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DEVELOPMENT AND TESTING OF INTEGRATED SEAT RESTRAINT SYSTEMS

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16. Abstract

The objective of this research was to develop, fabricate and test seat and restraint system combinations designed to offer a level of protection exceeding that found in current production seats and restraint systems. To accomplish this a series of analytical studies was carried out using two- and three-dimensional mathematical models of an automobile crash victim. These studies, in combination with a survey of the state of the art of seating and restraint systems, were used to formulate design concepts of integrated seat restraint systems. The most promising of the active systems was fabricated and subjected to front, oblique, side and rear impact tests using anthropometric dummies. The results of these tests were compared with current production seating systems and with the initial predictions of the mathematical models. Recommendations are made concerning performance requirements and compliance procedures for integrated seat restraint systems and for passive front seat occupant restraint systems.

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1. INTRODUCTION

The objective of this research was to develop, fabricate, and test seat and restraint system combinations designed to offer a level of protection exceeding that found in current production seats and restraint systems. To accomplish this a series of analytical studies was carried out using two- and three-dimensional mathematical models of an automobile crash victim. These studies in combination with a survey of the state of the art of seating and restraint systems, were used to formulate design concepts of integrated seat restraint systems.

The basic HSRI seat, incorporating the most promising active restraint system which included an inverted y-yoke harness, was fabricated and subjected to front, oblique, side and rear impact tests using various sizes of anthropometric dummies. The results of the tests were compared with current production seating systems and with the initial predictions of the mathematical models.

Performance in frontal impact was somewhat better for the HSRI system than for the current system. However, because of the contoured design of the seat back, the firm seat cushion, and the A-frame side structures, a level of occupant protection was achieved in oblique, side and rear impact exceeding that available with current production seating.

The initial predictions of system performance made using the mathematical models was verified by the encouraging test results. This demonstrates both the accuracy of analytical techniques and the power of this method when used as a design guide.

Recommendations for performance requirements and compliance procedures are made for integrated seat restraint systems and for passive front seat occupant restraint systems. Impact sled tests are recommended as being more reproducible than full-scale barrier crash tests. A set of injury criteria for the evaluation of test results are recommended which includes the HSRI Maximum Strain Criterion. In addition, a dummy structure is proposed which is matched to human dynamic response.

2. PERFORMANCE COMPARISONS OF CURRENT RESTRAINT SYSTEMS

Over three hundred impact sled tests and five hundred exercises of mathematical crash victim simulators have been conducted during the term of the current contract (1968-1971). In studying the results of this research program, guidelines for evaluating performance of restraint systems have been established. These include: 1. limitation of occupant motions to the environment of the seat; 2. limitation of forces and accelerations applied to the body; and, 3. prevention of excessive relative motions between adjacent body segments. The purpose of this part of the report is to document major problems in restraint which an integrated seat-restraint system should attempt to overcome. Unrestrained occupants and occupants using both belt and airbag systems are considered.

2.1 DESCRIPTION OF SLED TESTS AND RESULTS

During the current contract, subprojects have been carried out on various belt restraint systems, airbag restraint systems, and children's restraint systems. A description of test procedures, instrumentation, and data analysis for these subprojects are included in References 1, 2, 3 and 4. A small group of tests can be extracted to illustrate the need for restraint and to suggest potential solutions to problems in restraint.

A summary of test results is given in Table 1. The dummies listed in the table are 50th percentile male (50M), 95th percentile male (95M), and 3-year child. Directions of impact are front (F), 22.5° right front oblique (O), direct side (L), and direct rear (R). All additional quantities represent peak forces or G-levels.

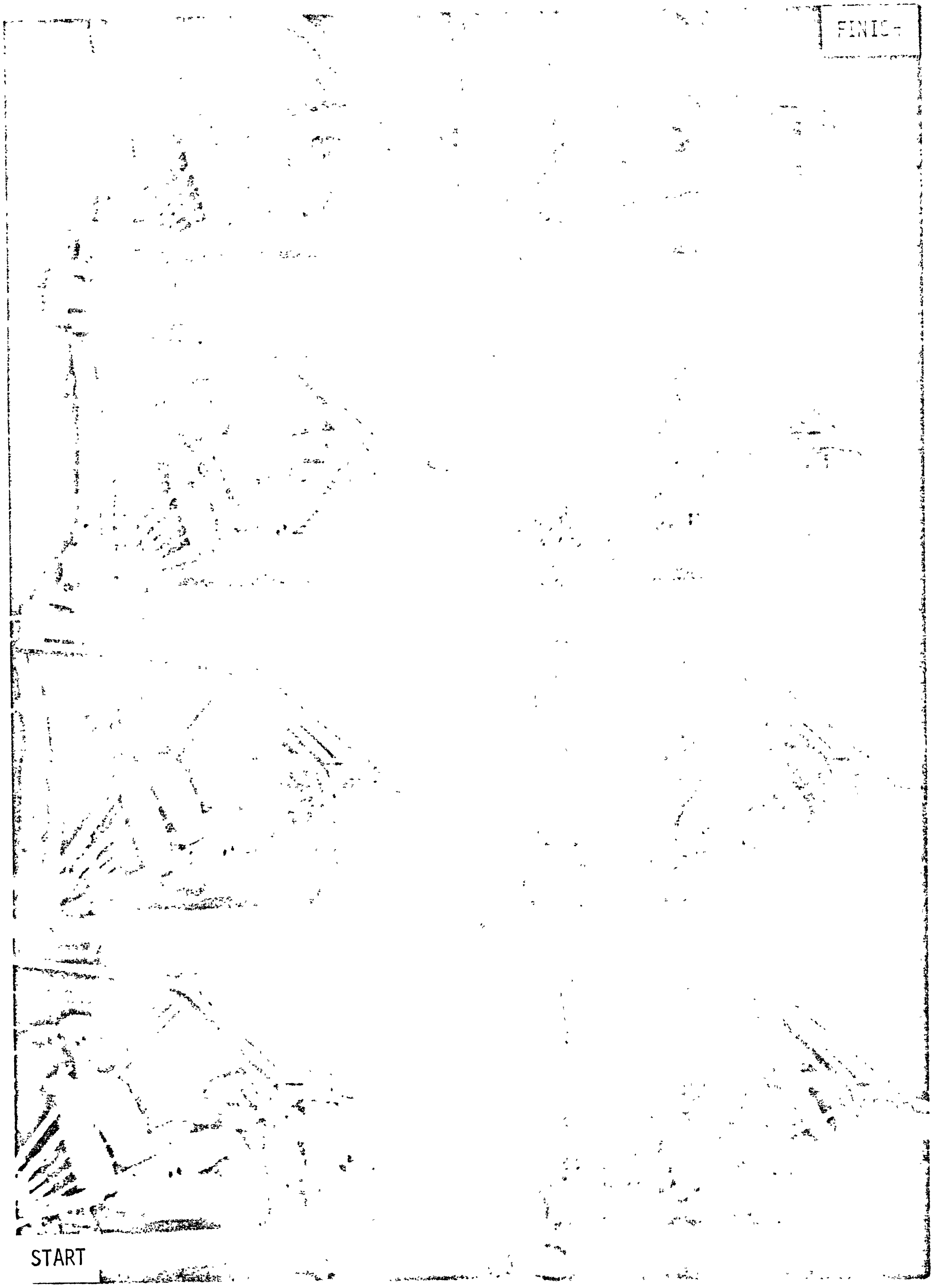
2.2 BASIC PRINCIPLES OF PROTECTION

Figure 1 shows the motions experienced by an unrestrained 50th percentile male dummy in a 30.4 mph frontal sled impact. He is observed to slide forward in the seat until the knees contact the instrument panel structures. His torso pitches forward and the head contacts the windshield, breaking it. Extremely high G-loadings were recorded in the head during this portion of the event. The neck and upper torso are then stopped by the upper instrument panel structures. The lower portion of the upper torso continued its downward motion causing the head to be bent to the rear (hyperextension) relative to the torso. The dummy then rebounded back into the seat. Complete ejection is prevented by the fortunate shape of the lower instrument panel.

The three basic problems in providing occupant protection are demonstrated by this test. The first of these is to restrict the motions of the occupant from contact with vehicle interior components capable of causing injury. The second is to limit the acceleration G-loadings and forces applied to the body based on human tolerance data. An initial proposal to limit body forces and G-loadings is included in Reference 5. The third is to limit extensive motions between adjacent body elements. Some whiplash is observed in this test illustrating the problem.

Several methods have been proposed and implemented to solve the three basic problems in restraints beginning with the lap belt and progressing to active 3-point belt restraint systems. Passive systems are being developed at the present time to solve problems inherent with active belt restraint systems.

The lap belt is effective in avoiding complete occupant ejection from the vehicle but is not capable of avoiding all potentially injurious contacts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with interior structures. Figure 2 shows the position of a right front occupant restrained by a lap belt at the peak of his interaction with the windshield and instrument panel in a 30 mph front impact test. In this case the hip and knees have been restrained from contact with the lower instrument panel structures but the head still impacts the windshield.

Similarly the lap belt is not effective in avoiding contact with vehicle structures in oblique impact as is shown in Figure 3. The head of the dummy was observed to contact the A-pillar. In side impact studies conducted under U.S. DOT Contract No. FH-11-7288 and described in Reference 6, the lap belt is also not effective in preventing the head of the occupant from penetrating the side window glass.

A number of upper torso restraint systems have been studied which are effective in providing restraint in frontal impact, the two most prominent being the shoulder belt and the airbag. Typical occupant motions when standard lap belts and shoulder harnesses are used are shown in Figures 4 and 5. In each case the belt system prevents the occupant from contacting the vehicle interior. The body G-loadings given in Table 1 are within current tolerance estimates indicating system effectiveness. The submarining shown in the two photographic sequences is due to the combination of a very soft seat cushion and the lack of an adequate pelvic structure in the Sierra Model 850 dummies without the new pelvis.

The airbag is observed to provide an even greater ride as illustrated in Figures 6 and 7 showing 30 and 40 mph impact tests involving a 50th percentile male dummy. In these cases the restraint system was completely passive as an energy-absorbing lower instrument panel was substituted for a lap belt. The G-loadings applied to the head were lower for the airbags as listed in Table 1 and the relative angle between head and torso kept minimal in the two tests.

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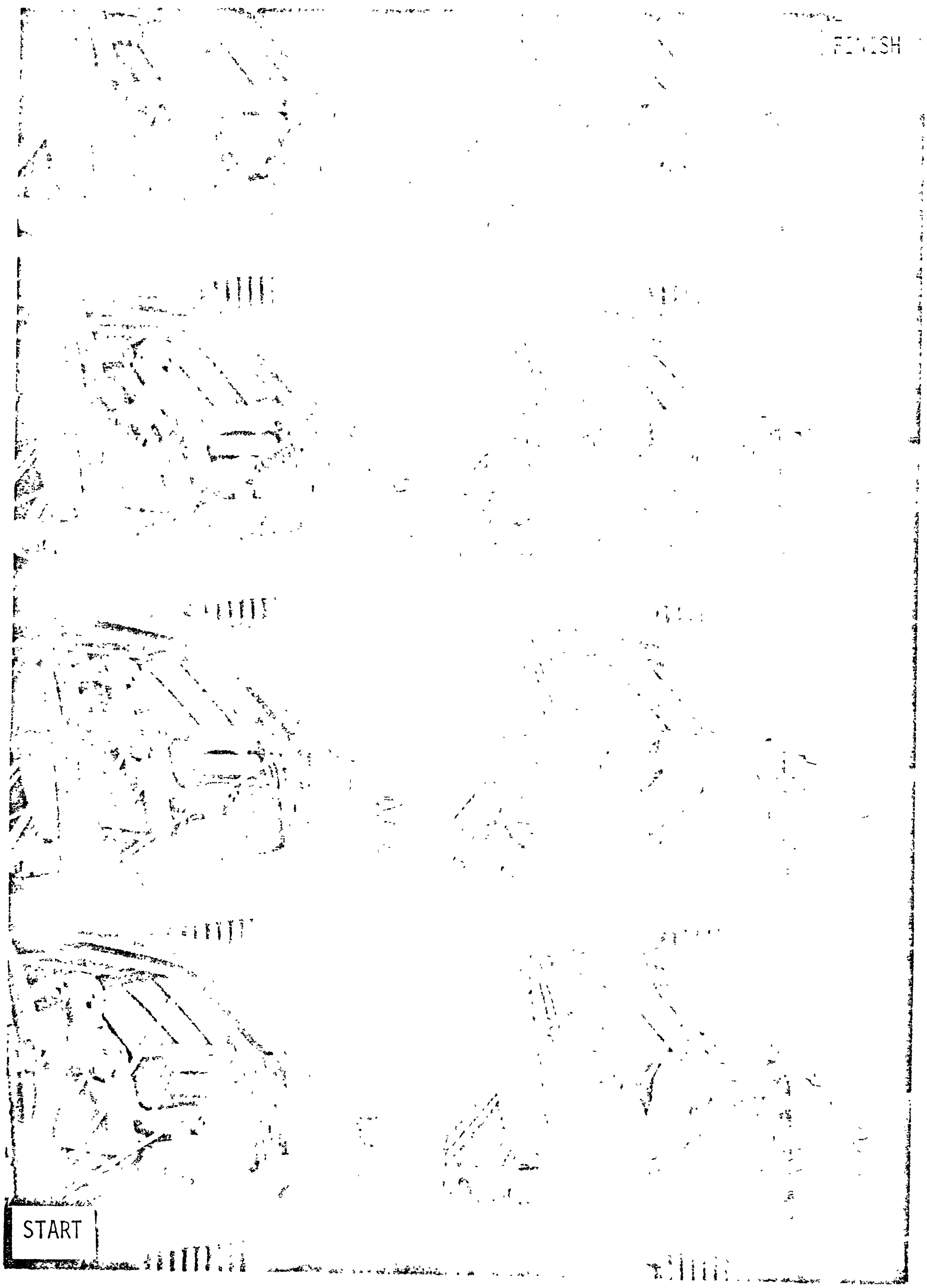
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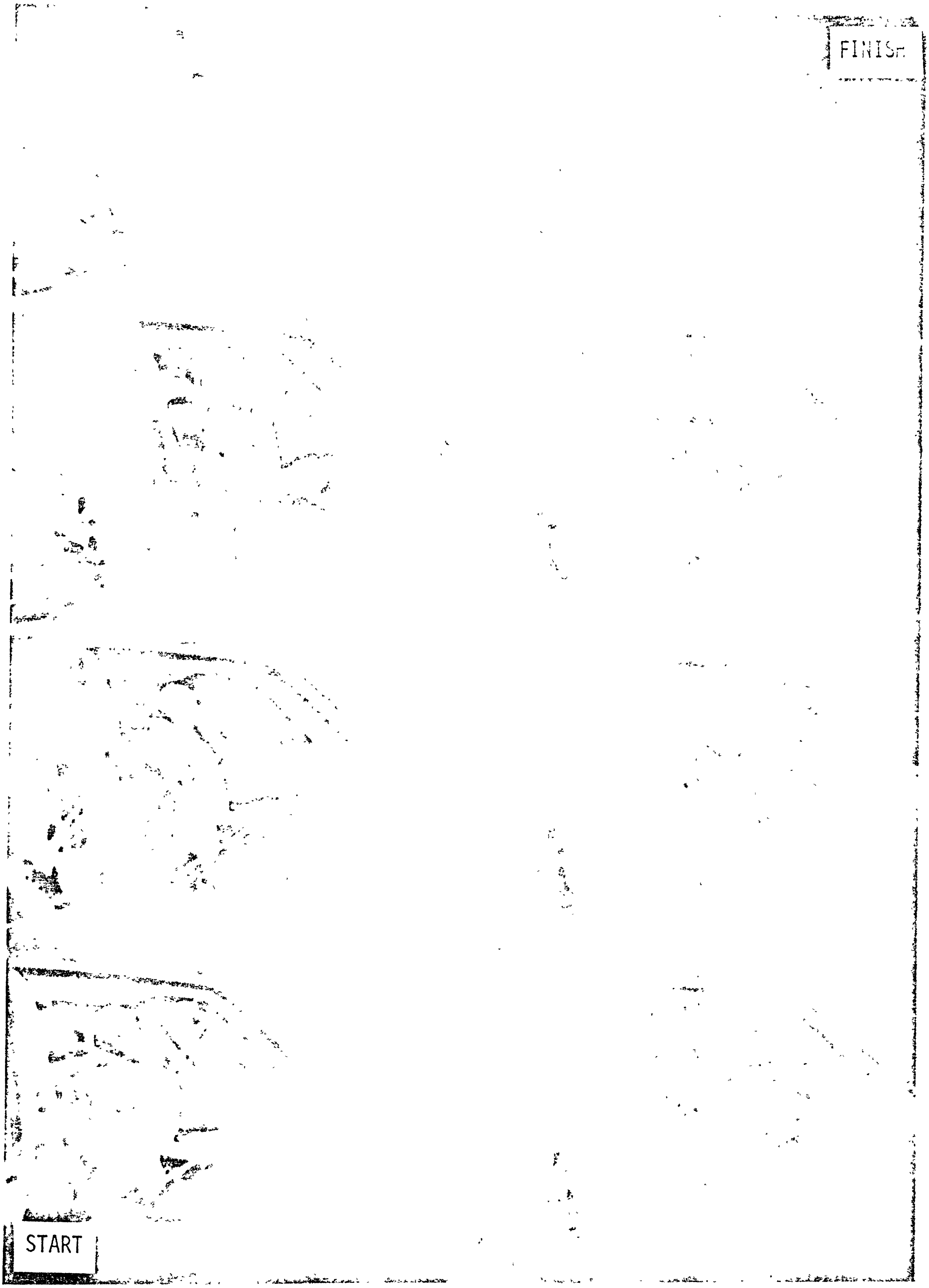
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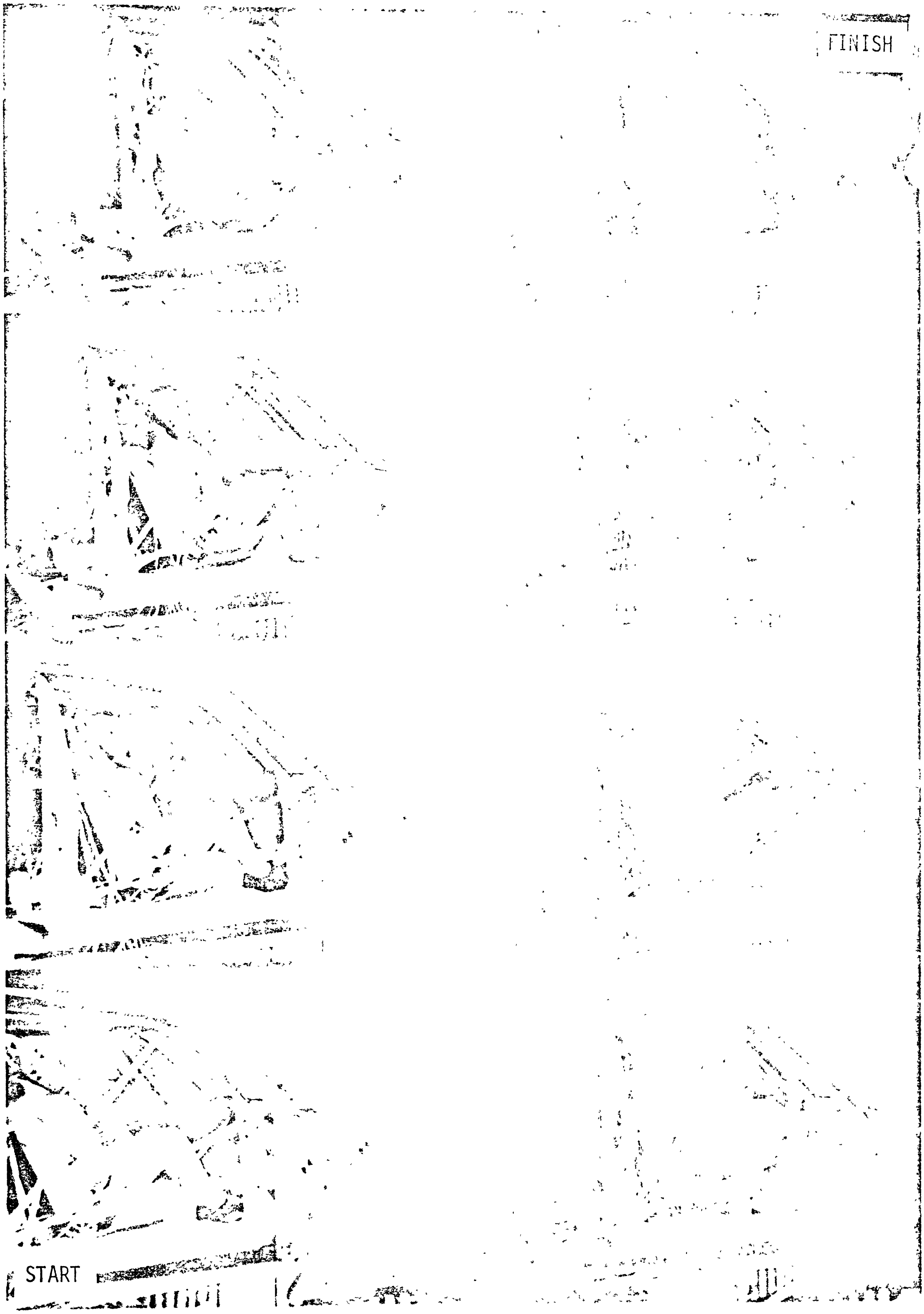
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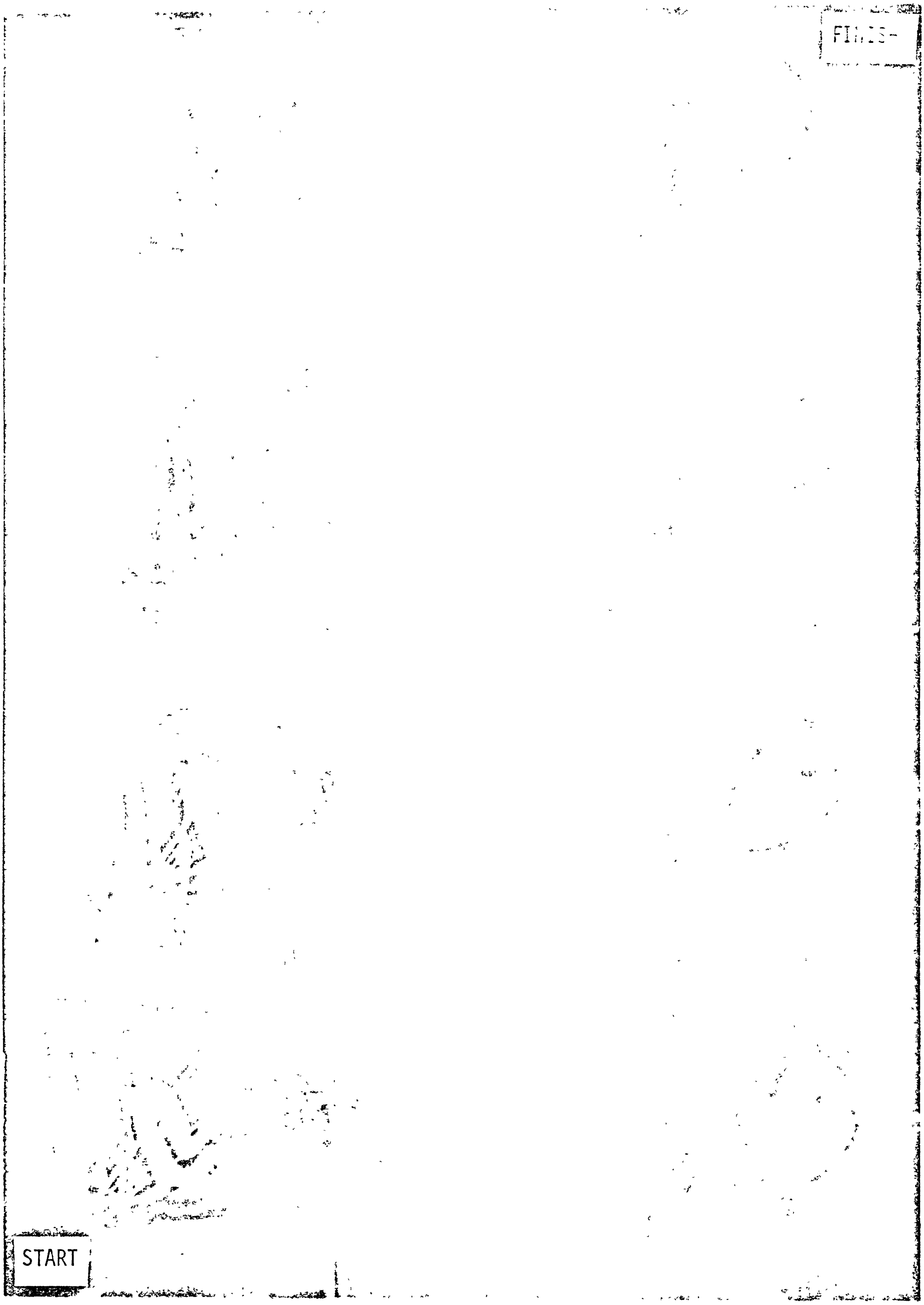
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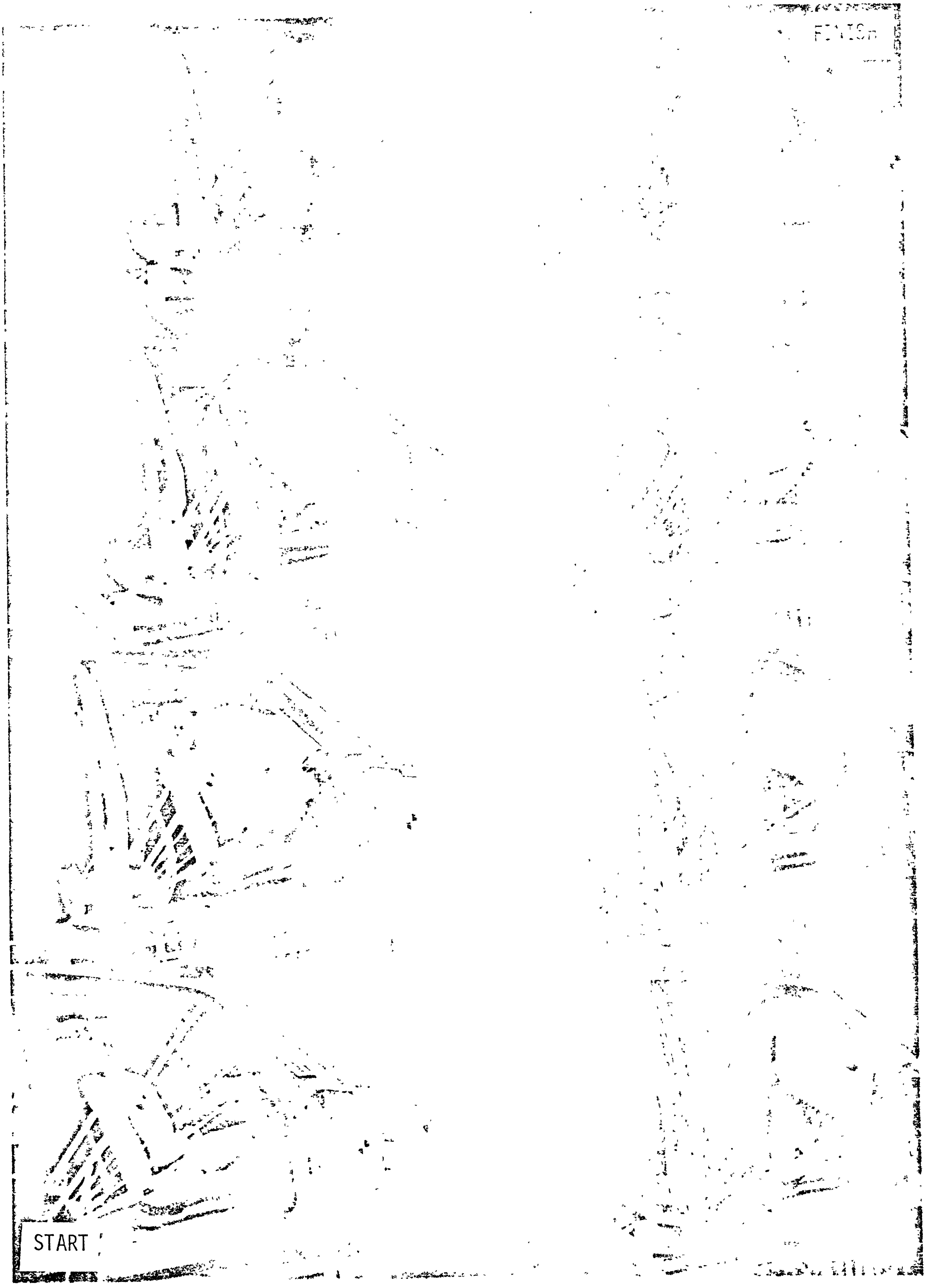
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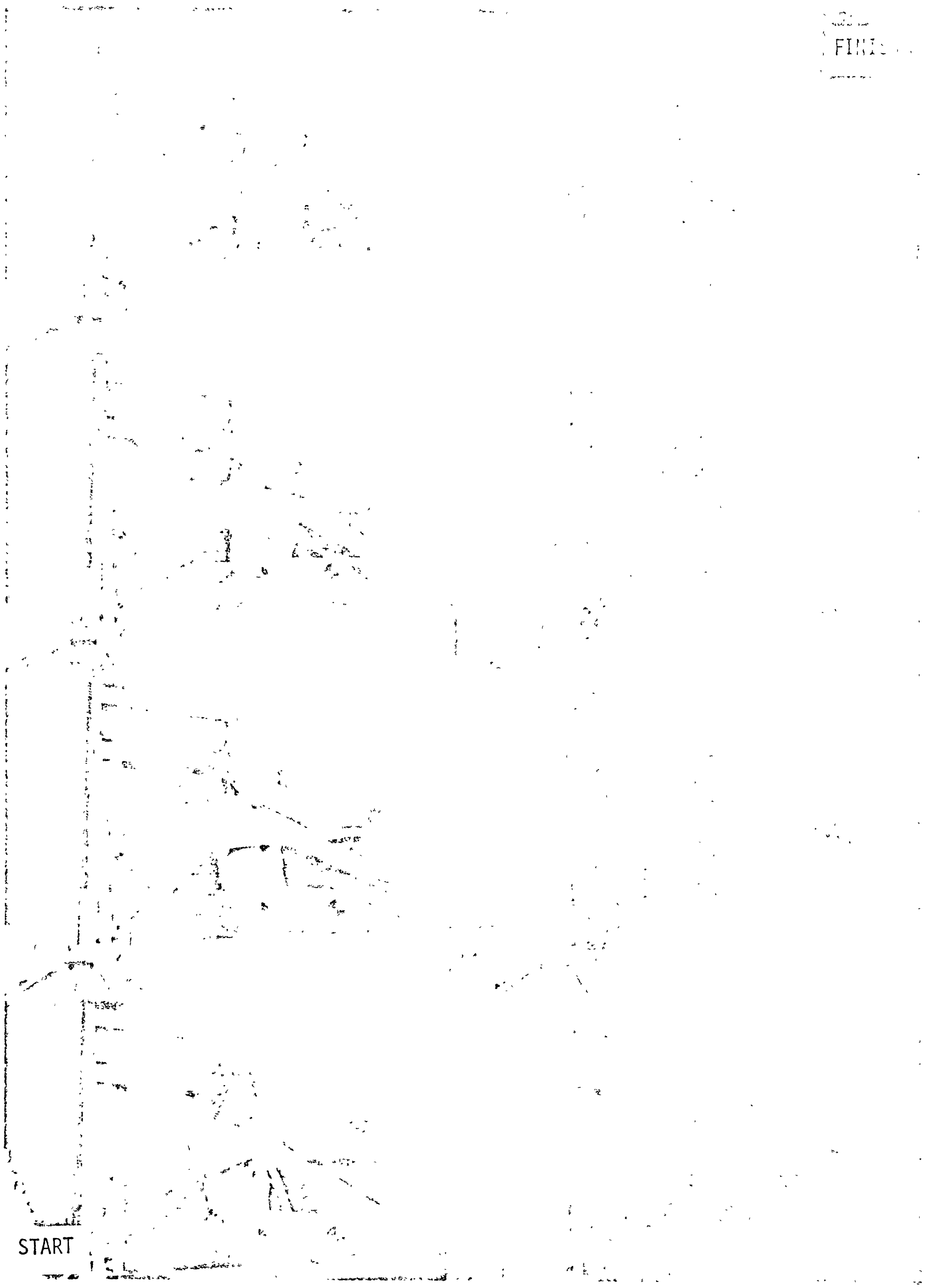
Current generation airbag and upper torso belt systems do not provide the solution to the restraint problem in side impact. Figure 8 shows the motions of a dummy restrained by a standard lap belt and shoulder harness arrangement when subjected to a 20 mph impact. He slides under the belts and ends up almost entirely off the seat. The lap belt would not restrain the pelvic region and the shoulder harness would not prevent the upper torso and head from contact with vehicle interior structures if they had been present.

Some insight into techniques for preventing motions to the side were gained in studying the protective potential of children's restraint systems as discussed in Reference 1. Figure 9 shows the test of a children's seat possessing substantial side structures to prevent motion of torso and head outside the "safe" environment of the seat. The children's seat was attached to the adult seat by means of a lap belt. The ideas incorporated in this seat arrangement can be incorporated successfully into adult seating as demonstrated in the analytical and experimental phases of this project which are discussed in the remainder of this report.

The major problem in rear impact protection is provision for head restraint. The subject of the test shown in Figure 10 was unrestrained. Although the G-loadings were low and the occupant's body remained in the seat, potentially injurious whiplash was observed as the head was bent backwards relative to the torso.

To summarize, the three basic problems in occupant protection have been illustrated by examples from HSRI impact sled tests. The problems are: 1. ejection from the seat; 2. application of excessive forces to the body; and, 3. the occurrence of large relative motions between adjacent body segments.

Solutions to these problems have been proposed and implemented as hardware at HSRI as described in the text which follows.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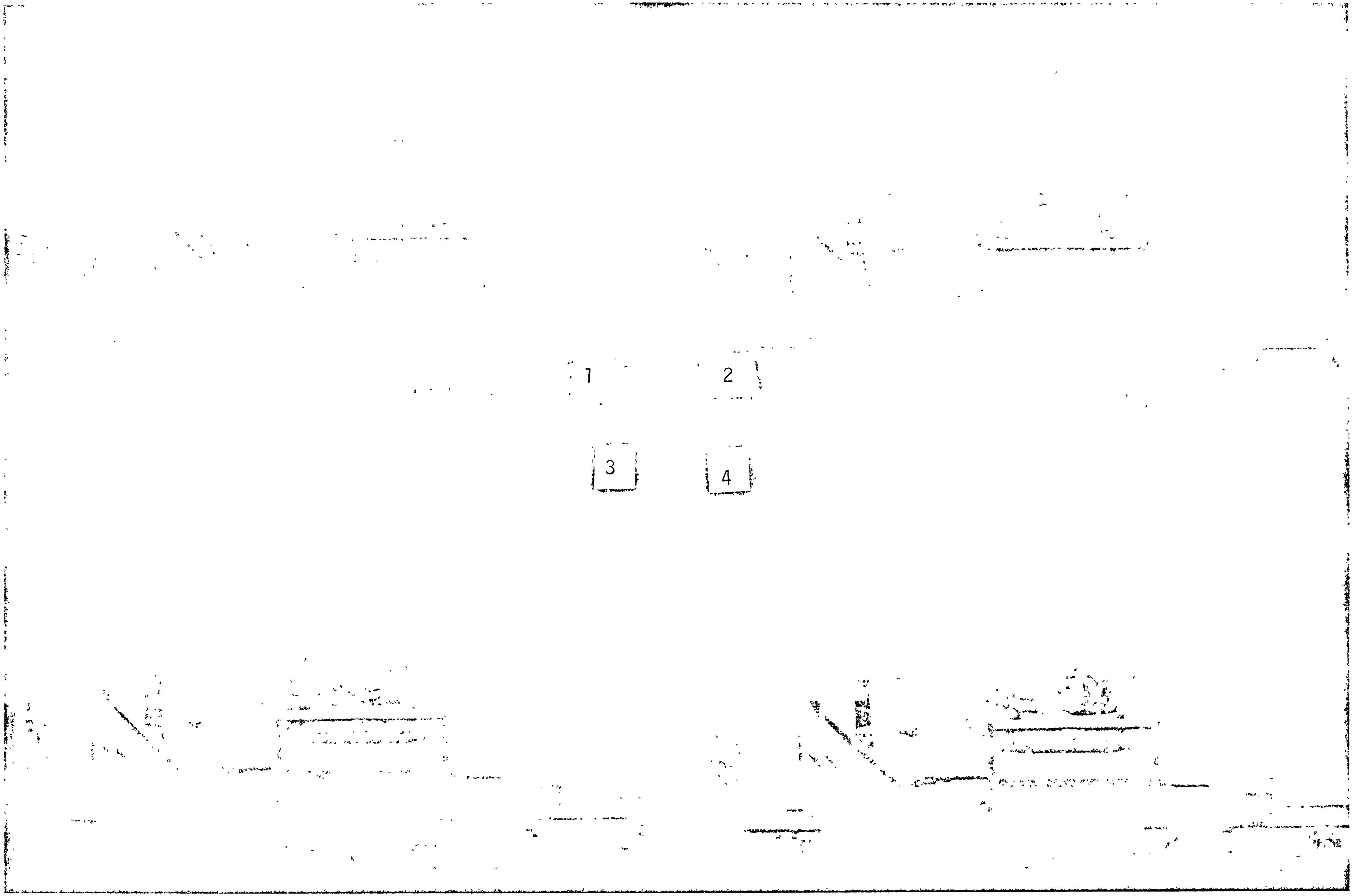
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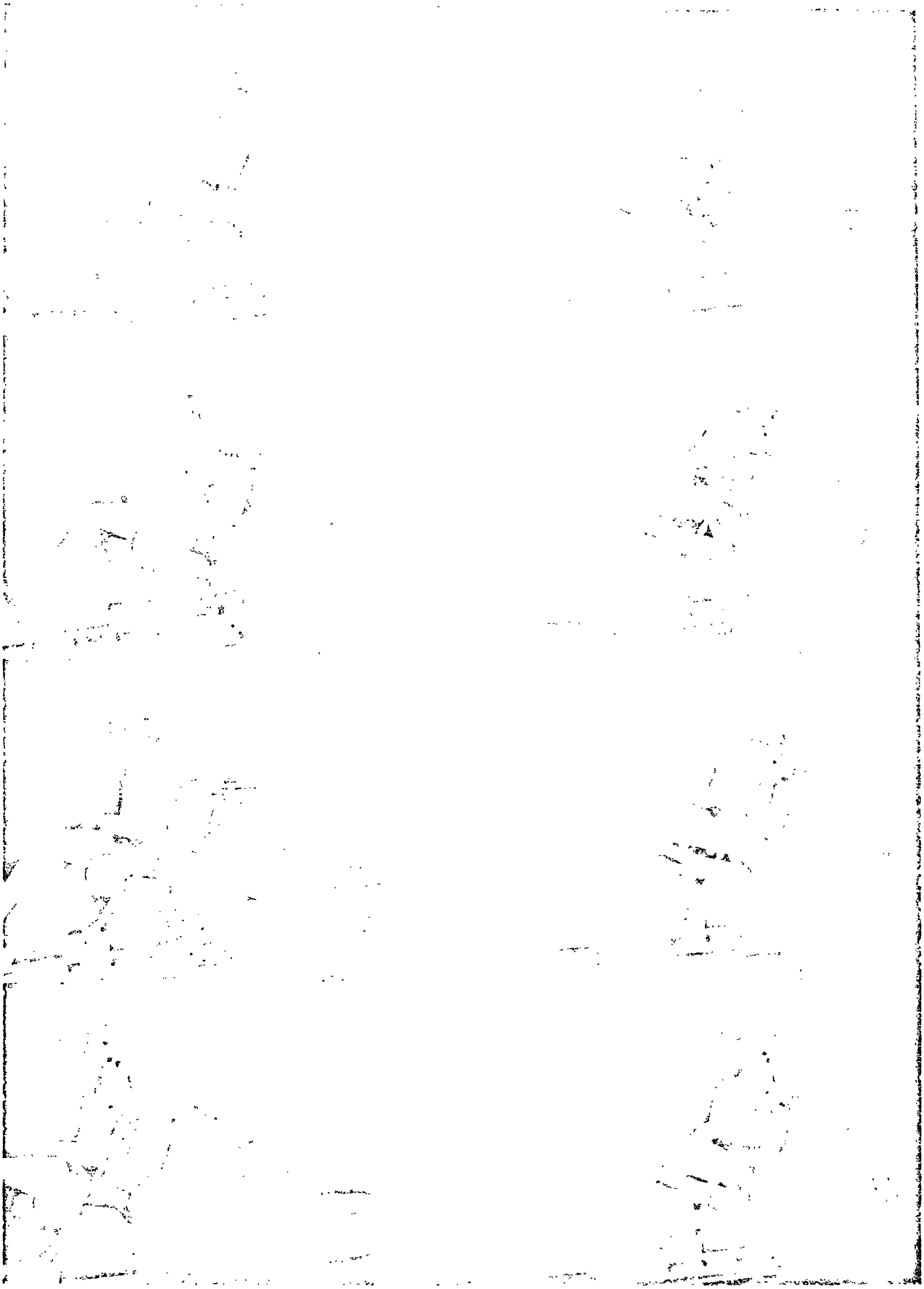

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3. ANALYTICAL STUDIES OF RESTRAINT SYSTEMS

Three major groups of parameters are considered in describing an integrated seat-restraint system subjected to a crash environment. They are the occupant, the seat restraint system, and the deceleration profile.

The occupant is difficult to describe both experimentally and analytically. Controversy arises over the use of anthropometric dummies, cadavers, or human volunteers. The physical properties of the dummies are the most easily obtained and controlled but there is a question whether or not they represent a living human. Four major sets of parameters may be considered in modeling the dynamic behavior of the body: 1. mass of the body elements; 2. strength and range of free motion of the various joint structures; 3. muscle tone; and, 4. body geometry.

The seat would seem to be easier to describe for use in a model. However, very little research has been carried out to determine dynamic deformation characteristics such as stiffness and damping of seats. The external restraint system is ordinarily defined in terms of specific devices such as a seat belt, airbag, energy-absorbing instrument panels, etc. One common feature of all the devices which have been suggested is the fact that they can be described in terms of dynamic force-deformation profiles. For example, an inertia reel used in conjunction with a shoulder harness will have a different characteristic curve than a controlled permanent deformation device or one of the common harnesses used in current production vehicles. Provisions must be made in any mathematical model for forces to be applied to the occupant in a rather general manner in order that they can be used in modeling any one of the proposed restraint devices.

The final parameter is the deceleration profile to which an occupant is subjected in a crash environment. In a two-dimensional simulation of crash motions the front or rear linear deceleration can be used, possibly supplemented by vertical and pitching components whereas in a three-dimensional simulation, all six components must be used. These include front, side, and vertical linear accelerations as well as spin, pitch, and roll angular accelerations.

3.1 THE MATHEMATICAL MODELS

During the course of this project two models have been developed and exercised extensively to study the force reactions between various occupants, seats, and restraint systems in a variety of crash configurations. The models are the subject of extensive reports and Users' Manuals (See References 3 and 4).

In the two-dimensional model the occupant is represented by a collection of eight lumped masses, viscous joints with realistic motion limits, muscles with resistive capability, and various geometric configurations. The seat, restraint system, and vehicle interior are represented by a series of contact surfaces and force-deformation profiles. Various deceleration profiles in two dimensions can be used.

The development of a three-dimensional model of occupant kinematics is necessitated by the fact that there is no possibility for using a planar model to simulate oblique or lateral collisions in that spin and other components of angular motion, as well as rotational inertia, have not been taken into account. This fact, plus the observation that many restraint systems are not symmetric, points out the need for models which simulate three-dimensional motion.

Two approaches may be taken in the development of models of this type. The first involves identification of as many variables and degrees of freedom as possible followed by the tedious and time-consuming task of developing a large-scale digital computer program. The second approach involves the developing of increasingly complex models beginning with simple one-mass models. This second approach was chosen in that short-term results seemed more likely.

The three masses (head, torso, legs) have inertia tensors $\overline{I}$, $\overline{J}$, $\overline{K}$. Coordinate axes have been chosen as principal axes so that the inertia tensors are diagonalized. The position of the torso link H-point has been defined by three rectangular coordinates. Each of the three links is then oriented by the use of three inertial Euler angles.

Ellipsoids are attached where desired to the three body masses and sense force interactions between the occupant and the interior of the vehicle. The interior of the vehicle is represented by a collection of contact surfaces. These surfaces can move as a function of time relative to the vehicle to simulate a deploying restraint system. Provision for the use of belt restraint systems, is also included in the model.

A variety of outputs are available when the three-dimensional model is used. The primary set of output is stored on file and printed in tabular form. This consists of translational and rotational displacements, velocities, and accelerations of body segments as well as all applied belt, contact, and deceleration forces.

In addition to this, three pictorial outputs are available. In all cases, a stick figure of the occupant is produced showing his motions as a function of time. All of these output techniques use an interface subroutine which operates on the stored file of program output. Output has been provided in the form of hardcopy as a sequence of Calcomp plots (power-driven pen written graphs). In addition to this, a time-sequence of the stick figures can be produced on a television screen.

The final output technique produces a 16 mm motion picture of the sequence of stick figures previously provided as hardcopy ink graphs or as still pictures projected on a cathode ray tube. In order to do this, a special tape is written and the movie produced by using auxilliary computer programs and hardware. The details of the three-dimensional model are included in Reference 4.

3.2 COMPUTER STUDIES

Both the Two- and Three-Dimensional Crash Victim Simulators have been exercised successfully for a total of approximately 500 times. Many of these have been presented in detail in other publications and reports and can be summarized as follows:

1. Belt material[7]
2. Belt slack[7]
3. Belt angles[7,8]
4. Lap belt only
5. Lap and torso belts[7,8,9]
6. Rear-end collision
7. Seat geometry and properties
8. Tilting seat
9. Inflating restraint systems[2]
10. Vehicle interior structures

11. Diagonal harness only

12. AMA vehicle interior

13. Verification of mathematical models[3,4,9,12]

14. Deceleration profiles

15. Belt angles in three dimensions[8]

16. Unsymmetric belt systems[8]

17. Geometry of seat side structures

18. Deploying restraint systems.

Belt materials with several load-deformation characteristics were considered: 1. elastic belt; 2. viscoelastic belt; 3. material with rate dependence only; and, 4. material with permanent deformation. In a simulated 30 mph barrier collision, the viscoelastic belt tended to reduce belt forces and peak body G's somewhat when compared to the elastic material. The amount of forward translational and rotational motion experienced by the simulated occupant in the two cases was similar. In the case of the elastic belts, the head of the occupant was rotated forward sufficiently to cause a high deceleration (91 G) lasting less than 5 ms as the head interacted with the joint stop limiting forward rotation. This interaction did not occur in the case of the viscoelastic belt. The third "belt material" consisted of velocity sensitive elements in which force is exerted only as a result of deformation rate. This type of action could take place if a pneumatic shock absorber were placed in series with the end of the belt system. Although the forward H-point movement was greater in this case, the reduced occupant loadings and accelerations point to this concept as one worthy of further study. An additional benefit is realized when forward momentum is reduced a zero. At this point body motion ceases, as there is no velocity difference to cause an elastic spring-back.

Other studies have been carried out for those belt materials involving the inclusion of permanent deformation or loss as a material property. In these cases, the elastic, viscoelastic, and rate dependent materials behaved as before during the loading cycle of the deceleration, however, rebound was essentially eliminated. Again, this feature of a belt material is desirable to prevent the occupant from bouncing around the vehicle in the event of a collision.

The studies of belt slack which were carried out tended to agree with the contention that a tight system of belts involves the occupant with the restraint system earlier in the collision event and makes more effective use of the available stopping distance in attenuating the effects.

The results shown in Table 2 are for an occupant simulating a 6-year-old child subjected to a 30 mph barrier impact. The results show the rather large benefits to be gained by using a tight restraint system.

It appears that tightening one belt and leaving another loose provides a benefit. However, in the case of a tight shoulder belt and a loose seat belt, this is not true. Submarining in this case was pronounced with the simulated child nearly slipping from under the belts.

TABLE 2. STUDIES OF BELT SLACK

Seat Belt Slack, In.	Shoulder Harness Slack, In.	Seat Belt Force, Lb.	Shoulder Harness Force, Lb.	Head Peak G	Chest Peak G
3.0	3.0	1700	1443	80	50
3.0	0.5	907	1384	58	41
0.5	3.0	1021	817	51	31
0.5	0.5	802	779	26(64)	24

In studying belt angles, insofar as is possible with a two-dimensional simulation it was found that a delicate balance is reached between anthropometry, belt forces, body G-loadings, and horizontal motion. Vertical belts are found to lead to gross horizontal body excursions. This is usually associated with violent contact with the interior of the vehicle. On the other hand, seat belts and harnesses with a horizontal line of action are unacceptable from the anatomical point of view as seat belts would ride over the pelvis into the abdominal area and it is possible that the concentrated thoracic loads could cause damage in this part of the body. It was found that an intermediate positioning of the belts at about 55° in each case, offered low belt loads, low G-loadings to the body, and an acceptable amount of forward body excursion.

A large number of simulations of rear-end collisions have been carried out to ascertain the effects of variation of seat back material properties, geometry, and head rests. Specific studies were carried out on seat back height, acceleration profile, seat back angles, head rest location, variable seat back properties including damping, and occupant anthropometry.

It was found that 21 inch, 23 inch, and 25 inch seat backs offered little protection against whiplash for a 50th percentile male occupant. The 27 and 29 inch seats offered some protection as the head was able to interact with the seat back. However, a substantial amount of relative rotation between the head and upper torso took place (45 degrees in a 15 mph collision for a 50th percentile seat belted male with two inches of belt slack). It also appeared from these studies that the head and upper torso, which were not initially in contact with the seat back, reacted more violently to the collision than did the lower torso which was in contact.

After additional studies, it was found that contouring the seat to conform to seated body geometry substantially reduced body "G's" and relative body angular motion. Thus, a contoured seat back with a vertical integral head rest has been proposed as a concept. This seat geometry was tested with individuals ranging from a six-year-old child to a 95th percentile man. It offered substantially greater protection to each than did a seat back and head rest with a constant angle.

The force deformation characteristics of the seat back were also varied. A variable stiffness back with a linear elastic characteristic, for example, a stiff lower seat back combined with a soft upper seat back and head rest, did not add to impact protection, but rather aggravated the situation for an occupant initially in contact with the contoured seat at all points. In this case high peak contact forces between occupant and seat are reached in a shorter time in the stiff seat regions whereas a longer time is required for reaching peak force values in the soft regions. This leads to relative rotation between body elements, a case which is avoided to a greater extent with a constant stiffness back.

A significant reduction in body loadings was realized when damping and energy absorption were added to the seat back. In addition rebound was minimized. The material chosen for padding the seat incorporated these properties to the maximum possible extent.

TABLE 3. SEAT BACK DAMPING

Seat Back Damping	Horizontal Hip Excursion (inch)	Force on Head (lb)	Force on Upper Torso (lb)	Force on Hip (lb)	Peak Head G's	Peak Chest G's
No	-5.2	284	2209	2371	28	41
Yes	-3.7	176	780	2032	15	14

Seat cushion properties including angle, force-deformation characteristics and friction were studied. Increasing the angle and adding friction to the cushion both tended to increase its role in attenuating the crash impulse thus reducing the loads placed on the remainder of the seat-restraint system. Decreasing stiffness allowed the hip to sink further into the seat bottom thus reducing the belt angle with respect to the horizontal and increasing the chance of an injury due to submarining. Unfortunately a stiff seat cushion with a large friction coefficient is not completely compatible with occupant comfort and the climbing in and out of a car. Thus, some compromise is necessary to make the seat usable.

Passive restraint systems were also considered. It was found that a tilting seat cushion could restrain an occupant in a frontal collision provided the seat cushion at the hip is very soft and the cushion under the knees if stiff. The pelvis and spine of the occupant were rotated upwards more in the direction of the impact. Because of the lower tolerance of the human body to spineward loadings, the tilt-seat concept appears to have less protective potential for high-G impacts than systems where the torso remains more nearly upright.

Inflating restraint systems were observed to have the greatest potential of any devices simulated for maintaining body relative geometry and for distributing the loading evenly over the body. It was necessary to restrain the forward motion of the pelvic region. This was most effectively accomplished by providing knee support. In practice this could be accomplished by energy-absorbing lower instrument panels[2] or by an inflating restraint system which deploys a section for knee support.

Three basic types of deceleration profiles have been used in the two-dimensional simulations. One is provided by the Automobile Manufacturers

Association and represents a 30 mph barrier collision as simulated on an impact sled. It is trapezoidal in shape and skewed at one end to provide a 19 G peak. The second has been obtained from an actual full-scale 30 mph crash. Finally, the trace obtained on the HSRI impact sled is used in all simulations used for comparison between test and analytical results. Additional waveforms have been used to study the effects of rise-time and duration of the deceleration.

A large collection of exercises of the three-dimensional model involving belt restraint systems are described in detail in Reference 8. Many of the conclusions reached are directly related to the current project and will be summarized here:

1. Unsymmetric motions and rotations of the body masses will result if an unsymmetric single diagonal shoulder harness is used. This can be partially eliminated by locating the harness anchorage at approximately 30° from a vertical center-plane through the occupant.
2. Symmetric belt systems such as the double shoulder harness and the inverted y-yoke harness system are to be preferred over a single diagonal shoulder harness because of the symmetric occupant response and improved performance in side impact.
3. It has been estimated that a seat belt should be located at an angle of 50° - 60° from the horizontal in order to comply with human anatomy and retain load carrying efficiency.
4. If belt attachment points are moved away from the occupant towards the sides of the vehicle, it has been shown that both load carrying efficiency and side impact performance are reduced.

5. It was found that the mathematical model can be used to identify important parameters in improving seat-restraint system performance. The addition of energy absorbing properties to both the seat structure and the restraint system resulted in a decrease in G-loadings as did the simulation of a seat contoured to body shape. Also, the use of energy management in the vehicle structure was shown to yield an equally high potential payoff.

In all direct side impacts where the occupant was restrained by a belt restraint system and used a standard bench seat arrangement which were simulated using the model, it was found that the occupant slid to the side sufficiently far so that half the torso and all the lower extremities were outside the seating position. The consequence of this is that a driver or passenger would slide into door structure if an impact were to occur on this side of the vehicle. In order to provide protection to the occupant using an integrated seat-restraint system concept, side structures were added to the seat to reduce side motions both of the upper torso and of the lower extremities of the occupant. The principles behind this are discussed in Part 2 of this report and illustrated in Figure 9.

Computer exercises evaluating this technique for side impact protection are summarized in Table 4. Four typical evaluations are included in this Table representing a three-point harness, an inverted y-yoke harness, and an airbag torso restraint with no supplementary lap belt. Three of the exercises involve a 50th percentile adult male and one a small child. In evaluating this data, it can be seen that all segments of the occupants body remain within the seat environment. Also, the padding selected had been chosen to limit the occupant loadings to acceptable levels. The high left-right torso

G-loading in the third run was caused by an interaction between the torso and a seat structural member underneath the padding. (This was corrected in seat fabrication by using stiffer padding). The deceleration profile chosen for these runs was a 20 mph direct side impact chosen from full-scale vehicle crash test data.

The conclusion which can be reached from this study is that side structures must be added to vehicle seating concepts in order to provide protection in side protection. It is unimportant whether they be included as part of the seat structure itself (as was done in this study) or integrated into the vehicle interior side structures.

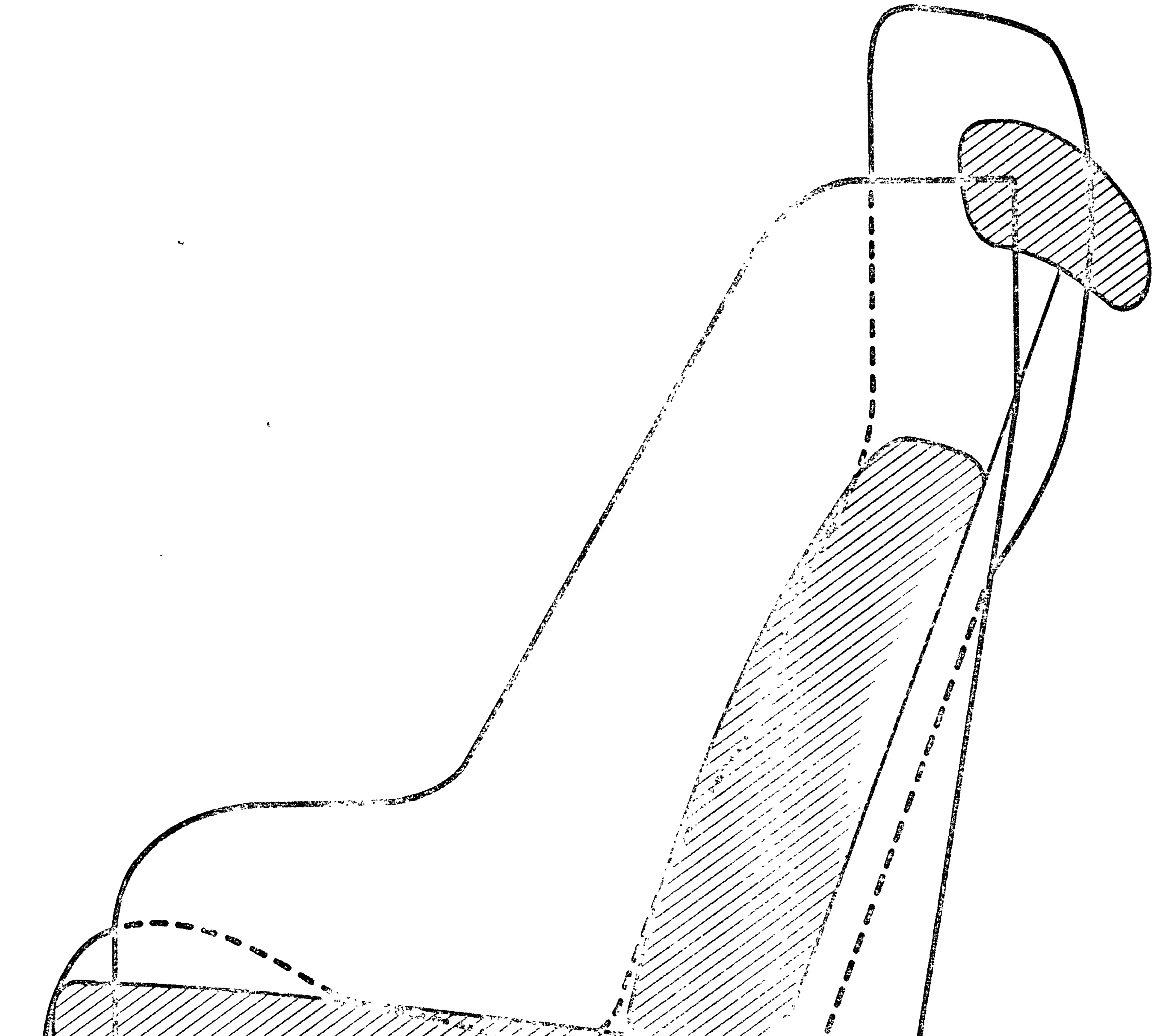
4. SYSTEM FABRICATION AND TESTING

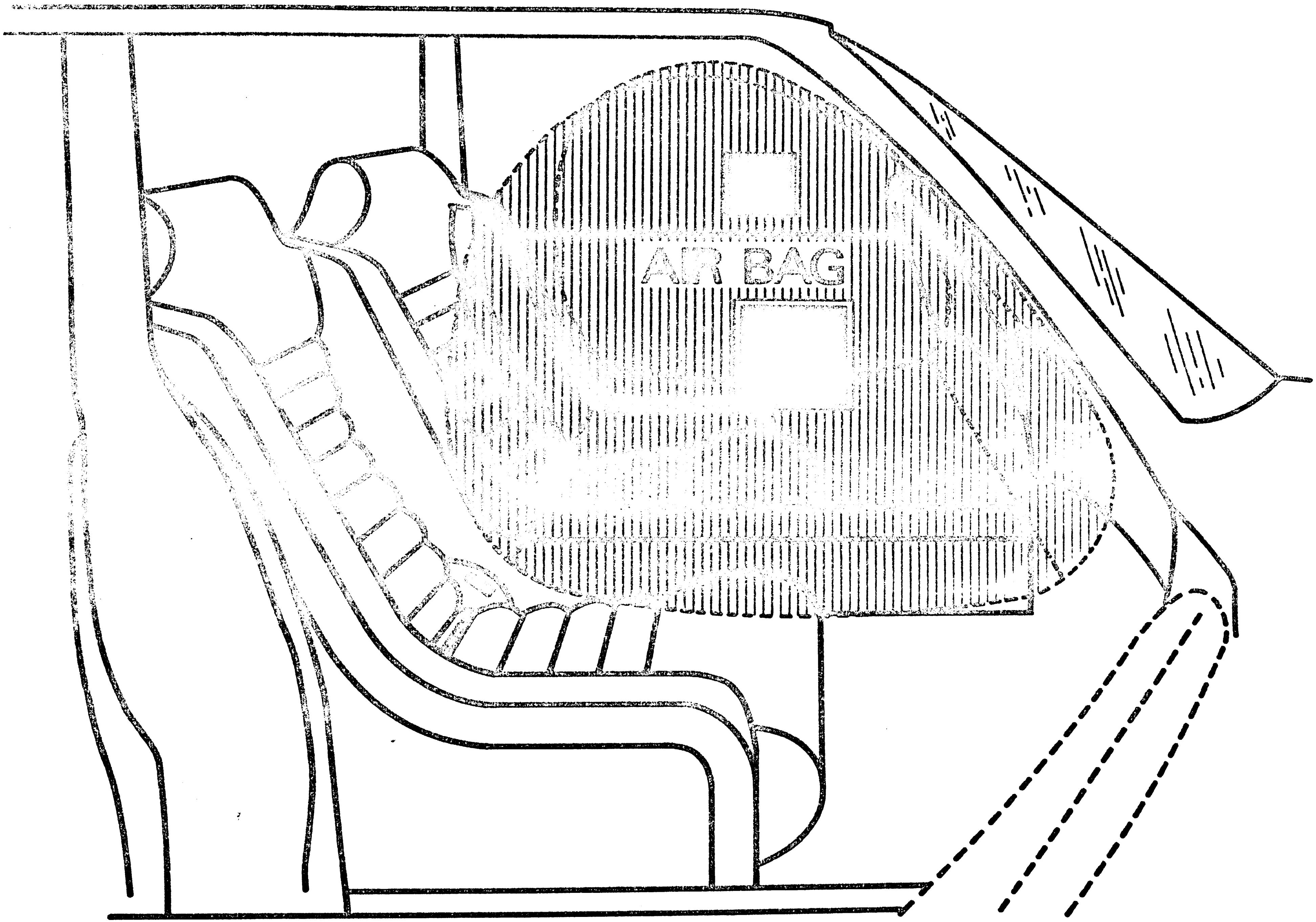
[illegible] studies presented in Part 3 of this report and [illegible] of restraint systems, four integrated seat- [illegible] three active systems involving [illegible] torso inflating restraint system. [illegible] fabricated and subjected to front, [illegible] rear impact sled tests. The results of the [illegible] involving current production [illegible] with the predictions of the HSRI Three- [illegible] Victim Simulator

4.1 [illegible]

[illegible] are included as Figures 11, 12 and 13. Figure 11 [illegible] profile of the seat. This is compared with a sta[illegible] (shown crosshatched). The major visible differences [illegible] and the HSRI seat are the addition of side structure [illegible] restraint. Structurally, the seats are intended for [illegible] than is usually found in current production seating. [illegible] is provided and the seat back is contoured to body shape. The headrest is located forward of most mounting points to reduce "slack" [illegible] head and headrest. This will allow the loads to be transmitted to the occupant's head, neck and back more nearly simultaneously.

Figures 12 and 13 show line drawings of two potential arrangements of this basic seat structure for installation in a motor vehicle. Figure 12 represents a two bucket seat arrangement. The torso restraint system is an




AIR BAG

airbag. Restraint for the pelvic region and lower extremities could be provided either by an energy absorbing lower instrument panel[2] making the system completely passive or by a lap belt.

Figure 13 illustrates the basic bucket seat unit modified for use in a bench seat arrangement. In the example shown, an active three-point harness is provided for restraint. Easy storage of this system is included in the concept. The upper element of the harness is attached to a retracting inertia reel. The lower element is attached to a locking retractor. This holds the system against the seat back when not in use. As an example of the use of a system such as this (refer to Figure 13), the right passenger would sit down and insert his right arm through the loop. He would then grasp the tongue with his left hand and insert it in the buckle by his left hip which would be permanently fixed in place. This system is automatically adjusting due to the locking retractor on the seat belt and the inertia reel on the harness.

It should be noted that the lower belt attachment points are located on the seat structure. This is done to allow more control over the angle of the seat belt, a problem plaguing current installation design. This will necessitate a strengthening of the seat attachment points, a problem which could be minimized by locating an energy absorbing link at the rear mounting point. The upper strap in the shoulder harness will be mounted in the automobile interior to minimize redesign of the seat back.

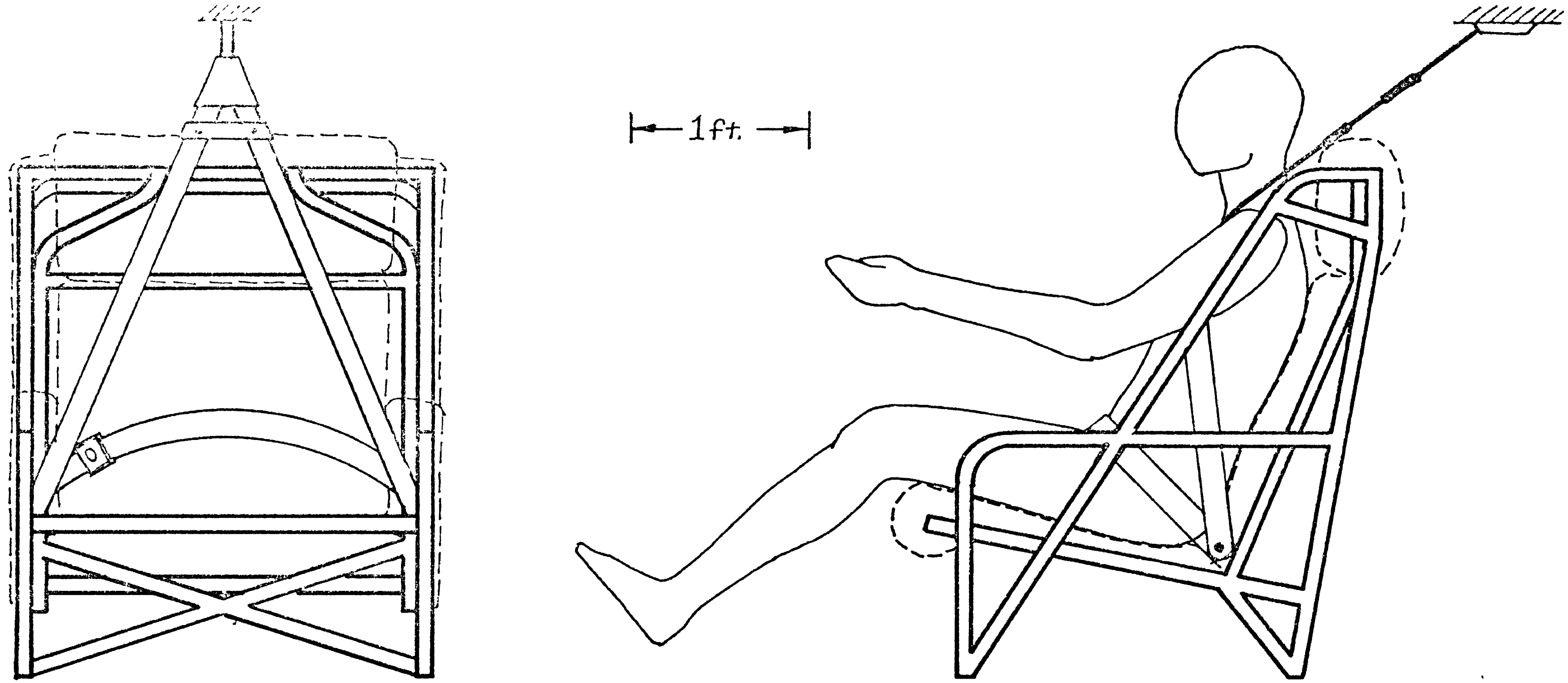
Based on the previous discussion, four concepts were proposed which should offer high level protection in front, oblique, lateral, and rear collisions. All these systems use the basic bucket seat concept illustrated in Figure 11. Three are bucket seats and the fourth is the bench seat shown in Figure 13. They are described as: 1. bucket seat with airbag torso restraint and energy [illegible] lower instrument panel (pure passive system); 2. bucket seat with [illegible] yoke harness and lap belt combination using a retracting inertia reel as the upper attachment point in the vehicle interior and using a locking [illegible] on the lap belt; 3. bucket seat with three point harness system [illegible] in Figure 13; and, 4. bench seat arrangement using three bucket [illegible] equipped with three-point harnesses.

[illegible] AND COSTS

[illegible] of the prototype seat is shown in Figure 14. The frame of the seat is fabricated from one-inch square hot rolled mild steel tubing with 0.[illegible] wall thickness. There are twenty welded junctions in the framework. The A frame side structures are designed to withstand 40 mph, 40 G [illegible] from [illegible] direction with the added loading of a 95th percentile [illegible].

[illegible] side-to-side the width of the seat is 27 inches. This width leaves [illegible] space for installation of energy absorbing material to offer protection in side impact and for seating a 95th percentile male. The distance between attachment points of the seat to the floor is 24.75 inches. The top of the [illegible] is 40 inches from the floor providing headrest structure for a 95th percentile male.

[illegible] to the framework is a sheet of 22 gauge sheet steel. It covers the seat pan, the seat back including the headrest, and wraps around the tubular side structures. The purpose of this is to deform and absorb energy during impact. A 2-inch layer of HD300 styrofoam covers the seat back, headrest, seat cushion, and the inside of the side structures. This material is crushable under a load of about 150 lb/in^2. A layer of 3 lb/ft^3 urethane foam,


1 ft.

which is a conventional composite cushion foam, is placed between the styrofoam and the seat cover which is naugahyde ST. This layer, varying in thickness from 1 inch to 1-1/2 inch is contoured to provide lower back support and a comfortable seating surface. An additional curved piece of 6 lb/ft^3 ehtafoam is added at the front edge of the seat cushion to aid in restricting forward motion of the H-point during impact and to absorb energy when the hip does move forward.

Only the most promising active restraint system was selected for testing. This involved the use of a symmetric inverted y-yoke harness. The hardware mounted in the seat was provided by American Seating Co. of Grand Rapids. The upper element is an inertia reel. It is activated by 1/2 G acceleration of the strap material as it leaves the reel. The device also locks automatically if it is turned upside down. The lap belt segment consisted of a locking retractor on one side and a fixed receiver for the buckle on the other.

The seat weighs 30 lbs. This is 23 lbs heavier than a current production bucket seat. No unusual construction techniques or materials have been used in the seats. However, because of the welding involved in the fabrication, it is estimated that the prototype HSRI seat used in the tests would cost about three times that of a current production seat. This figure could be reduced substantially for two reasons. First, the seat withstood the severe tests described in Part 4.3 without noticeable deformation. This suggests the presence of overdesign in some structural members, a problem which could be eliminated in redesign. Also, due to the small deformations observed in the energy absorbing foams during the tests, the seat could be made narrower by as much as three inches, a weight, space and cost reducing change. The second possibility for cost reduction of the seating unit is integration of the side impact protective structures in the door or side structures of the vehicle.

4.3 TEST PROGRAM

A total of fifteen impact sled tests were conducted on the HSRI bucket seat described in Part 4.2 of this report. The test matrix is given in Table 5.

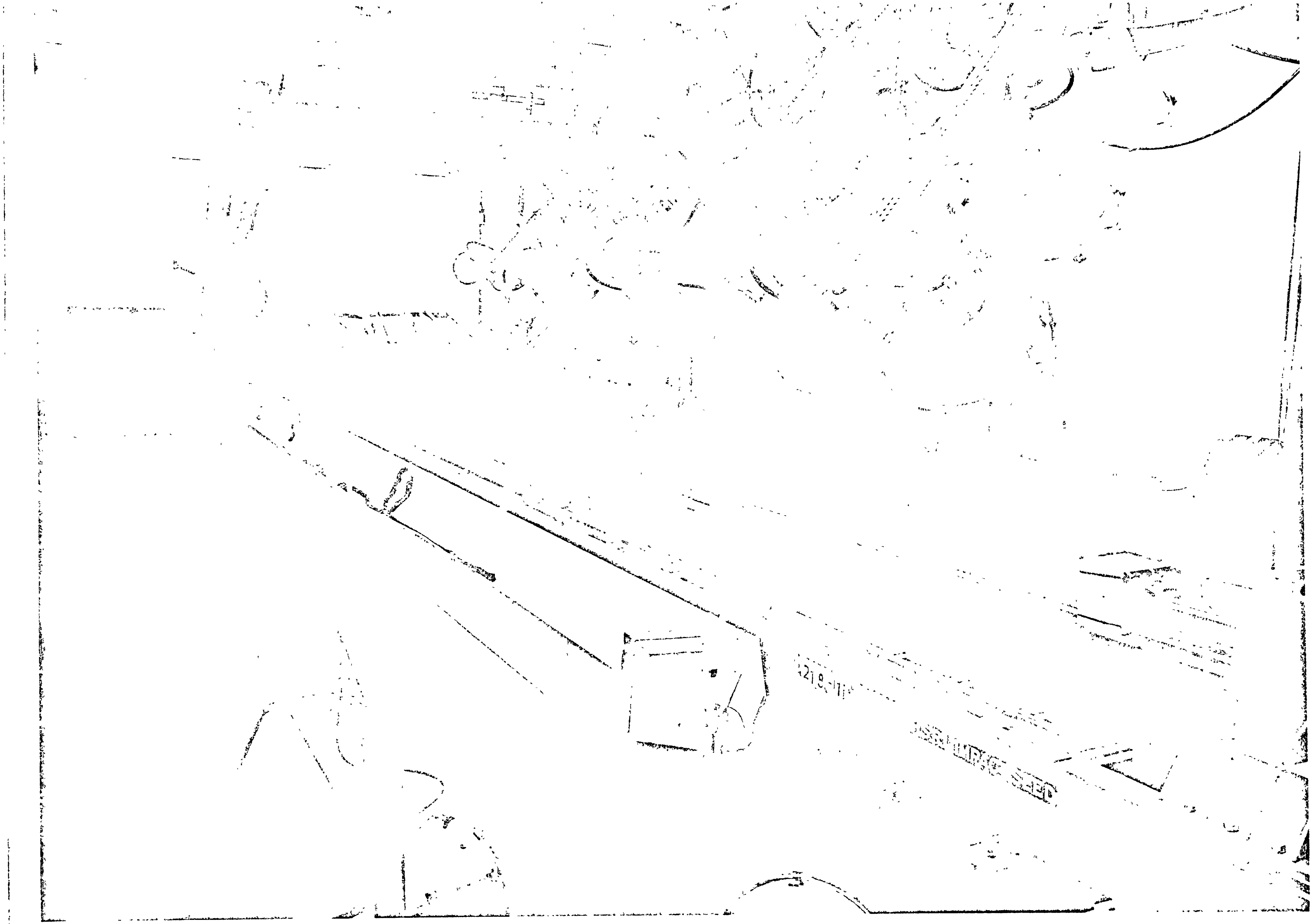
The tests were conducted on the HSRI Impact Sled (Figure 15) which is of the acceleration-deceleration type. It can be accelerated over a 12-foot distance up to a top speed of 40 mph using a compressed air-actuated pulley arm. The deceleration stroke has a maximum length of 3 feet and a maximum potential of 88 G's. For the purpose of high-speed photography, a total of 50 kw of lighting is available. Real time and high-speed movies are taken as well as still photographs before and after each test. The Kistler Piezotron Model No. 818 triaxial accelerometer packs were located in the head and chest of the Sierra dummies. A Statham strain gage accelerometer was used to record the sled deceleration pulse. Strain gage force transducers were mounted on the harness and lap belt segments.

The data was recorded simultaneously on a Honeywell 7600 tape recorder and a Honeywell 1612 Visicorder. No filtering was used during the initial recording other than the limitation of the light-beam galvanometers to frequencies under 1000 cps. A sample set of transducer data is shown in Figure 16 which is a photograph of the light beam oscillographic test record. A sequence of photographs illustrating the motions of the test dummy is given in Figure 17.

A summary of the test results is given in Table 6 based on an evaluation of the oscillographic and photographic data. Code letters define dummy size as follows: 1. 50M (50th percentile male); 2. 5F (5th percentile female); and, 3. 95M (95th percentile male). The body accelerometers are referred to

TABLE 5. SEAT TEST MATRIX

Test No.	Impact Velocity mph	Direction of Impact	Occupant
A-310	20	front	50th percentile male
A-311	30	front	50th percentile male
A-312	40	front	50th percentile male
A-313	40	front	95th percentile male
A-314	40	front	5th percentile female
A-315	20	rear	50th percentile male
A-316	30	rear	50th percentile male
A-351	30	rear	95th percentile male
A-353	30	rear	5th percentile female
A-380	40	45° oblique	50th percentile male
A-381	40	45° oblique	5th percentile female
A-382	40	45° oblique	95th percentile male
A-383	30	side	50th percentile male
A-384	30	side	5th percentile female
A-385	30	side	95th percentile male



ILL. C.1

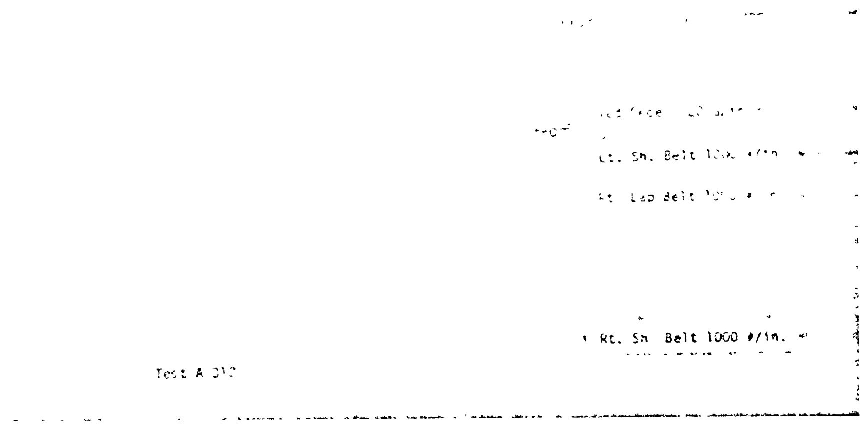

Lt. Sh. Belt
Rt. Lap Belt
Rt. Sh. Belt 1000 #/in.
Test A

TABLE 6. SUMMARY OF TEST RESULTS

Test Number	Dummy	Impact Velocity, mph	Direction of Impact	Head G-Loads			Chest G-Loads			Left Lap Belt lb.	Right Lap Belt lb.	Left Shoulder Belt lb.	Right Shoulder Belt lb.	Head Angular Motion deg.
				a-p	s-i	l-r	a-p	s-i	l-r					
A-310	50M	30	front	28	43	5	60	12	25	-	970	750	750	104
A-311	50M	30	front	50	65	17	45	25	18	-	1000	1100	1000	119
A-312	50M	39	front	50	65	10	56	30	10	-	1150	1060	1150	134
A-313	95M	40	front	27	45	10	35	18	30	-	1900	1100	1200	105
A-314	5F	40	front	45	48	13	55	33	40	-	800	650	625	89
A-315	50M	20	rear	18	19	3	18	9	5	160	160	-	-	43
A-316	50M	31	rear	18	30	5	45	15	10	420	420	-	-	42
A-351	95M	30	rear	32	16	2	27	8	3	-	-	-	-	42
A-353	5F	30	rear	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-	-	-	-	-	3
A-380	50M	38	45° oblique	26	-	35	[illegible]	19	[illegible]	242	-	[illegible]	[illegible]	103
A-381	5F	38	45° oblique	35	14	44	25	-	-	[illegible]	-	[illegible]	[illegible]	70
A-382	95M	38	45 oblique	[illegible]	-	23	[illegible]	[illegible]	[illegible]	-	[illegible]	[illegible]	[illegible]	[illegible]
A-383	50M	30	side	17	25	25	5	9	42	-	445	170	100	49
A-384	5F	30	side	42	26	92	18	7	53	-	236	80	160	34
A-385	95M	29	side	7	37	22	17	12	38	-	785	655	337	82

as: 1. a-p (anterior-posterior); 2. s-i (superior-inferior); and, 3. l-r (left-right). Instantaneous peak values are given for body G-loads and belt loads. A blank space for an acceleration indicates a malfunction of the data recording system, or most often, a break in the cables connected to the accelerometer. A blank shown for a belt segment load indicates that a belt was not used in the cases of Test Nos. A-315, A-316, A-351 and A-353. The value was not recorded in other cases. The last column shows the maximum angular displacement of an arbitrary line through the center of gravity of the dummy's head. This was obtained from photographic analysis of the high speed movies. It represents a combination of pitching and rolling motions of the head. Yaw (spinning) motions of the head around this axis are not included.

The deceleration pulse used in these tests was a trapezoid with a rise time of approximately 10 ms. The average magnitude was 16 G's.

The motions experienced by the dummies are illustrated in Figures 17-20. In all cases it should be observed that the dummy remains within the environment of the HSRI integrated seat-restraint system and does not experience any unusual motions which could lead to potential injuries.

6.4 COMPARISON OF RESULTS WITH CURRENT SYSTEMS AND WITH ANALYTICAL PREDICTIONS

The results given in Table 1 based on current production and airbag prototype systems can be compared with the results of the HSRI seat tests. Test No. A 246, a frontal 30 mph test using a 50th percentile dummy restrained by a lap belt and single diagonal shoulder harness and sitting on a standard production bench seat, can be compared with Test No. A-311. The body G-loadings are similar in the two cases and the belt loads somewhat lower for the HSRI prototype. Tests A-278 and A-313 at 40 mph involving 95th percentile

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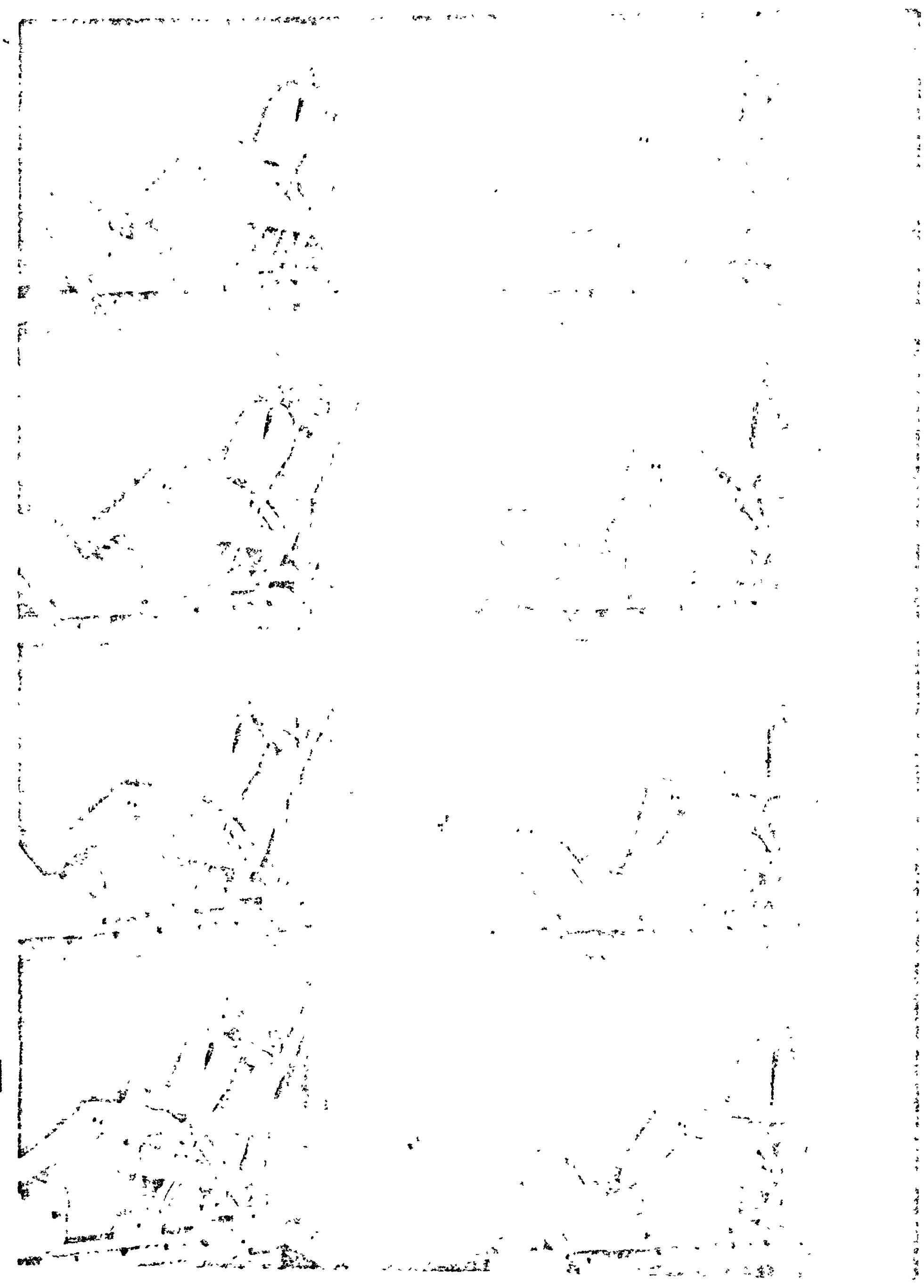


1

A-315


START
FINISH

dummies can also be compared. In this case both body G-loadings and belt loads are somewhat lower for the HSRI seat.

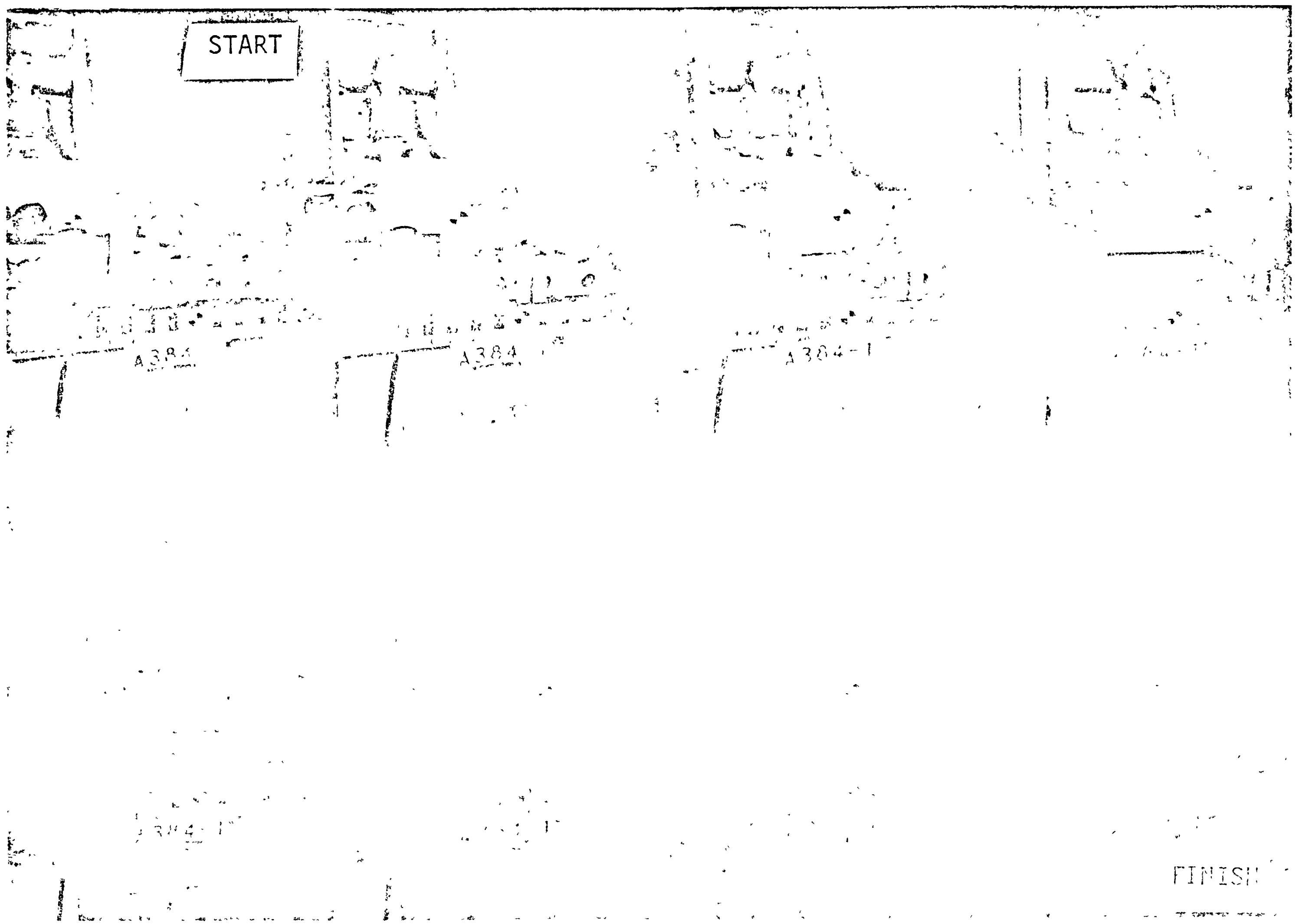
Test Nos. A-292 and A-309 using the 50th percentile male dummy both involve airbag upper torso restraints and are at 30 and 40 mph, respectively. In these cases body G-loadings are lower than for the HSRI seat. Substitution of the airbag for the inverted y-yoke harness used with the HSRI seat would most likely lead to a similar reduction in body G-loadings.

Although the G-loadings experienced by the dummy restrained by a lap belt and shoulder harness and using a standard seat are relatively low in side impact, the motions are extreme. Figure 8 (20 mph side impact with standard system) can be compared with Figure 20 (20 mph side impact with HSRI system) to show the distinct advantages of the prototype system possessing substantial side structures. Similar improvements in kinematics are observed in the cases where head restraint is provided (Figure 10 versus Figure 18).

The HSRI seat and restraint system is observed to outperform standard production seat and restraint system configurations in most respects. In frontal impact tests the HSRI seat equals or betters the current one while in side impact the HSRI integrated seat-restraint system is far superior.

Comparisons can also be made between the initial predictions of the HSRI three-dimensional crash victim simulator and the results of the impact sled tests. Figures 21-24 are graphs showing some of the important physical variables in the case of HSRI Impact Sled Test No. A-383, a 30 mph direct side impact involving a 50th percentile male dummy.

Figure 21 shows predicted versus experimental side head motions. The extent of the motions experienced by the head are similar in both cases with a difference in the peak values of approximately 15%.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A384
A384
A384-1
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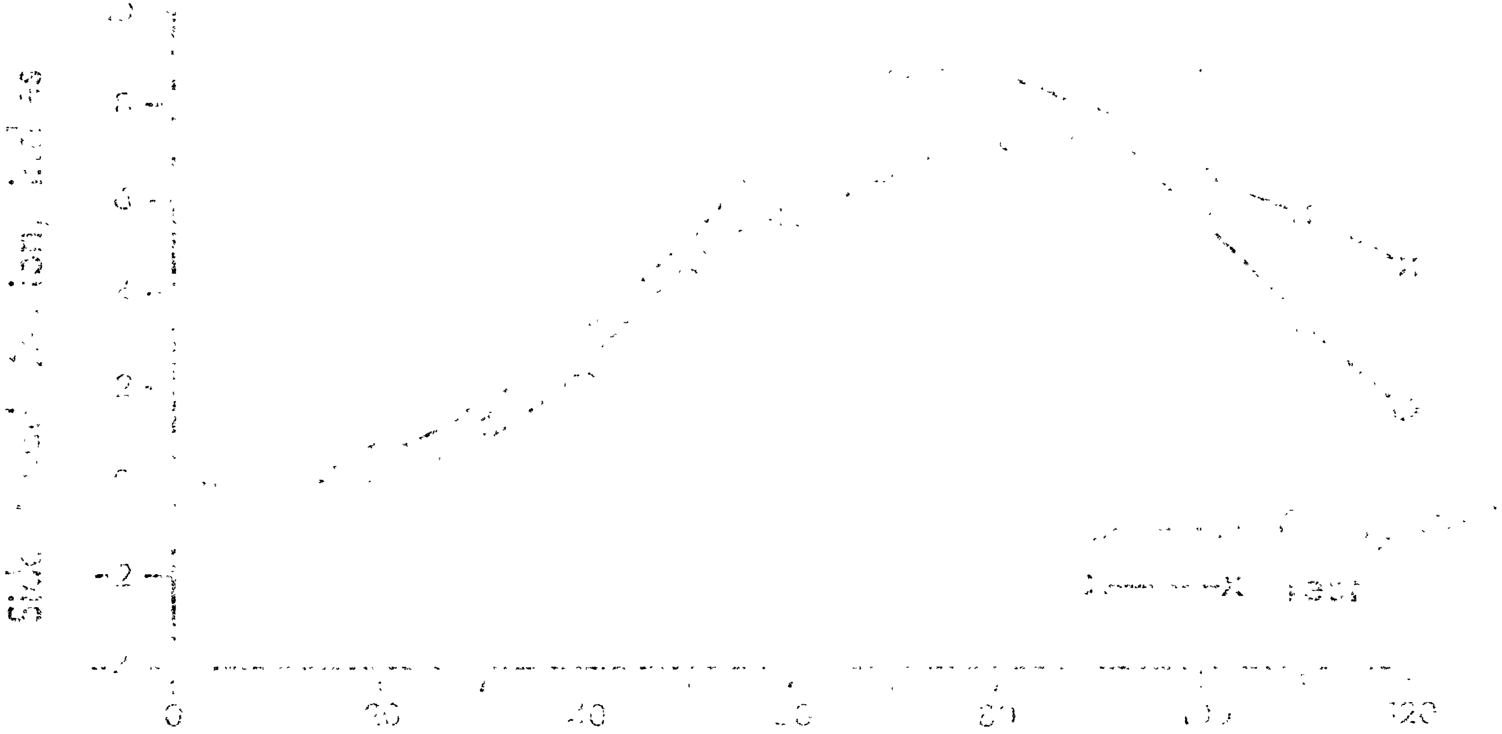


FIGURE 21. PREDICTED vs EXPERIMENTAL SIDE HEAD MOTIONS

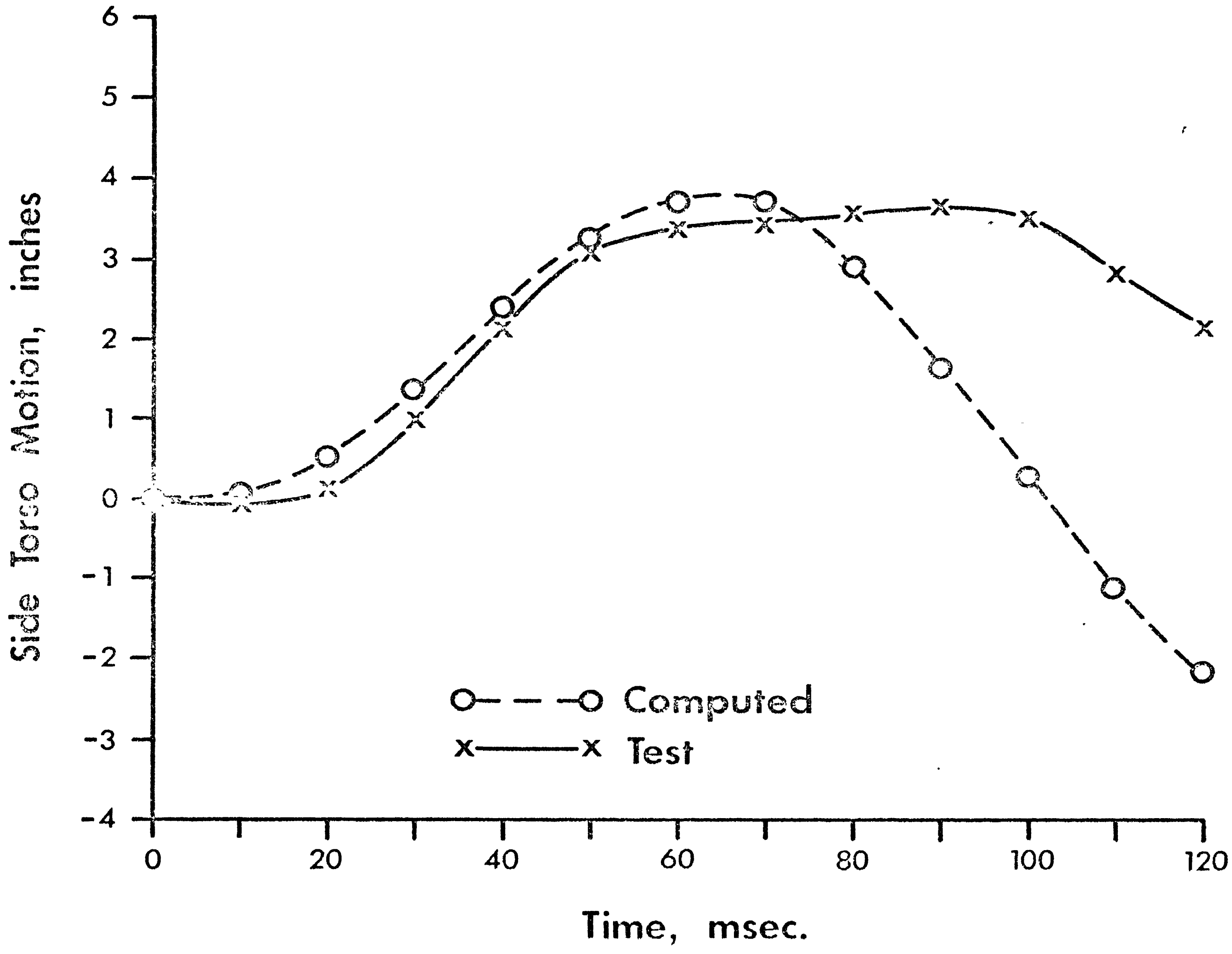
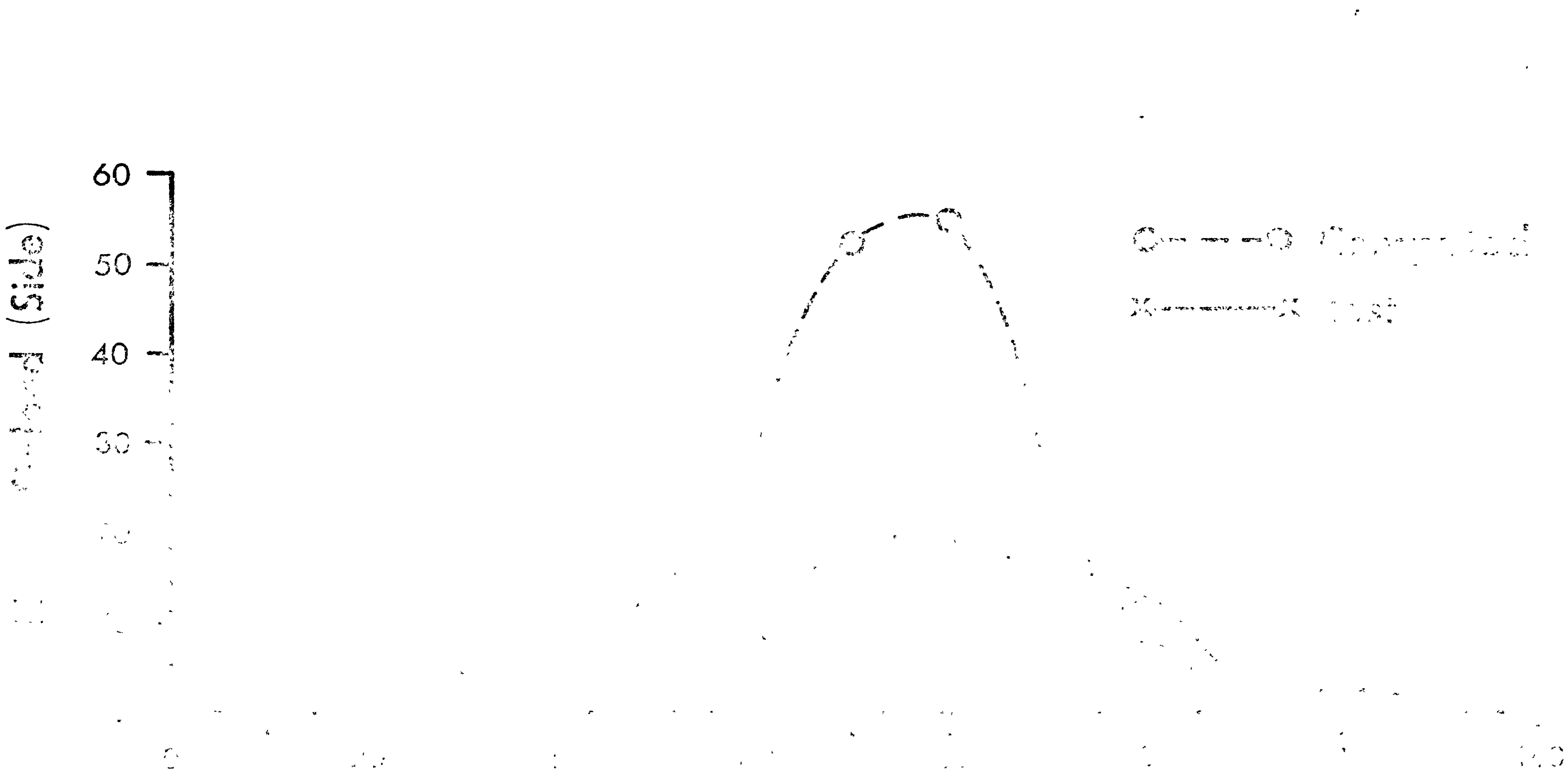


FIGURE 22. PREDICTED vs EXPERIMENTAL SIDE TORSO MOTIONS


60
50
40
30
(Side)

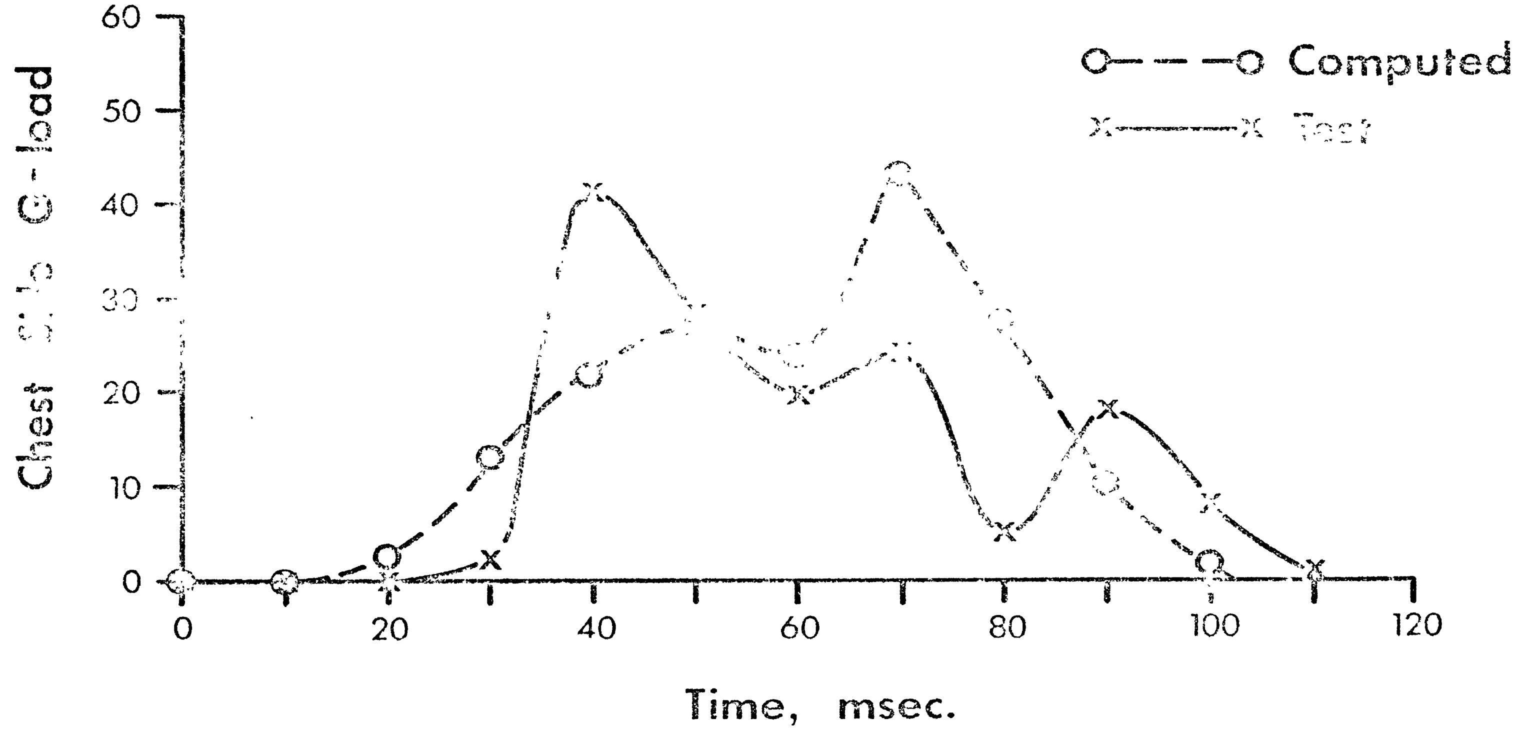


FIGURE 24. PREDICTED vs EXPERIMENTAL TORSO SIDE G - LOADINGS

Figure 22 shows predicted versus experimental side torso motions. The prediction of maximum side motion of the torso agrees with the sled test within 5%. In Figure 22 as in Figure 21, rebound is observed to take place more quickly in the case of the computer predictions than in the case of the impact sled test. The styrofoam padding used to cover the steel frame of the HSPI seat apparently absorbed more energy in the test than the contact surface included in the computer model which had force-deformation properties defined by a nonlinear spring.

Figure 23 shows predicted versus experimental head side G-loadings. Although the duration of the two pulses is the same, the computed G-load was much higher than the test value. Further examination of the computer printout revealed that the head interacted with one of the stiff steel members of the seat frame at the time when the high G-loadings occurred. Examination of the high speed movies of the test showed that the head missed this member by approximately one inch. Figure 21 shows the head moving approximately one inch further to the side in the computer simulation.

Figure 24 shows predicted versus experimental torso side G-loadings. The peak G-loadings are similar and the shape of the two curves is generally the same.

The purposes of the analytical work has been accomplished. Predictions have been made to define the geometry of an integrated seat restraint system capable of protecting a variety of occupant sizes in front, oblique, lateral, and rear impact. The predictions have been used as a design tool in preparing seat mockups and the prototypes for use in the test programs. The test results suggest the value of an integrated seat restraint system design in providing occupant protection. To close the circle, the test results also correlate well with the initial predictions made using the mathematical models.

5. PERFORMANCE REQUIREMENTS AND COMPLIANCE PROCEDURES

We have chosen to present our recommendations roughly in the format of a Motor Vehicle Safety Standard to recommend performance requirements and compliance test procedures for integrated seat restraint systems and for passive front seat occupant restraint systems. Comments are added to the text to support the recommendations.

5.1 SCOPE

This recommendation specifies performance requirements for the protection of vehicle occupants in crashes.

5.2 PURPOSE

The purpose of this recommendation is to reduce the number of deaths of vehicle occupants, and the severity of injuries, by specifying vehicle crashworthiness requirements in terms of forces, accelerations, and motions measured using anthropometric devices in impact tests.

5.3 APPLICATION

This recommendation can be applied to passenger cars, multipurpose passenger vehicles, trucks, and buses.

5.4 GENERAL REQUIREMENTS

5.4.1 Integrated Seat Restraint Systems

An integrated seat restraint system is defined to be a combination of seat restraint system, and vehicle interior components designed to provide protection to the occupant in the event of a crash. The system shall be tested in front, lateral, and rear impact as outlined in Part 5.5. The test shall be conducted in accordance with the requirements outlined in Part 5.7 and the data gathered from the anthropometric test device shall meet the injury criteria of Part 5.6.

5.4.2 Passive Front Seat Occupant Restraint Systems

The system shall be tested in front impact as outlined in Part 5.5.1. The test shall be conducted in accordance with the requirements outlined in Part 5.7, and the data gathered from the anthropometric test device shall meet the injury criteria of Part 5.6.

Comments: It is felt that all restraint systems ultimately should be required to offer impact protection when a vehicle is subject to any sudden linear and/or angular decelerations. However, experience at HSRI with passive restraint systems has been limited primarily to front impact studies. Because of this the performance and compliance recommendations for passive front seat occupant restraint systems are limited to the front impact case only..

5.5 OCCUPANT CRASH PROTECTION REQUIREMENTS

5.5.1 Frontal Impact

When a full-scale vehicle interior complete with all interior components as well as the seat and restraint system, rigidly mounted to an impact sled platform, is impacted under conditions approximating a 40 mph perpendicular barrier collision using the anthropometric test device specified in Part 5.7.2, the system shall meet the injury criteria of Part 5.6.

Comments: Our experience has shown that full-scale barrier impacts are less reproducible than their laboratory counterparts, the sled impact. Furthermore, our studies employing sled tests as well as mathematical simulations of occupant kinematics (see references 3 and 4) indicate that the barrier acceleration profiles may be reasonably reproduced by simpler acceleration waveforms than those encountered in a full-scale crash and yet accomplish the desired kinematic response on the part of human simulators such as anthropometric dummies. Given that greater reproducibility is possible with an impact sled and that the occupant response is reasonably insensitive to the fine structure measured in a vehicle-barrier acceleration crash profile, then a laboratory test is highly preferred over a less controllable barrier crash evaluation. An impact velocity of 40 mph represents an achievable goal and has been chosen on the basis of the encouraging performance of the HSRI integrated seat restraint system at this velocity.

5.5.2 Lateral Impact

When a full-scale vehicle interior complete with all interior components as well as the seat and restraint system, rigidly mounted to an impact sled platform, is impacted under conditions approximating a 30 mph direct side impact using the anthropometric test device specified in Part 5.7.2, the system shall meet the injury criteria of Part 5.6. Unsymmetric seat and restraint system configurations shall be subjected to lateral impact from both left and right sides.

Comments: An impact velocity of 30 mph has been chosen on the basis of encouraging performance of the HSRI integrated seat restraint system at this velocity.

5.5.3 Rear Impact

When a full-scale vehicle interior complete with all interior components as well as the seat and restraint system, rigidly mounted to an impact sled platform, is impacted under conditions approximating a 30 mph direct rear impact using the anthropometric test device specified in Part 5.7.2. the system shall meet the injury criteria of Part 5.6.

Comments: An impact velocity of 30 mph has been chosen on the basis of encouraging performance of the HSRI integrated seat restraint sytem at this velocity.

5.6 INJURY CRITERIA

5.6.1 Head Anterior-Posterior Acceleration

Acceleration of the head center of gravity in the anterior-posterior direction resulting from the test shall not produce a maximum strain for the head in the a-p direction which exceeds 0.0061 in/in. Compliance shall be based on Figure 25 with the anterior-posterior head G-level remaining below the "Front Head" curve.

Comments: Our experience gained in studies of the tolerance of the human head to impact indicates that the Maximum Strain Criterion, developed on U.S. DOT Contract No. FH-11-7288, "Door Crashworthiness Criteria" (Reference 6), is a viable and realistic approach to the assessment of the injury potential of an acceleration input to the cranium and its contents. As a result of other studies we have documented the lack of sound data to support the WSU head injury tolerance curve. Without an adequate data base to support the

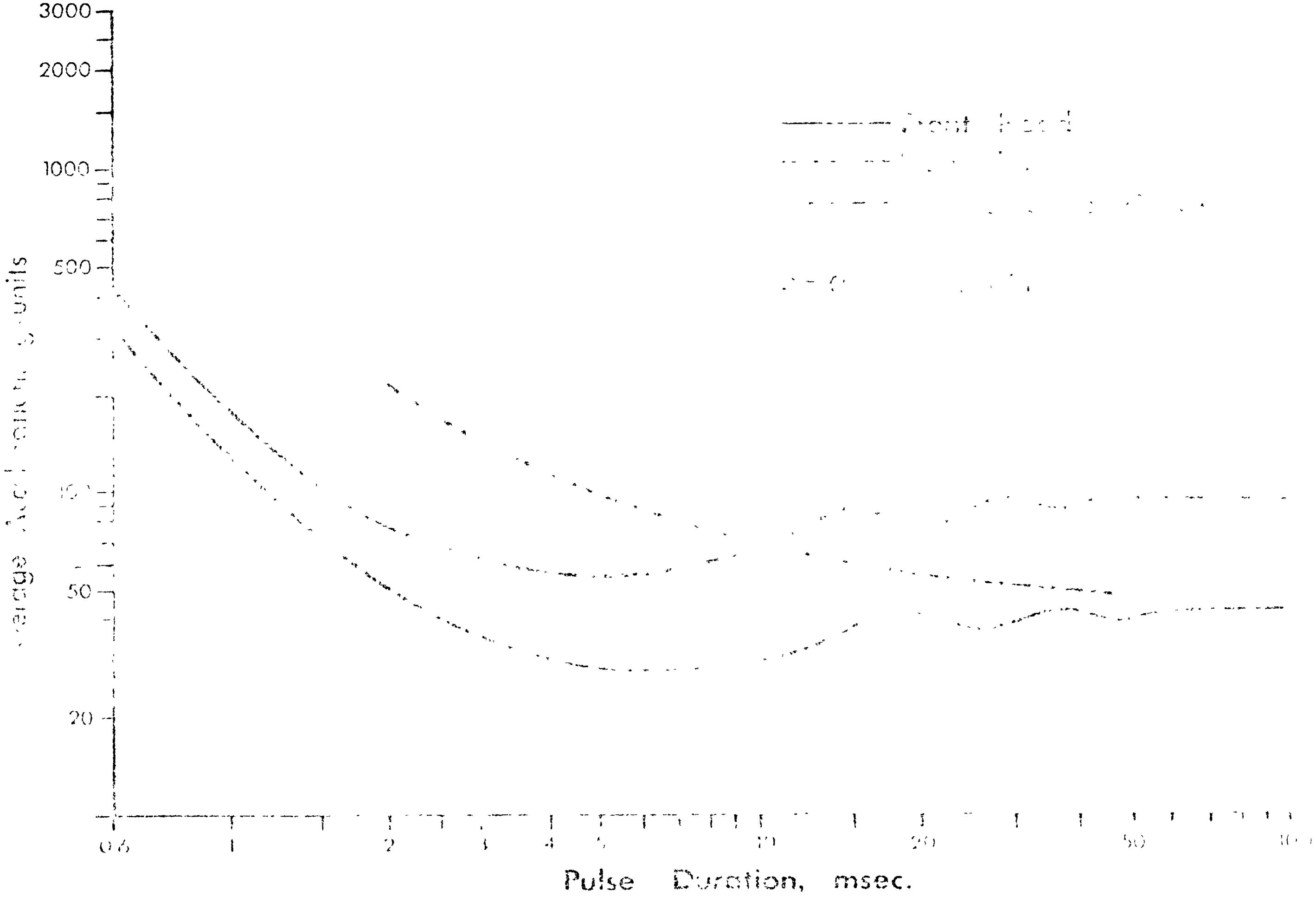


FIGURE 25. HEAD INJURY TOLERANCE CURVE

WSU curve, the use of other criteria derived from it, i.e. Gadd Severity Index, is even more futile.

We do not recommend the use of a resultant acceleration pulse in the assessment of the potential for head injury. Although criteria for tolerance to individual blows on the front or on the side of the head have been proposed, tolerance information is not available for up-down accelerations of the head or for oblique impacts combining the directions. Until it can be documented through biomechanical research as to how the directionally dependent tolerance levels might be additive, the use of a resultant acceleration pulse could prove to be unrealistic.

5.6.2 Chest Anterior-Posterior Acceleration

The anterior-posterior component of the chest acceleration at the center of gravity of the upper thorax shall not exceed 45 G's. The restraint device shall apply its load over a contact area of at least 100 in^2.

Comments: The Biomechanics literature adequately documents the ability of the human thorax to sustain a 45 G pulse without cardiovascular effects if the load is properly distributed.

5.6.3 Leg Force

The force transmitted axially through each upper leg shall not exceed 1,400 lbs.

5.6.4 Head Side Acceleration

Accelerations of the head center of gravity in the left-right direction resulting from the test shall not produce a maximum strain for the head in the side to side direction which exceeds 0.0061 in/in. Compliance shall be based on Figure 25 with the left-right head G-level remaining below the "Side Head" curve.

Comments: See Figure 25 and the comments associated with Part 5.6.1.

5.6.5 Chest Side Acceleration

The side component of chest acceleration at the center of gravity of the upper thorax shall not exceed 45 G's. The restraint system and seat shall apply the load over at least one square foot.

Comments: The above is considered to be a preliminary recommendation. It is based on a series of impact sled tests at 34 mph, using anthropometric dummies. These tests were designed to duplicate an automobile accident (direct side impact at the same estimated velocity) where the occupant received moderately severe internal injuries resulting from contact with door side structures. The damage to the doors of the automobile resulting from occupant contact was similar in the sled tests and in the accident. The G-level is the average of the peak values recorded in the six impact sled tests. These tests are discussed in more detail in Reference 6.

If the loading is not distributed over a large area of the side of the body, this G-level should be reduced. In animal tests (which have been scaled to human tolerance) where the area of the side impactor was reduced from 40 in^2 to 7 in^2, it was found that the average pressure applied to the surface of the impactor remained constant at 27 psi for the production of serious damage to the contents of the upper thorax. For impacts lower on the side, a value of 19 psi resulted in serious spleen and liver damage. This implies that smaller contact surfaces can produce injury at decreasing G-levels. These tests are also discussed in Reference 6.

5.6.6 Rear Impact

The anterior-posterior center of gravity G-level due to [illegible] to the rear of the head shall be computed using [illegible] as described in Part 5.6.1. The angle of hyperextension [illegible] 80 degrees and preferably under 60 degrees. The angular acceleration [illegible] head to the rear relative to the torso shall be less than [illegible] the angular velocity shall not exceed 50 rad/sec.

Comments: A three-fold criteria for head rear impact [illegible] been recommended which consists of both angular and linear [illegible] ponents[10] as well as a restriction on relative rotation [illegible] chest.[11] Similar values should be obtained for all [illegible] components of the head and for all three possible [illegible] combinations) before any proposed, recommended, or existing [illegible] formance can be regarded as complete. This points out the [illegible] Biomechanical research which must be carried out before [illegible] injury criteria can be recommended, but does not detract [illegible] present knowledge in current standards.

5.6.7 Limitation of Body Motions

The motion experienced by the test dummy shall be limited [illegible] and restraint system to prevent ejection, contact with other [illegible] contact with potentially injurious vehicle interior components. [illegible] shall be limited to the inside of a volume defined as follows: 1. [illegible] the volume shall be the bottom of the foot well used by the [illegible] of the volume shall be defined by any vehicle components not associated with the protective elements of the seat and restraint system; 3. [illegible] volume shall be defined by vertical surfaces, located four inches from the widest part of shoulders of a 95th percentile male dummy positioned as specified in Part 5.7.4 or vehicle components not associated with the protective elements of the seat and restraint system, whichever is closer; 4. rear of the volume shall be four inches behind the surface of the seat back and headrest combination; and, 5. top of the volume shall be one inch above the top of the head of a 95th percentile male dummy positioned as specified in Part 5.7.4. The lower arms and lower legs need not remain within this volume.

Comments: This recommendation, specifically designed to limit occupant motions to the side, is based on experience with the HSRI integrated seat restraint system and represents performance which has been demonstrated in the laboratory.

5.7 TEST CONDITIONS

5.7.1 General Conditions

The following conditions apply to the frontal, lateral, and rear-end impact sled tests.

5.7.2 Test Devices

Anthropometric test devices should conform to the size and range of motion requirement of SAE Recommended Practice J 963, June 1968. The dynamic structural characteristics of the head and thorax of the test device shall provide the same mass, damping and stiffness characteristics as the human. Compliance with such requirements shall be demonstrated by comparing the variation in mechanical impedance over a range of 5 to 3,000 hertz for the head and chest assemblies with the demonstrated variation of mechanical impedance for the [illegible] same frequency range. The mechanical impedance of the te[illegible] not [illegible] from the human by more than 10% at any frequency [illegible] hertz range. The pelvic structure of the test devi[illegible] MVSS 208, Notice 9, March 10, 1971.

Comments: [illegible] statements concerning the mass and [illegible] and dynamic properties of test [illegible] is chosen to provide size and range of [illegible] test [illegible]. This is supplemented by the pelvic str[illegible].

[illegible] and elsewhere have indicated that [illegible] devices can vary widely from human [illegible], a test procedure has been chosen [illegible] impedance of the dummy with values obtained from [illegible] is that the recommended test dummy can provide [illegible] structural response than is possible [illegible] current [illegible] filtering of data is necessary to eliminate ringing of [illegible] members.

5.7.3 Joints

Shoulder, [illegible], knee, head and neck joints shall be set at 1 G barely restraining the weight of the body segment when extended horizontally. Articulated torso joints shall not move at a horizontal acceleration load of 1 G, in the test position, but move at a horizontal acceleration load of 2 G's.

Comment: The only function of this recommendation is to fix dummy position prior to the test. The settings are not based on human data and hence the recommendation must be regarded as very preliminary. In order to update this recommendation, it will be necessary to conduct research to define quantitatively the degree to which an occupant can stiffen himself prior to or during an actual impact, a factor believed to greatly alter occupant kinematics.

Joint friction torques are used to approximate a constant torque resisting angular motions at the joints. In human volunteer tests conducted at Holloman Air Force Base[12] the subjects, restrained by a lap belt, sat on an instrumented seat and pushed as hard as possible on a toeboard instrumented with triaxial load cells. Most subjects voluntarily pushed with a force sufficient to represent a 20 G torque at the knees. During impact sled tests involving a variety of restraint systems, subjects initially exerted foot forces sufficient to represent knee torques far in excess of 1 G. Research must be conducted on other joints, particularly the hip and neck, to estimate joint settings typical of the human case.

5.7.4 Occupant Positioning

Each test device shall be placed in a designated seating position in the following manner: 1. with the test device in an erect sitting position as shown in Figure 1 of SAE Recommended Practice J 963, locate the H-point (SAE J 826a) on the test device pelvis 5.28 inches from the back reference line and 3.84 inches above the seat reference line used in Figure 1 of J 963; 2. center the test device about a vertical plane parallel to the longitudinal axis of the vehicle which passes through the seating reference point; 3. place the test device's head so that its vertical centerline is perpendicular to the vehicle's longitudinal centerline and in a vertical plane parallel to the longitudinal centerline of the vehicle; 4. place the hands on top of the thighs with the palms down and with the elbows resting against the seat back and as close to the body as possible for passenger positions; 5. position the occupant's feet against the vehicle's toepan or, with the leg outstretched as far as practical, position the heel on the floor and the long axis of the foot at 90° ± 20° to the tibia; 6. the long axis of each foot shall be parallel within ±5° to a vertical plane through the longitudinal axis of the vehicle; and, 7. separate the knees and ankles such that a six inch wide rigid block will just fit between them.

5.7.5 Transducers

Any force, velocity, displacement, or acceleration transducers used during the test shall not affect the motion of the test device during impact. The response of the data gathering and recording system shall be flat ±1 db to 1000 Hz. No sensing devices shall be used which have resonance frequencies within this range.

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