duodenal ulcer, alcoholism
VA 16 PL	47	C	M	Hodgkin's disease, pneumonia
VA 17 PL	47	C	M	Cancer of lung
VA 18 PL	95	C	M	Lung cancer
VA 19 PL	74	C	M	
VA 20 PL	76	C	M	Carcinoma of pancreas
VA 21 PL(brain)	48	C	M	Cancer of bladder
VA 22 PL	75	C	M	Obstructive jaundice
VA 23 PL(brain)	44	C	M	Carcinoma of lung
VA 24 PL	50	C	M	Smooth muscle malignant tumor
VA 25 PR	25	C	M	Pulmonary hemmorhage and renal failure
VA 26 PL	73	C	M	Respiratory death
VA 27 PL(brain)	92	C	M	Heart failure
VA 28 PR	72	C	M	Pulmonary emphysema
VA 29 PL	57	C	M	Cancer
VA 30 PR	57	C	M	Cancer

Figure 4. Continued

Bone Specimen	Age	Race	Sex	Cause of Death
VA 31 PL	58	C	M	Cancer
VA 32 PR	62	C	M	Tuberculosis (inactive)
HB2(brain)	77	C	M	Pulmonary edema-myocardial infraction
Embalmed 1.	68	C	M	Myocardial infraction
Embalmed 2.	66	C	M	Congestive heart failure
Embalmed 3.	73	C	M	Systicema due to pyelonephritis

In the shear tests which have been carried out on embalmed calvariums, a modified version of the West Virginia University scheme has been developed for identifying a large number of specimens in a single skull. This is described in detail in Appendix E. Modifications of this scheme will be developed as needed for other tests involving regional variation.

An additional aspect of identification which should be mentioned involves the individual autopsy bone plugs themselves. Each one can be split into a number of specimens for various tests, some more than 10. This means that an additional data sheet on each specimen must be kept providing the entire history of a specimen after it has been brought into the laboratory.

Bone specimens are stored in a freezer at -10°C. It is felt that enough evidence has become available in research at The University of Michigan and elsewhere to validate this technique.

It has been found that brain tissue must be tested as soon as possible after the time of death. Fresh autopsy material is placed in a sealed plastic bag and transported in a solution of ice and water at 3°C to the laboratories of Dow-Corning Corporation where testing begins immediately. The time lag between opening the head at autopsy and the beginning of testing is about 2-1/2 hours. Visual examination of the brain material indicates no noticeable breakdown between the opening of the head and the physical testing.

Attempts at freezing brain material by various techniques have proved unsuccessful. In one set of experiments some brain material was frozen in dry ice and alcohol and transported at the same time as some cooled brain material from the same source. The frozen material deteriorated upon thawing.

The importance of this phase of the research is not being underestimated. Indeed it is felt that many of the biological variations which are so often mentioned are but the result of uncontrolled or unobserved parameters. Therefore, the time spent in anatomical identification and in storage studies is considered time well spent.

C. Experiments and Results

Tension, tension-compression and hysteresis tests.

A tensile test has been developed for the purpose of determining moduli of elasticity, failure stresses, and cyclic loading behavior. Because of the geometric restraints of the skull the specimen size was limited to 1/2 inch in length and 0.0025 in.^{2} in area. Small strain gages are mounted on the specimen for deformation measurements and the load is applied by an Instron testing machine. The specimen is loaded alternately in tension and compression for a few cycles to a moderate load for the purpose of determining the hysteresis or energy absorbing properties of the bone, tension and compression moduli, and the elastic modulus as the load goes from tension into compression or vice versa. Finally the specimen was loaded to failure. A typical data curve is shown as Figure 5 and details are included in Appendix C.

So far 43 tests have been performed on human autopsy material. The average value of elastic moduli is 2.11 x 10^6 psi. For breaking stress the average value is 9500 psi. No identifiable regional variations have yet been found. The large hysteresis loop and the large amount of recoverable strain induced in a specimen stressed to failure points out that skull bone is a highly viscoelastic, brittle material. This indicates that the results of the dynamic tests which are now being started should indeed be interesting.

The next step is the gathering of more data points and the histological examination of the specimens to determine the relationships between physical properties and microscopic structure.

Compression.

The objective of this test series was the determination of the crush failure characteristics of the diplöe layer of the skull and the measurement of an average structural compression modulus of elasticity for small rectangular blocks of skull bone. The compressive load was applied to the block in a direction perpendicular to the surface of the skull. The series of 70 tests performed on human bone obtained at autopsy is described in detail in Appendix D.

The mean value of structural moduli obtained in these tests is 2.02×10^5 psi whereas the failure stress is 5300 psi. The load-deformation curve exhibited by most specimens is shown in Figure 6. This indicates that the diplöe layer collapses rather suddenly while absorbing a large amount of energy in the process. The relatively low modulus of these specimens reflects the fact that spongy bone is only a light weblike arrangement of compact material. It also reflects that the skull can be thought of as a sandwich shell possessing transverse orthotropy, the middle layer being an energy absorber.

Shear.

The purpose of this shear test is measurement of the capacity of the diplöe layer of the skull bone to resist shear. A total of 370 plugs with diameters of 3/8 inch have been cut from three embalmed human calvariums. Each specimen is identified by means of a standard grid pattern drawn on the skull. Each circular plug is loaded in shear to failure as shown in Figure 7. The average value for failure stress is about 1900 psi. This can be compared with the failure stress of 5300 psi obtained in the compression test. Details of the shear tests are included in Appendix E.

Puncture.

It is the purpose of this series of experiments to measure the resistance of the scalp to puncture by the use of a penetrometer[1]. This instrument gives an indication of the relative resistance offered by skin when pinched between the skull and a hard, sharp impacting object. The tests were carried out at autopsy on subjects giving 63 data points. Comparisons are planned with skin on other parts of the body and with embalmed cadavers. Details are in Appendix F.

Measurements of Dynamic Shear Modulus and Bulk Modulus.

The complex dynamic shear modulus (G^*) of a viscoelastic material consists of two components, G' and G'', such that $G^* = G' + iG''$. G' is the dynamic elastic modulus, a measure of the spring-stiffness of the material whereas G'', the dynamic loss modulus, is a measure of the material's ability to dampen vibration by absorbing and dissipating energy. The relative damping ability, $\tan \delta$, is defined as G''/G'. See Appendix G for details .

Dynamic shear tests have been completed using brain material from pigs, Rhesus monkeys, and humans as test specimens. All tests were conducted using Dow Corning's Dynamic Mechanical Apparatus (DMA), which supplies a sinusoidal stress of controllable constant amplitude and

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[1]The penetrometer used in this series of experiments was furnished by General Motors Corporation.

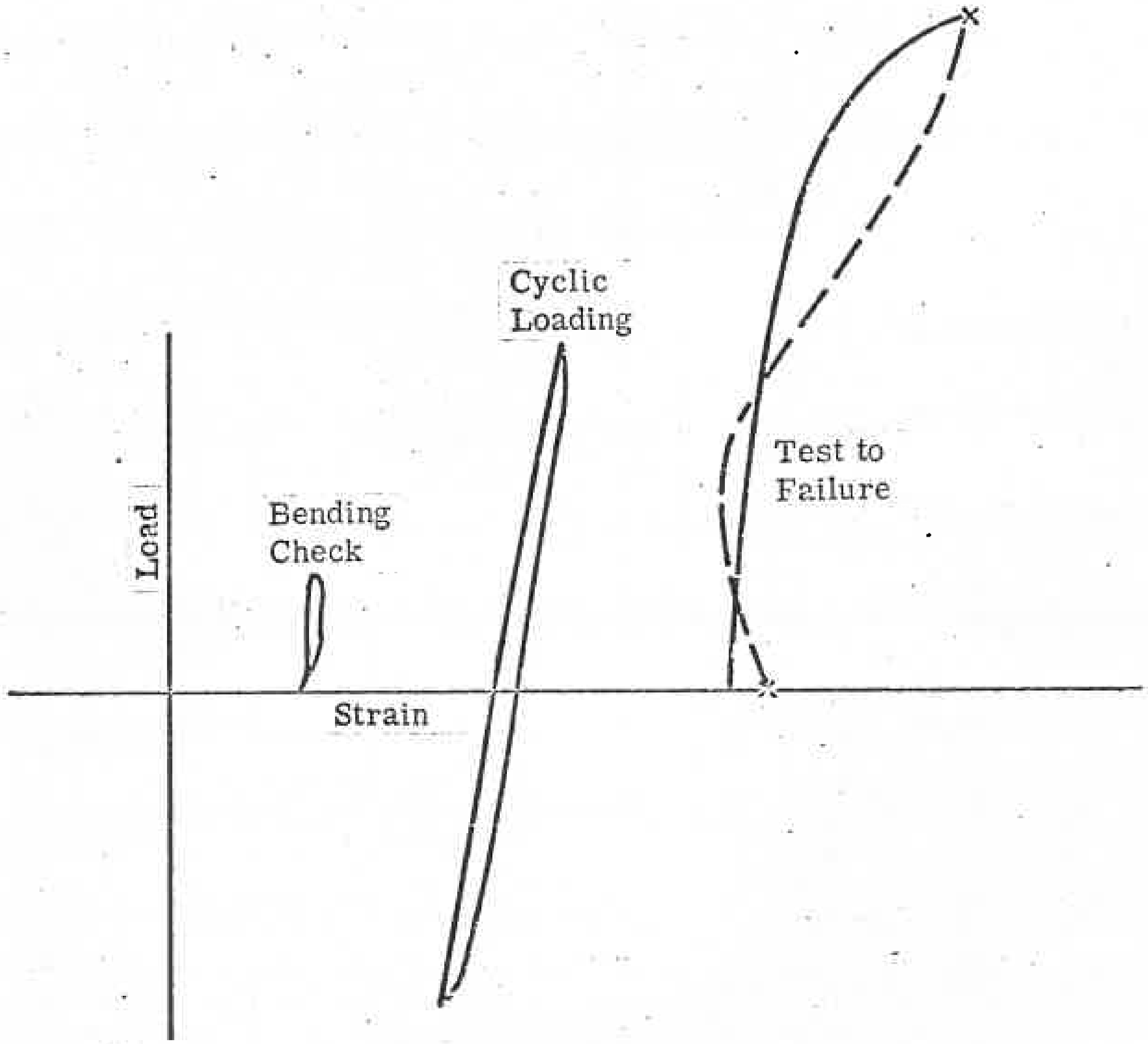

FIGURE 5. TYPICAL TENSION TEST

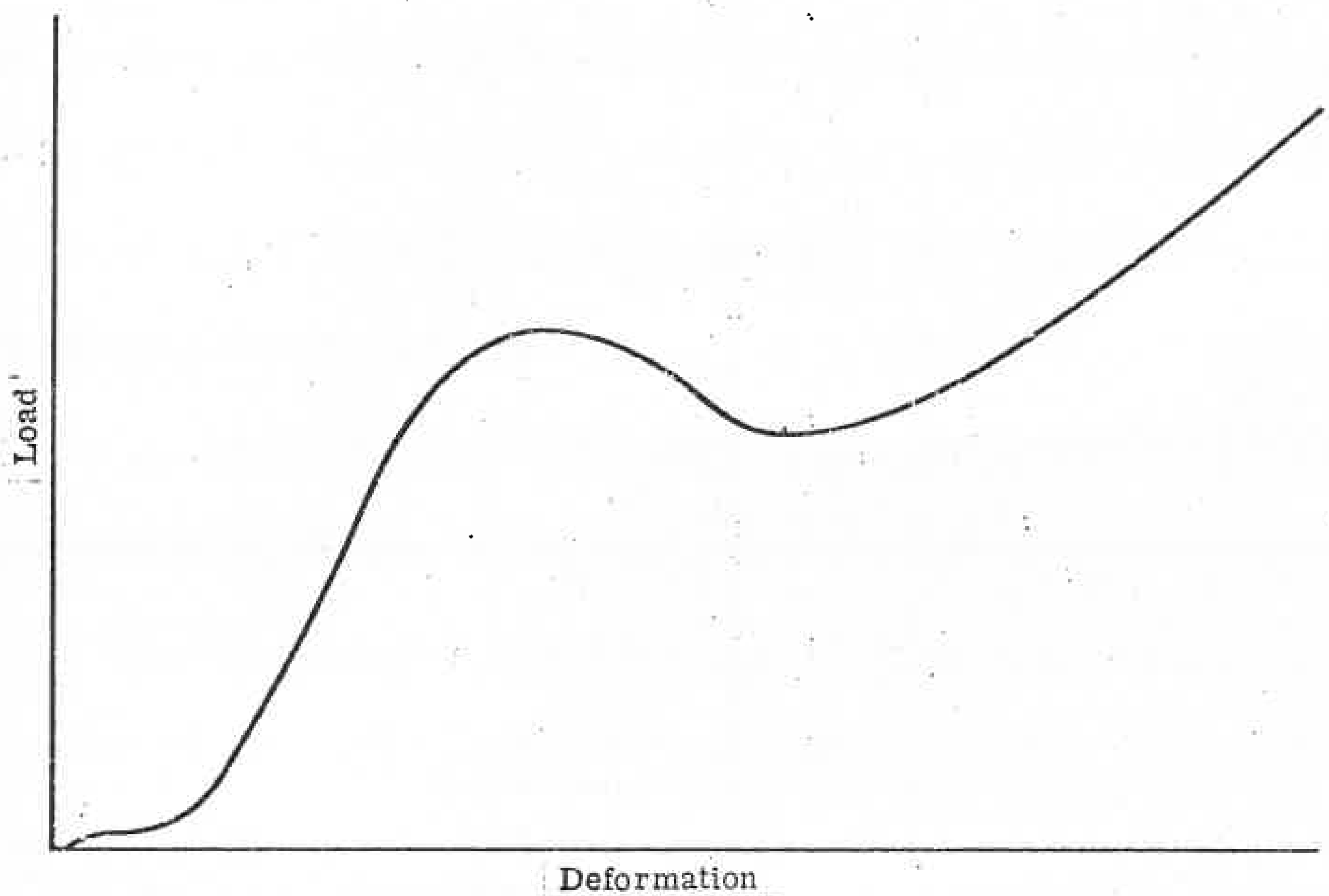

FIGURE 6. COMPRESSION TEST

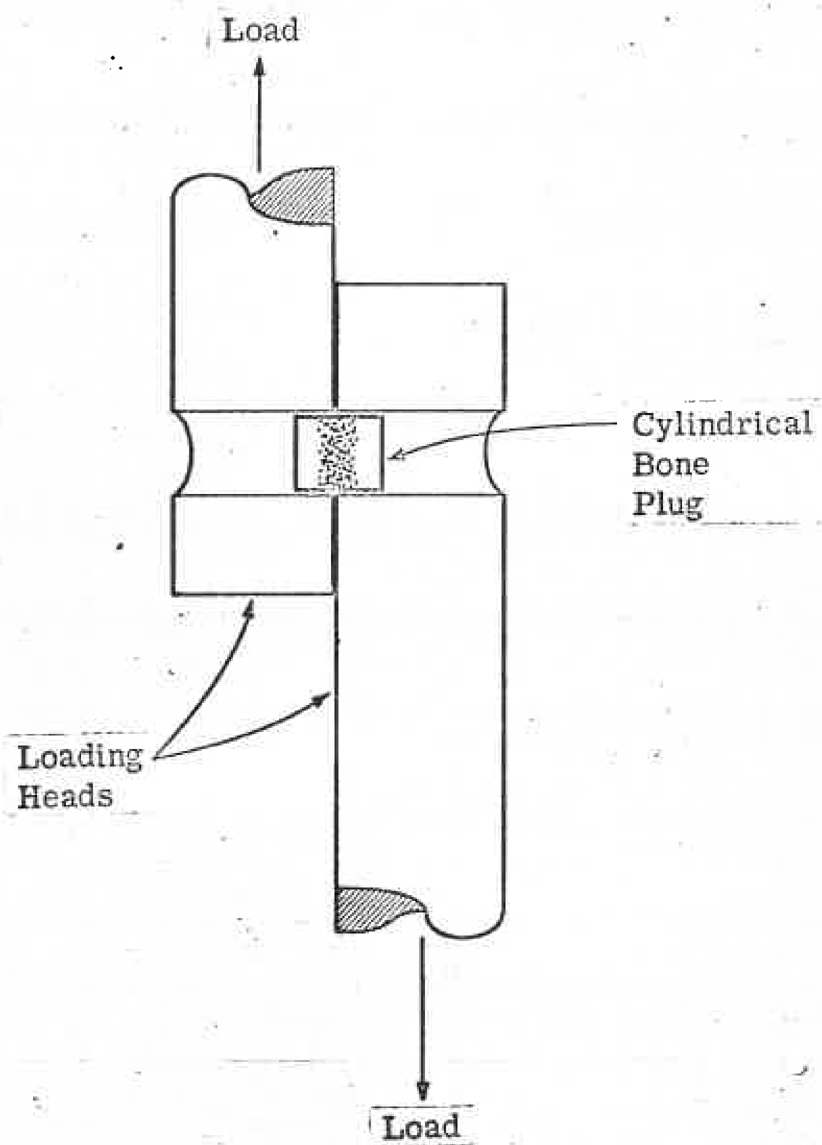

FIGURE 7. SHEAR TEST

frequency to the test piece. Monitoring the transmission of this applied stress through the test piece yields the data necessary to measure the elastic stiffness and energy absorbed within the material. A schematic of this apparatus is shown in Figure 8.

The testing program thus far has been an effort to determine the three values (G', G", and tan δ) as a function of the maximum shear displacement of the test piece. The shear displacement is defined as the angle whose tangent is the maximum linear displacement of one surface of the specimen relative to the other, divided by the sample thickness. All tests have been conducted under resonant conditions, i.e. with stress and strain in-phase. Applicability of the instrument and test procedure to brain tissue has been evaluated and significant test variables defined.

A preliminary test of fresh pig brain was conducted during test development. Several tests of fresh, unfrozen Rhesus monkey brain were carried out as well as one test of frozen Rhesus brain. The majority of the test effort has been directed toward the determination of the shear modulus of the human brain. A number of pertinent variables have been considered, including time post-mortem, shear degradation, thixotropy, storage temperature, and loss of water (drying on the test apparatus). Currently, the effects of these variables are being evaluated. Specimens from four human brains have been utilized. Typical values obtained include:

Type of Brain	G' (dynes/cm^2)	G" (dynes/cm^2)	tan δ
Pig	8×10^3	3×10^3	0.4
Rhesus Monkey	$4\text{-}8 \times 10^3$	$2\text{-}4 \times 10^3$	0.3-0.5
Human	$3\text{-}12 \times 10^3$	$4\text{-}10 \times 10^3$	0.4-1.0

The secant bulk modulus (β) of a compressible material is defined as:

$$\beta = \frac{V_o \, \Delta p}{\Delta V}$$ where: V_o = original volume of test material.

Δp = change in applied pressure.

ΔV = change in volume of test material for a corresponding Δp.

The determination of the modulus consists of applying a variable pressure (stress) to a sample in a compression cell and recording the resulting stress-strain relationship. The applied pressure is divided by the fractional strain ($\Delta V/V_o$) to yield the secant bulk modulus.

Tests were conducted on material from the same series of Rhesus monkeys' brains and the same human brains as were used for dynamic shear tests. Typical values for the secant bulk modulus at 20,000 psi for Rhesus monkey and human brain are 4.2 and 3.8 x 10^5 psi, respectively.

The dynamic shear tests, as conducted, involved a very small load for the DMA, when compared with the usual testing of rubber. This indicates that machine and operator error are potentially of more significance than in the customary tests. A brief error analysis indicates that the combined errors should be greatest at high shear angles. Yet the test data reveal less variability of results at high shear angles than at the lower angles. Further, with few exceptions, data points fit repeatable smooth curves well. It is, therefore, concluded that one or several of the above-mentioned parameters (sample aging, shear degradation, thixotropy, storage conditions, or drying), along with real variations in the tissues tested, account for the major portion of the variability encountered. Instrumental precision is adequate for the brain material tested.

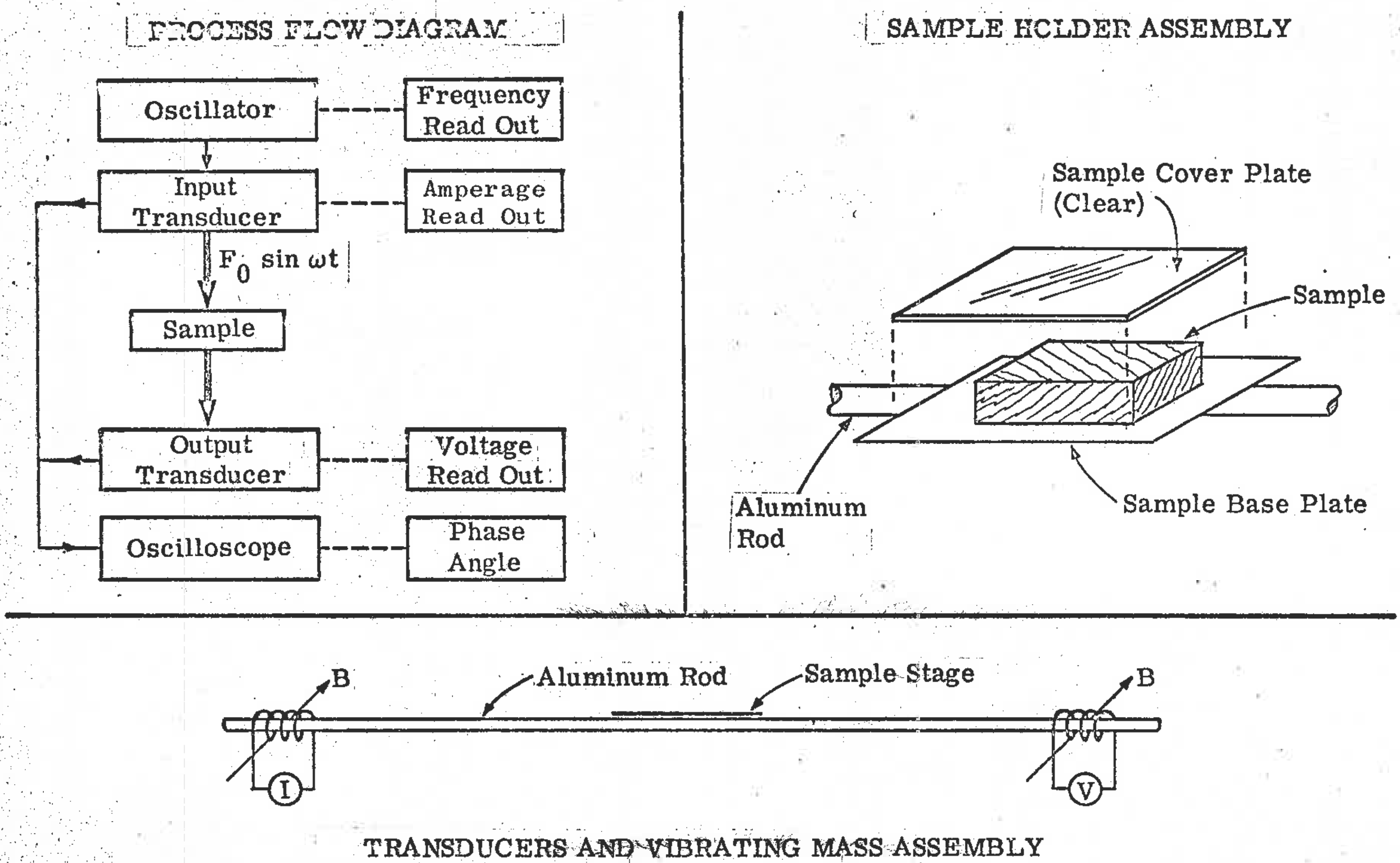

FIGURE 8. SCHEMATIC VIEWS OF THE DYNAMIC MECHANICAL APPARATUS

Several general trends are noticeable. Both G' and G" values decreased with increasing shear angles. The effects of drying during test figure prominently and are apparently modified by immediate previous shear history. Values at moderate to high shear amplitude are believed to be least distorted by drying. There is some evidence that, with drying eliminated, G' will not vary with shear displacement. G' values rose several hundred percent in 1-2 hours on the test apparatus. G" also rose, but less rapidly. Time post-mortem has not proven to be a major factor in the limits of +10-50 hours. Pre-test freezing of brain tissue has been found to severely modify dynamic responses.

Based on present interpretation of data, we anticipate that G' may be found to lie at the low end of the range listed above and tan δ at the high end.

In order to confirm tentative conclusions above and to evaluate the dynamic properties more accurately, future tests will be designed to reduce the effects of drying and also determine any variation, due to fiber orientation differences in the various tests. Histological slides of sample tissue will be utilized for these purposes as well as for determination of any shear degradation.

A smaller version of the DMA is being planned and will incorporate a test in which a probe is vibrated normal to the test surface, as well as the above-mentioned shear test. This should make possible the determination of two moduli and a correlation between them. The probe test can also be used in vivo, and at short intervals post-mortem to complete the investigation of changes with time.

A positive pressure of approximately 50 mm Hg will be applied to test specimens, thus duplicating intracranial pressure, if this factor is found to be significant in initial trials.

Two types of test procedure have been used to determine secant bulk modulus. The first involves the compression of only brain tissue as a one-phase system, whereas the second uses a two-phase system, with the brain matter being suspended in a fluid. The one-phase system was used first, primarily for testing of Rhesus monkey brain. The two-phase system has been found preferable and used almost exclusively for the human brain. A good correlation exists between the two systems.

The secant bulk modulus of the human brain appears to be fairly well-defined at present for the range of 5 to 25 x 10^3 psi. There are indications of real variations from brain to brain and also a possible correlation with the age of the individual. The modulus is presently being evaluated on more sensitive equipment at low pressure (under 1000 psi) to complete the curves and look for evidence of damage to the brain tissue under low stress.

A series of tests on Rhesus monkey brains will be conducted to determine the effects of time post-mortem. It is anticipated that testing will begin within 15 minutes of sacrifice. Both the secant bulk modulus and a dynamic modulus will be determined, the latter possibly with a probe-type tester. These data will then enable one to correlate the time effects present in the current data. These new techniques, along with those presently in use, will be utilized to determine the bulk and dynamic properties of scalp and dura mater as is required for modeling purposes.

Dynamic Tests.

Several of the tests previously described (tension, tension-compression, hysteresis, compression, and shear) have been carried out as static tests up to the present time. However, the test results thus far obtained during the course of the Head Injury Project and by others indicate the time and loading rate dependency of properties measured in tests of this type. Therefore all testing apparatus, load, and strain measurement techniques, and specimens have been designed for use at high rates of loading. An extensive series of tests is being planned for execution on a Plastech testing machine which is currently being installed in the Biomechanics Laboratory. This machine is capable of a 30,000 inch/minute deformation rate which is adequate for impact simulation. It is felt that this test serjes is more pertinent to dynamic head injury than any series of tests carried out thus far and thus it will be the subject of most of the effort of the next six months of testing in conjunction with the parallel histological studies.

THEORETICAL PROGRAM

A theoretical program has been included in the early stages of the Head Injury Project for two reasons: 1.determination of techniques for generating constitutive equations relating stress to strain, and 2. development of first generation mathematical models of head injury. It is felt that mathematical models must be studied early in the research to help guide the selection of the physical properties which are most pertinent in the modelling procedure. Thus far it has been found that basic properties such as elastic and visco-elastic moduli, shear modulus, compressive modulus, bulk modulus, viscosity, Poisson's ratio, and the various failure stresses are more pertinent than structural properties such as bending strength, hardness, etc. From this point of view, mathematical modelling must parallel the experimental program which comprises the bulk of the research effort.

First generation mathematical model for head injury.

The first mathematical model for head injury which is being studied is a closed spherical shell subjected to a local radical impulse. The

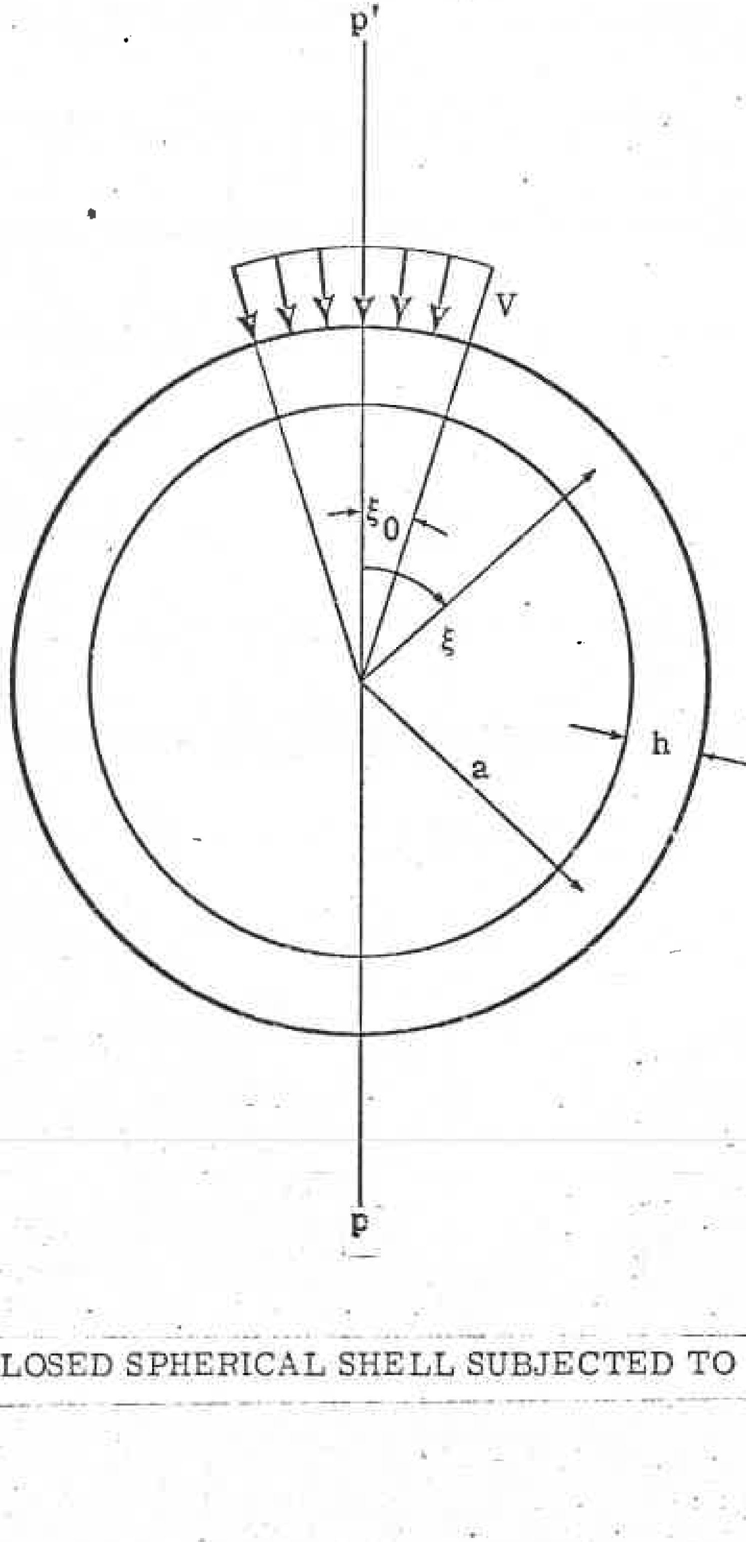

FIGURE 9. CLOSED SPHERICAL SHELL SUBJECTED TO LOCAL IMPULSE

shell is not filled with a fluid. The problem of a deformable, fluid-filled shell subjected to this loading (shown in Figure 9) has not been solved in the published literature. At the present time numerical values for the solutions are being determined on a digital computer for the following set of parameters, roughly representative of human skull properties.

Skull thickness = 0.15 inches	Velocity of impact = 30
Young's modulus = 2×10^6 psi	Diameter = 3.0 inches
Poisson's ratio = 1/4	Density = 1.82 gm/cm^3

Area of impact = 0.262 radians

Constitutive equations.

A technique for the generation of constitutive equations based on experimental data is now being tested. A complete program is being used which generates coefficients relating stress to strain and strain-rate. The objective of this regression program is the generation of a linear regression equation of the form

$$Y = B_o + B_1X_1 + B_2X_2 + \dots + B_kX_k \quad (1)$$

from a set of N observations of a set of K independent variables (X_1, X_2, ..., X_k) and a single dependent variable Y.

For the present case σ (stress) serves as the dependent variable while the independent variables are various functions of ε (strain) and $\dot{\varepsilon}$ (strain-rate). At present the thirty-five functions listed in Table 1 are being used. The coefficients B_o, B_1, ..., B_k are determined so that the regression equation minimizes the sum of the squares of the deviation between the observed and predicted values of stress. The stepwise regression procedure generates equation (1), variable by variable in order of relative importance until all significant variables are included in the equation, according to the specified level of significance.

This program has been applied to data gathered on bovine femur and nylon. Sets of sixty points were used for each model. With the thirty-five independent variables which were used a maximum deviation of 5% was achieved with a series of seven terms for nylon and eight terms for bovine femur bone. A maximum deviation of 2.2% was achieved for nylon with twenty terms and a maximum deviation of 3.1% was achieved for bovine femur with seventeen terms. The order of significance of the terms was considerably different for the two materials and in many cases terms of high significance for one material were not even present in the expression for the second material.

The equation for nylon at the 5% level is

$$\sigma = 2.95 + 6.8\,\varepsilon \ln \dot{\varepsilon} + 5.5 \ln \varepsilon - \varepsilon \ln \varepsilon - 113\varepsilon^2 + 28\varepsilon^2 \ln \mathring{\varepsilon} + .00024\,\frac{1}{\varepsilon} \ln^2 \mathring{\varepsilon} - .75 \ln^2 \mathring{\varepsilon}.$$

Similar equations will be developed for the skull and its contents on the basis of the dynamic experiments which are currently being carried out.

FIGURE 10. Terms Used in Generating Constitutive Equations

$\ln \dot{\varepsilon}$

$\frac{1}{\varepsilon}$

$\frac{1}{\varepsilon^2}$

$\frac{1}{\varepsilon^3}$

$\frac{1}{\varepsilon} \ln \dot{\varepsilon}$

$\frac{1}{\varepsilon^2} \ln \dot{\varepsilon}$

$\frac{1}{\varepsilon^3} \ln \dot{\varepsilon}$

$\ln^2 \dot{\varepsilon}$

$\frac{1}{\varepsilon} \ln^2 \dot{\varepsilon}$

$\frac{1}{\varepsilon^2} \ln^2 \dot{\varepsilon}$

$\frac{1}{\varepsilon^3} \ln^2 \dot{\varepsilon}$

$\varepsilon \ln \dot{\varepsilon}$

$\varepsilon^2 \ln \dot{\varepsilon}$

$\varepsilon \ln^2 \dot{\varepsilon}$

$\varepsilon^2 \ln^2 \dot{\varepsilon}$

$\varepsilon^3 \ln^2 \dot{\varepsilon}$

$\ln^3 \dot{\varepsilon}$

$\frac{1}{\varepsilon} \ln^3 \dot{\varepsilon}$

$\frac{1}{\varepsilon^2} \ln^3 \dot{\varepsilon}$

$\varepsilon \ln^3 \dot{\varepsilon}$

$\varepsilon^2 \ln^3 \dot{\varepsilon}$

$\varepsilon^3 \ln^3 \dot{\varepsilon}$

$\frac{1}{\varepsilon^3} \ln^3 \dot{\varepsilon}$

$(\varepsilon)^{1/2}$

ε

ε^2

ε^3

ε^4

$(\varepsilon)^{1/2} \ln \dot{\varepsilon}$

$(\varepsilon)^{1/2} \ln^2 \dot{\varepsilon}$

$(\varepsilon)^{1/2} \ln^3 \dot{\varepsilon}$

$\ln \varepsilon$

$\ln \varepsilon \ln \dot{\varepsilon}$

$\dot{\varepsilon}$