DOT HS-801 720

INFLATABLE BELT DEVELOPMENT FOR SUBCOMPACT CAR PASSENGERS
EXECUTIVE SUMMARY

Contract No. DOT-HS-4-00917
September 1975
Final Report

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U.S. DEPARTMENT OF TRANSPORTATION
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16. Abstract

This report summarizes the analyses, design, and testing that were conducted to develop an airbelt restraint system for the subcompact car capable of protecting the passenger in frontal and frontal oblique crashes up to 50 mph. The result of this work has been the development of a rapidly inflating 3-point airbelt mounted to three stroke efficient energy-absorbing belt anchors. The system ultimately proved capable of protecting subcompact car passengers throughout the adult anthropometric size range at velocities exceeding 50 mph. In addition, the finalized restraint system is constructed of components that are oriented toward eventual mass production.

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1.0 INTRODUCTION

This report documents the work conducted on NHTSA Contract DOT-HS-4-00917 "Inflatable Belt Development for Subcompact Car Passengers."

The objectives of this program were:

1. To design a passively operating inflatable belt restraint capable of protecting the full anthropometric size range of right front passengers in the subcompact vehicle in frontal crashes up to 50 mph.
2. To accomplish these goals with a system that is amenable to mass production.

In this program the injury criteria used to determine attainment of the first objective were:

Head Injury Criterion < 1000
Peak Resultant Chest g's < 60 g's
Femur Loads < 1700 pounds

The crash environment specified for this program consisted of:

1. The standard 1974 Ford Pinto compartment dimensions.
2. The crash pulse typical of a subcompact car structurally modified to prevent excessive compartment intrusion and to crush in a stroke efficient manner. We chose the crash pulse of the modified Pinto developed on NHTSA Contract DOT-HS-113-3-746 to fulfill this requirement (Figure 1.1).

For several reasons, the subcompact car presents a crash environment much more severe than standard size cars. The reasons are:

1. Higher average crash pulse g levels due to the relatively low mass of the subcompact car.
2. Reduced compartment volume which decreases the allowable space the passenger has available in the compartment to come to rest.

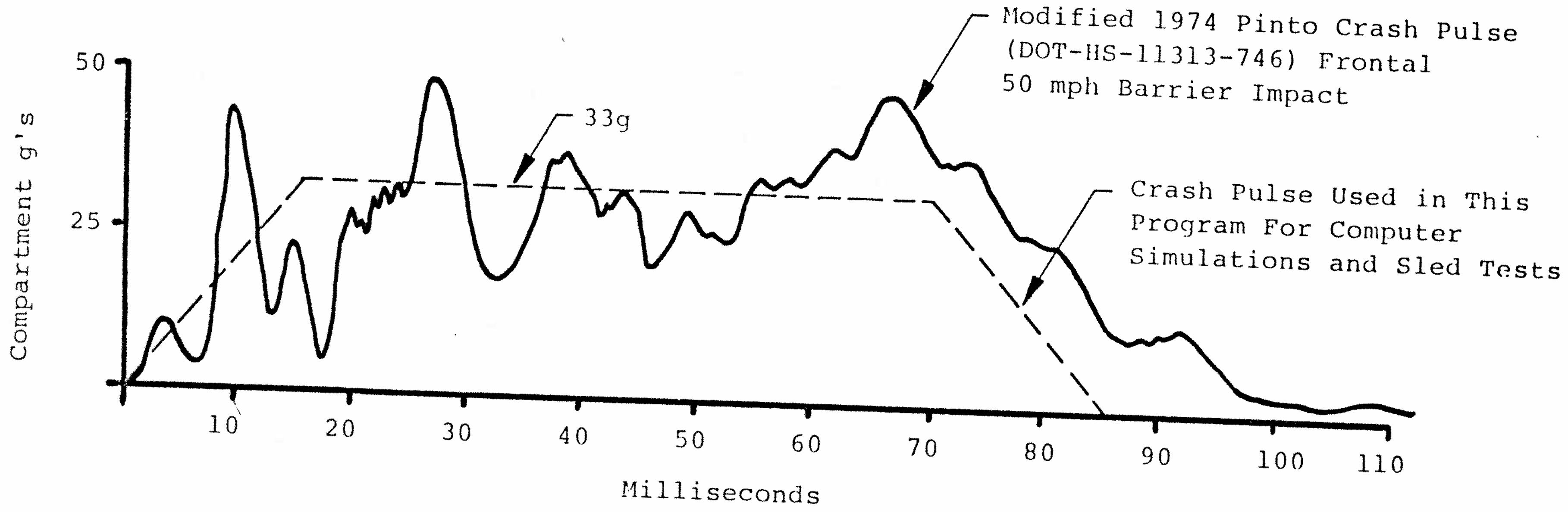

FIGURE 1.1 COMPARTMENT G'S VS. TIME

3. The relatively greater statistical probability of being involved in a high-speed accident. This is due to the fact that in car-to-car accidents, the smaller car has a greater total velocity change than the larger car due to the required momentum exchange between the two unequal mass cars.

In this report we will discuss each of these items in detail and show how the finalized airbelt design overcomes each of these potential problems.

However, prior to discussing the details of the studies, analyses, trade-offs, and testing that went into the development of the final airbelt system, it would be informative to discuss a bit of background that will shed light on the desirability of such a system.

Background

As just mentioned, the subcompact car presents special problems in the design of safety restraint systems. In the last restraint program Minicars worked on for NHTSA (Contract DOT-HS-113-3-742 "Development of an Advanced Passive Restraint System for Subcompact Car Drivers"), we dealt exclusively with the subcompact car crash environment. In this program we learned a number of things that are "musts" when designing the restraint for this particular crash environment. Here we will list those that have a bearing on this discussion.

1. Due to the higher crash pulse g levels experienced in a subcompact car, the restraint must exhibit a low amplification factor on crash pulse g's.

2. The restraint must be relatively insensitive to the crash pulse variability that can be experienced in the realm of the traffic mix in which the subcompact car must operate.

3. Due to the limited compartment space available in the subcompact vehicle, the restraint must be extremely "quick," intercepting the occupant before he picks up a high velocity relative to the compartment.

4. The restraint itself must be stroke efficient with rapid onset to the threshold force level of the restraint system. This means a relatively high airbelt pressure is required. This minimizes stroking space required by the occupant by maximizing the percentage of kinetic energy absorbed in the "ride down" mode.

1.1 The Conventional Belt System

For several reasons, conventional 3-point belt systems fall far short of providing adequate protection under these conditions. Evidence in the form of sled tests and car crash data indicates that at impact velocities above 30 mph* the belted passenger exceeds the injury criteria. To understand the function of the airbelt, it will help to look at some of the reasons for this.

Four things can be identified as primary contributors to reducing the effectiveness of the 3-point belt system at high velocities (greater than 30 mph).

1. The relatively small area over which the lap and torso belt loads are distributed.
2. The lack of head support.
3. Non-yielding belt anchors.
4. Belt slack.

We will take a look at each one of these items.

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* This is based upon the results of the injury measures experienced in testing conventionally belted dummies in the "other car" of the two-car crash tests reported in Section 6.0, as well as recent sled tests conducted by Minicars for Allstate Insurance Company.

Item 1. The rather small area over which the belt loads are applied to the passenger mean that very high contact pressures are applied at critical points. Since the torso belt passes across mid sternum, high pressures bear directly over the heart. Injuries to the heart and actual crushing of the chest are very common with conventional belt systems in high-speed frontal impacts.

To perform as desired, the lap belt should pass over the hips. Often, due to poor belt placement, the lap belt rides up and presses inward on the soft abdominal cavity so that the only solid point of resistance is the backbone. Abdominal organs are violently squeezed and pushed upward into the thoracic cavity.

Item 2. Critical injury can also result from the unsupported head whipping forward during a frontal impact. Here several injuries are possible. First, the uncontrolled head can impact some exterior surface in the compartment such as the windshield, A-pillar, or dash.

Second, the extremely rapid rotation results in very high centripetal acceleration levels applied to the brain. Even without contact with the compartment, the brain can experience g levels on the order of 120 g's just due to this rotational component.

Third, the chin eventually impacts the sternum -- so hard, in fact, that this impact alone can be enough to impart a fatal concussion to the passenger.

Fourth, the neck must react an extremely high tension load as the head rotates forward. This force is sometimes great enough to break the neck in tension.

Items 3 and 4. Non-yielding anchors and the slack in conventional belts combine to produce inefficient usage of the stopping distance or stroke that is available to decelerate the passenger. There are three primary ways these inefficiencies are introduced.

First, the belt slack that is necessary for user comfort prevents the immediate application of decelerative forces being applied to the passenger undergoing the crash. The time that elapses and the passenger forward travel that is used up before the belt slack is taken up (or before the inertia reel locks up), is lost.

Second, since there is not much "give" in the system due to the fixed anchor points, the force applied to the passenger is very violent and of relatively short duration. The body of the occupant is brought up short so that the remaining compartment space available within which to stop the passenger is wasted.

Third, the non-yielding anchors and the elasticity of the belts combine to produce a devastating rebound effect. Since the anchor points are fixed, "give" in the system comes only from elastic deformation of the belt material. Therefore, most of the passenger's kinetic energy is merely <u>stored</u> in the belts and not <u>absorbed</u>. This stored energy is then returned to the occupant in the form of a violent rebound. He is actually propelled backward at a velocity that can approach the original forward velocity, thus increasing the effective velocity of the accident by a substantial amount.

In order to retain the positive features of a belt system, such as its rollover protection, lower cost (as compared to airbags), and mass production features, and to cope with these difficulties, the airbelt was conceptualized.

1.2 The Force-Limited Airbelt

The airbelt is basically a 2-point or 3-point belt restraint modified to inflate upon impact. The anchor points have also been modified to provide a controlled yielding in the system. In the following, we will show how these features of the airbelt promise to solve the high velocity impact problem typical of the conventional 3-point system.

First of all, the belt inflation itself performs three very important functions.

1. The belt contact area is substantially increased, thereby lowering the probability of fracturing the chest or rupturing internal organs.

2. The head is supported by the inflated torso belt capturing the chin and face, thereby preventing substantial forward head rotation.

3. The rapid inflation of the belt takes all belt slack out of the system.

Further, the belt is force-limited due to the installation of energy absorbing units at the belt anchors. This minimizes the effect vehicle crash pulse has on g levels imparted to the passenger.

The project undertaken by Minicars was to design, develop, and test just such a system so that the resulting design met or exceeded the program objectives listed earlier.

2.0 SUMMARY

In this program we conducted the analyses, design, and testing necessary to design a force-limited, passive airbelt restraint system for the right front passenger of a subcompact vehicle which would satisfy the requirements listed in the Introduction. We used computer simulations of the airbelted passenger undergoing specific crash environments to narrow the field of potential restraint designs and to select a preliminary restraint system which we could use to begin the sled test phase of the program. This preliminary design consisted of two separate approaches to meeting the requirements of the contract.

The first approach consisted of a 2-point force-limited airbelt in which the belt portion passed only across the torso of the passenger (Figure 2.1). The upper and lower ends of the inflatable torso belt were connected to force-limited anchors. The lower body kinetic energy was absorbed by a crushable knee restraint.

The second approach was a 3-point version of the airbelt. Here the configuration was much like a conventional 3-point belt system except the torso belt inflates in the crash and each of the three anchors are force limited. In this case, the lower body energy is absorbed by the yielding anchors at each end of the lap belt (Figure 2.2).

The development test series consisted of two phases. Phase I testing had the objective of obtaining a "developmental" design that met the first objective of the program, i.e., minimum injury levels for the range of potential passenger sizes in a sled simulated 50-mph frontal barrier crash.

Phase II testing was structured to take into account those changes mandated by accommodating a passive belt design while, at the same time, maintaining the low injury levels established as possible during the Phase I testing.

We concluded the development sled test phase when we felt the airbelt had been tuned to the greatest degree possible in the sled test crash environment.

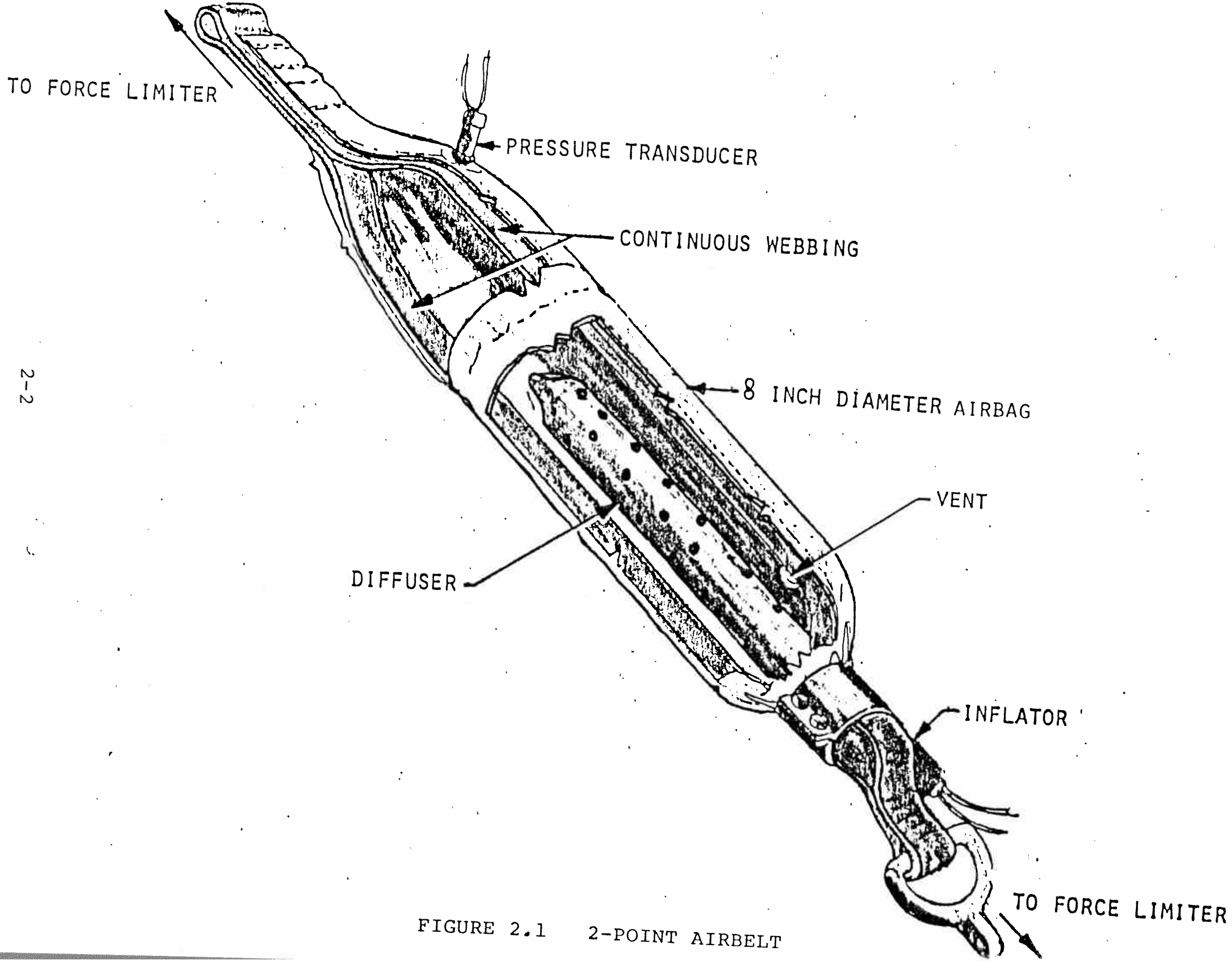


FIGURE 2.1 2-POINT AIRBELT

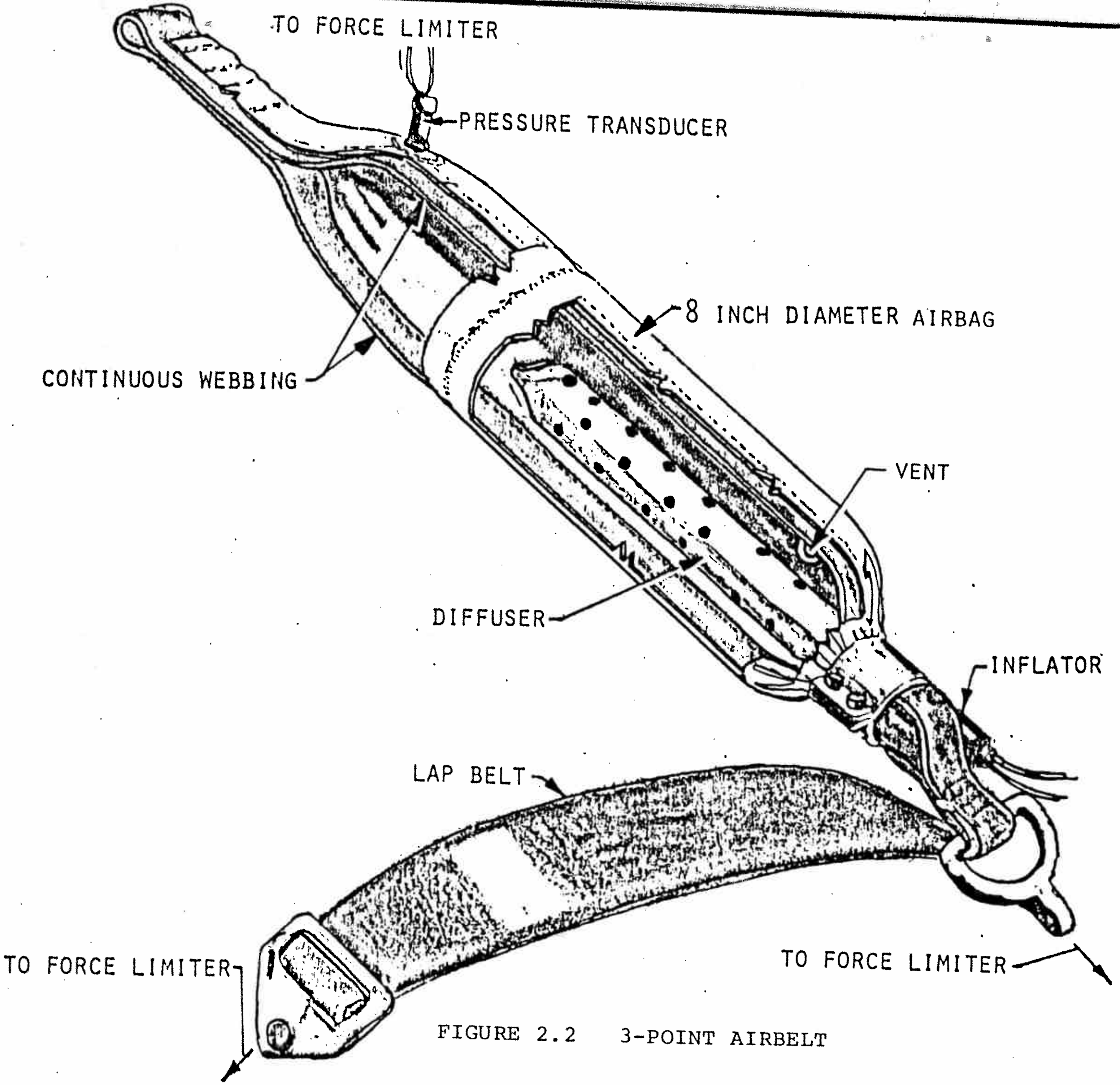


FIGURE 2.2 3-POINT AIRBELT

In order to demonstrate the capability of the finalized restraint to repeatably meet the injury criteria in a variety of crash situations, a series of evaluation tests were conducted.

These evaluation tests were of two basic types. First, a series of sled tests were conducted in which the passenger size, impact velocity, and impact angle were varied. Second, in order to demonstrate restraint performance in an actual crash situation, we installed the airbelt in three structurally modified 1974 Ford Pintos and crashed them in various modes.

Results of the evaluation sled tests are presented in Figures 2.3 through 2.6. From these figures we conclude that the size range from 5th percentile female through 95th percentile male are protected by the airbelt in frontal impacts to impact velocities greater than 50 mph. The six year old child exceeds the allowable criteria at velocities greater than approximately 47 mph.

In oblique impacts, the six year old child, the 50th percentile male, and the 95th percentile male all easily meet the injury criteria. However, the 5th percentile female, for reasons discussed in Section 3.0, slightly exceeded the allowable HIC through head impact with the door window opening.

The three car crash tests are discussed in detail in Section 6.0 of the technical volume. The tests are designated as car crashes 1, 2, and 3 in that report.

Crash No. 1 was a car-to-car crash in which a modified Ford Pinto was crashed into a 1974 Ford LTD at a nominal 80-mph closing velocity. The impact was a full frontal impact across the full width of the cars.

Crash No. 2 was a barrier impact in which the modified Ford Pinto impacted a rigid barrier frontally at 42 mph.

Crash No. 3 was the second car-to-car crash, and again the modified Pinto was crashed into a 1974 Ford LTD at a nominal

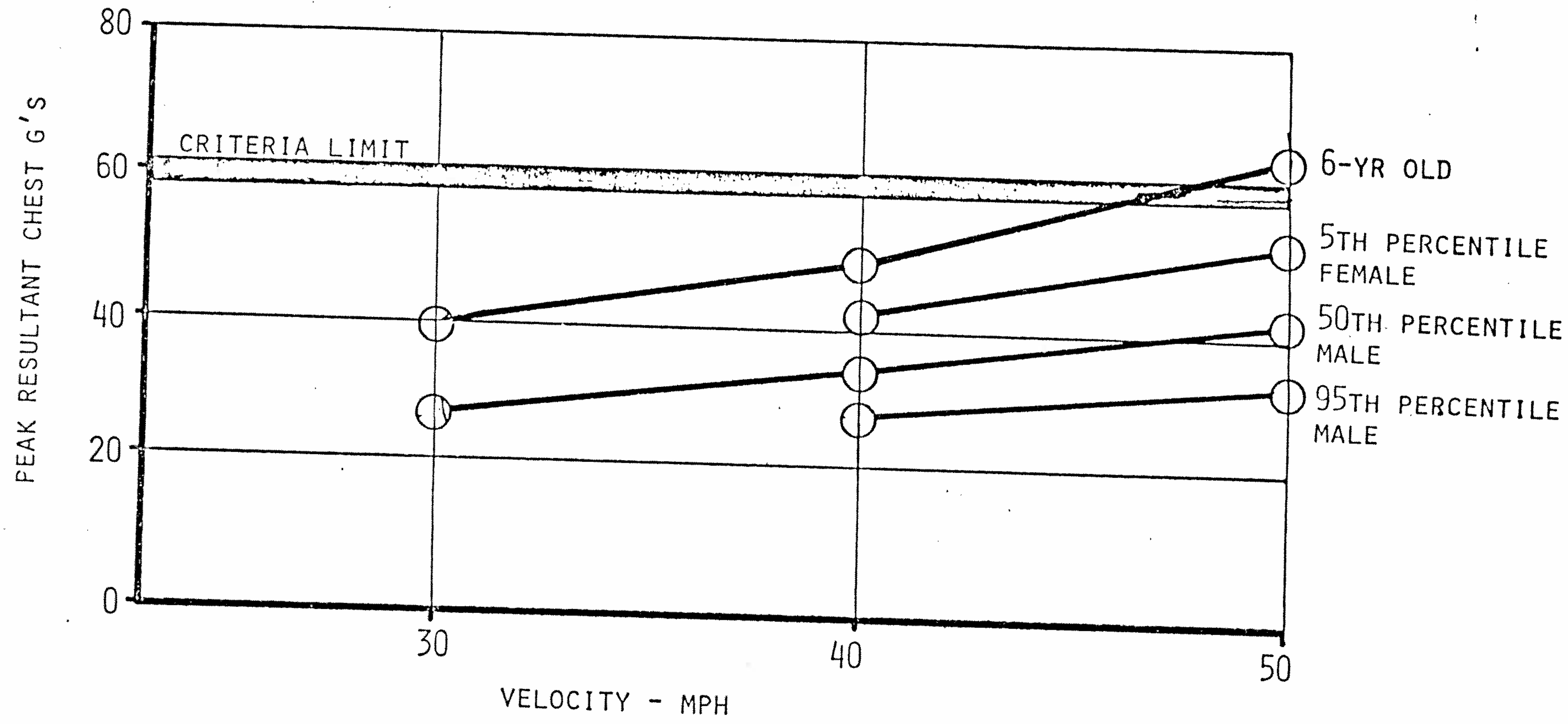


FIGURE 2.4 EVALUATION SLED TEST RESULTS - FRONTAL IMPACT

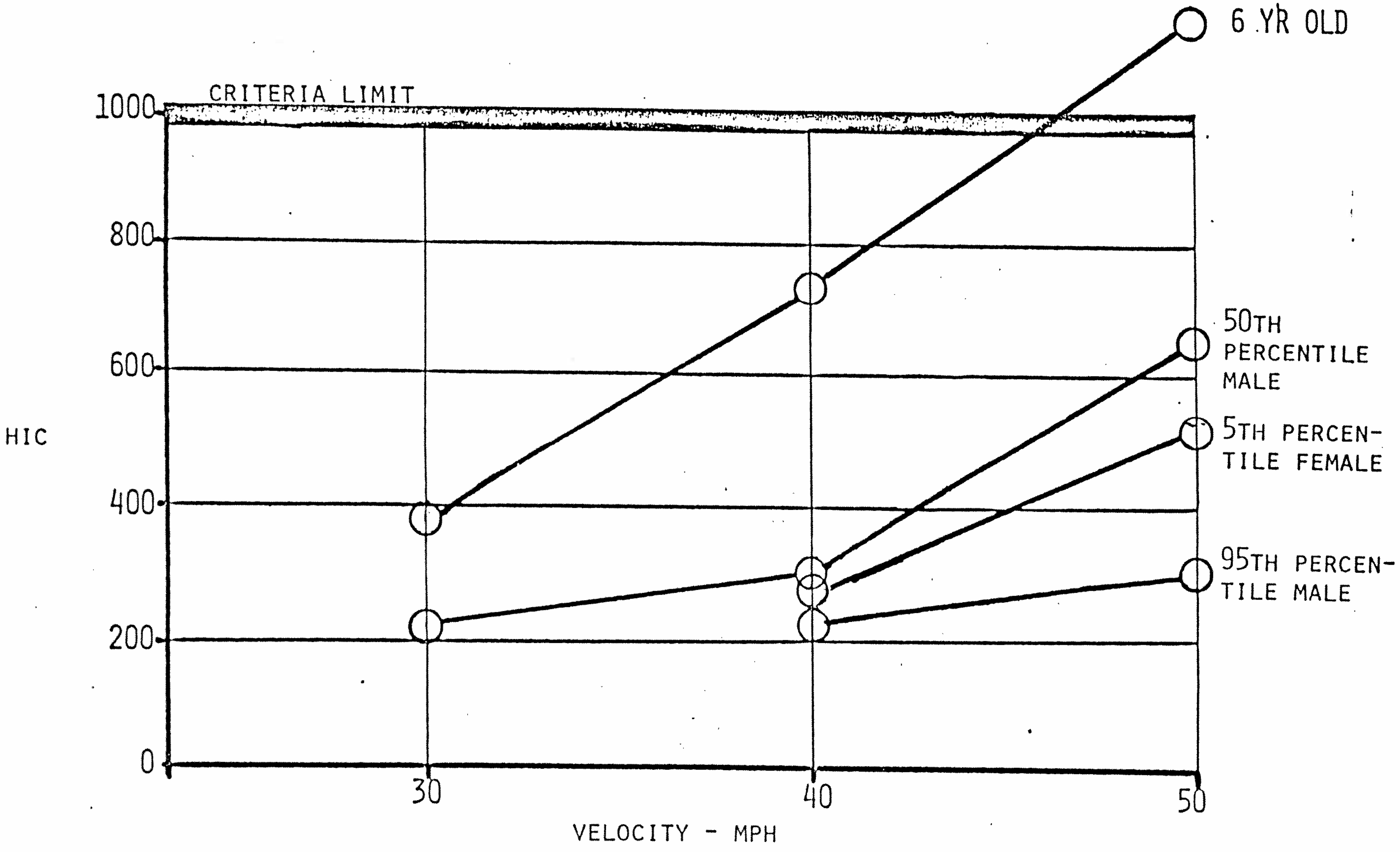


FIGURE 2.3 EVALUATION SLED TEST RESULTS - FRONTAL IMPACT

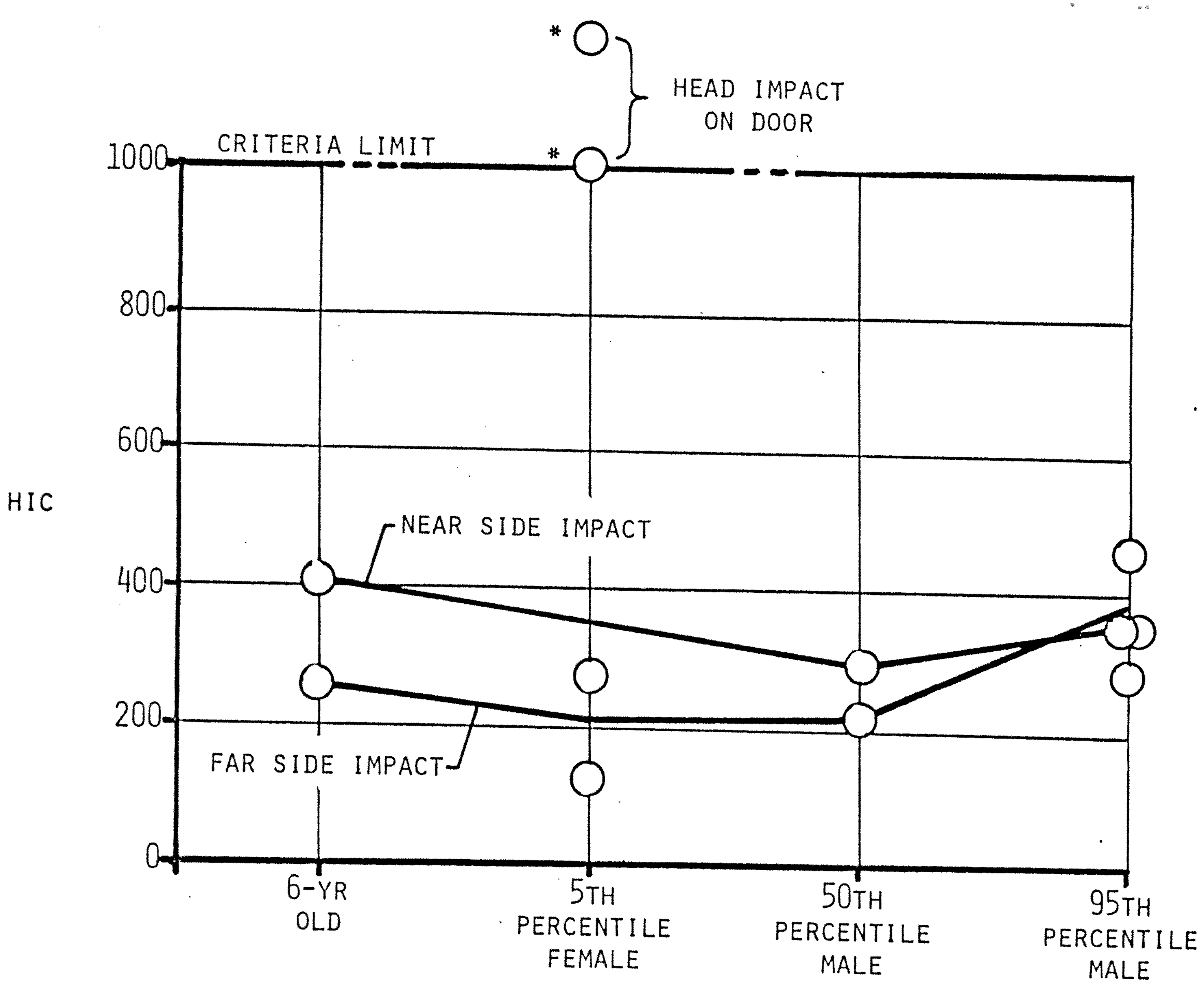


FIGURE 2.5 EVALUATION SLED TEST RESULTS - 38 MPH OBLIQUE IMPACT

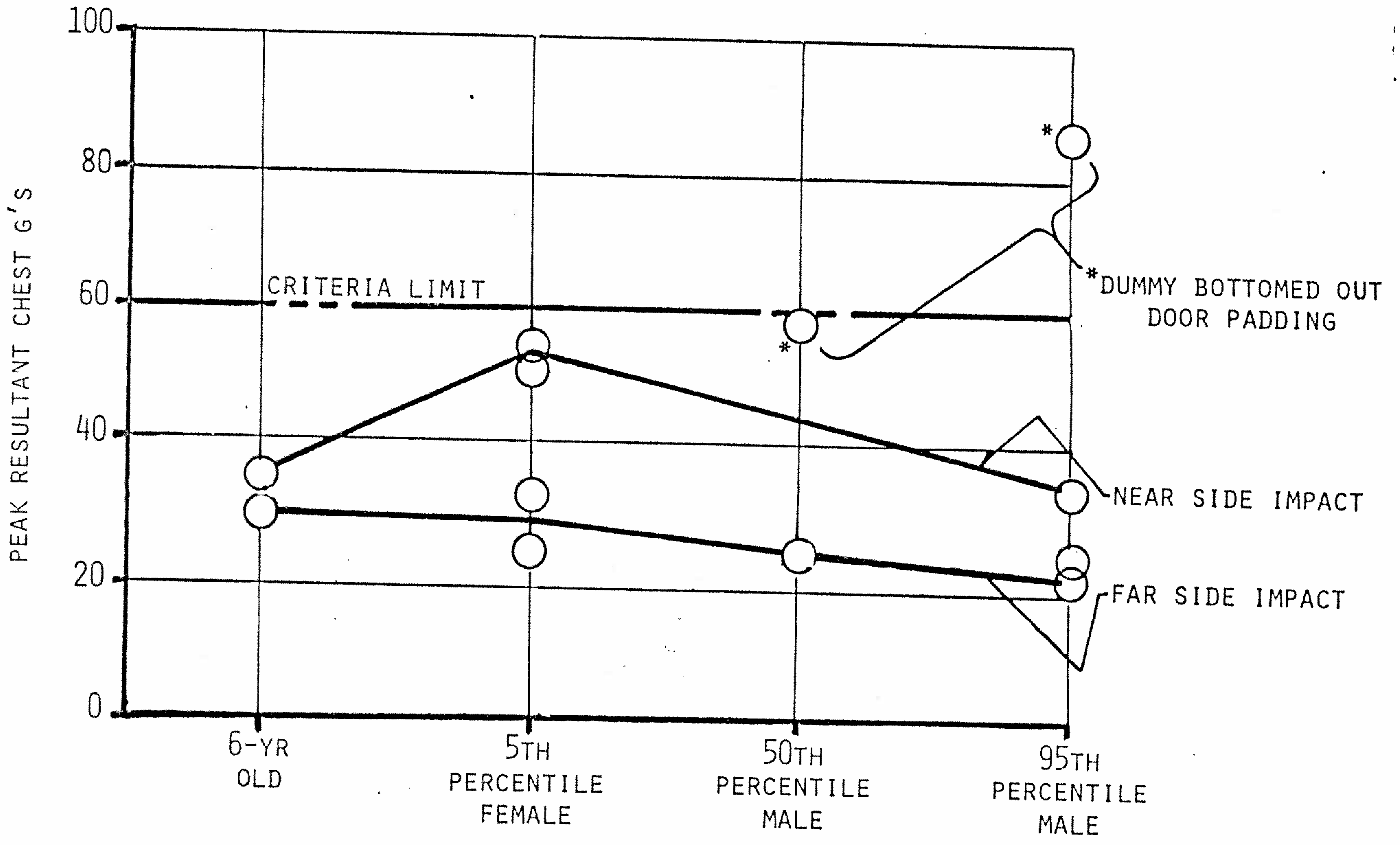


FIGURE 2.6 EVALUATION SLED TEST RESULTS - 38 MPH OBLIQUE IMPACT

80-mph closing velocity. However, this crash was offset frontally so that only one-half of the front of each car contacted the other.

The results of these three tests are shown in Figure 2.7. As can be seen from these results, the airbelted passenger received extremely low injury levels considering the severity of the subcompact car crash environment.

We feel that because of the airbelt's rapid deployment time, its force-limited anchors, and the fact that the inflated torso belt supports the head and results in much lower body contact pressures than conventional belt systems, it has the potential for the lowest injury levels of any restraint system ever developed. We further feel this has been demonstrated by the results obtained in this program.

Figure 2.8 shows the finalized airbelt configuration.

INJURY MEASURE	CRASH NO. 1 FRONTAL CAR-TO-CAR IMPACT ΔV = 55 MPH	CRASH NO. 2 FRONTAL BARRIER IMPACT V = 42 MPH	CRASH NO. 3 OFFSET CAR-TO-CAR IMPACT ΔV = 55 MPH
HIC	549	302	457
PEAK RESULTANT CHEST G'S	44	36	41

FIGURE 2.7 AIRBELT PERFORMANCE - EVALUATION CAR CRASH TESTS

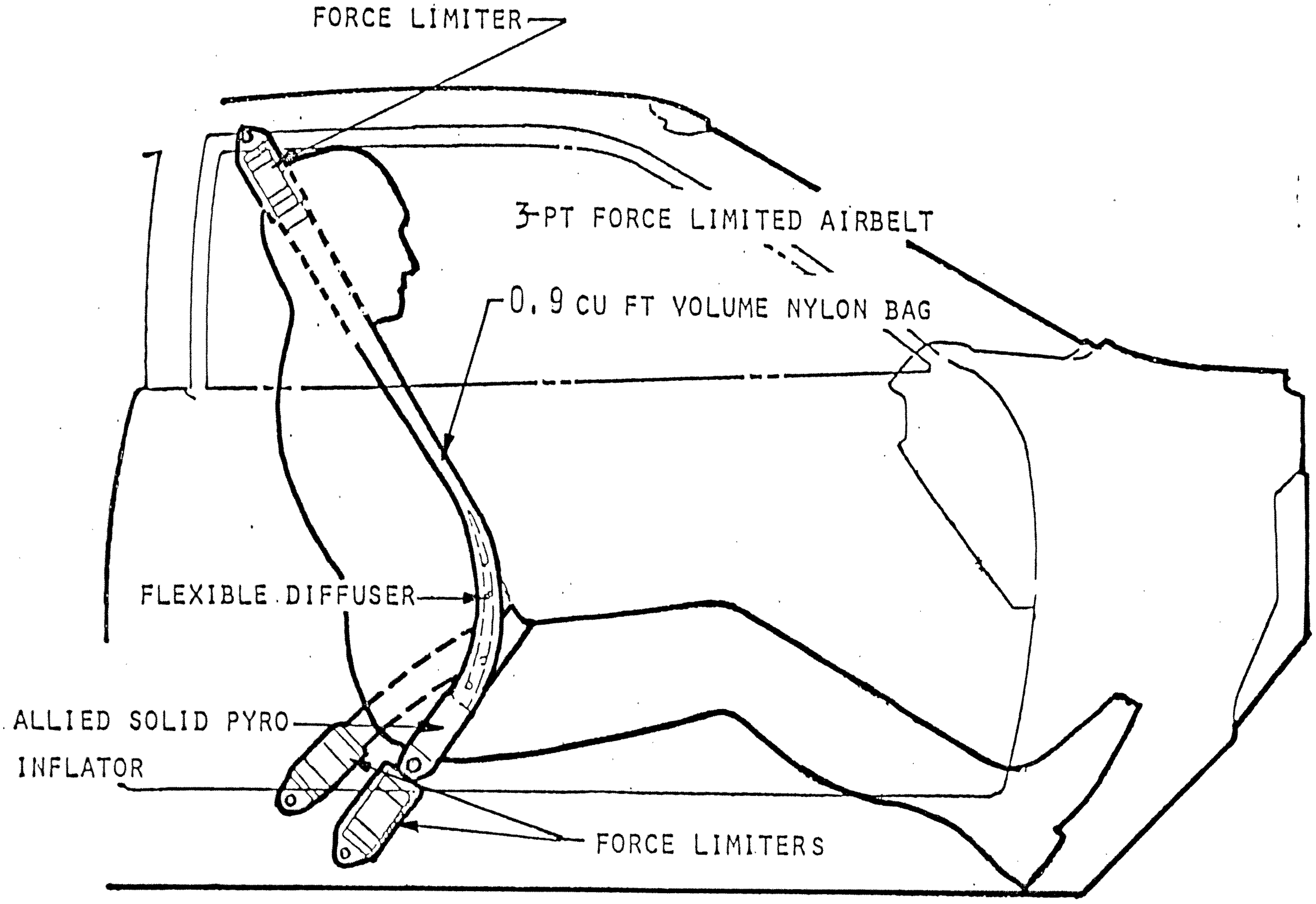


FIGURE 2.8 FINAL DESIGN OF AIRBELT RESTRAINT SYSTEM

3.0 CONCLUSIONS AND RECOMMENDATIONS

During the course of the contract, especially during the test phase, we became progressively conscious of the great potential the airbelt has for reducing the degree of passenger injury and, therefore, societal cost of accidents. First, during the analytical phase of the contract, we began to see that the combination of the rapid inflation, low stroking mass, and force limiting aspects of the belt system had great potential for reducing vehicle occupant injury levels to values lower than any other system with which we were familiar. The reasons for this are discussed in detail in Section 4.2.2 of the technical volume. Briefly, they have to do with the fact that the g amplification common to most restraint systems can be virtually eliminated by proper design of the force limiters attached to the airbelt at each anchor point.

Once this had been shown by computer simulation of the crash environment, we were eager to verify the analytical predictions during the sled test phase.

During the test phase and through the remainder of the program, we were able to verify our analytical technique as well as to arrive at certain conclusions regarding the airbelt design, which we will discuss in the following.

3.1 Conclusions

1. The force-limited 3-point airbelt restraint system will meet the injury criteria for the anthropometric size range of passengers from 5th percentile female to 95th percentile male in frontal impacts to velocities substantially greater than the required 50 mph. This is based upon sled test and car crash test results in which the injury measures were well below the criteria limit, with room available in the compartment for additional stroke of the passenger (Figures 2.3, 2.4, and 2.7).

2. The six year old child is protected to approximately 47 mph in frontal impacts. At velocities above 47 mph, both the HIC measure of injury and the peak resultant chest g levels exceed the criteria limits of 1000 and 60 g, respectively (Figures 2.3 and 2.4).

3. The six year old child, 50th percentile male, and 95th percentile male all easily met the injury criteria in 38-mph 30-degree oblique impacts from both the near (1 o'clock) and far (11 o'clock) sides of the vehicle (Figures 2.5 and 2.6). However, the 5th percentile female meets the criteria for far side oblique impact only. In near side impacts, the head rotates toward the door window opening and eventually contacts the door at the point where the window rolls in and out of the door. This phenomenon is peculiar to the 5th percentile female only since the 50th and 95th percentile males sit high enough in the seat that their head does not rotate over far enough to contact the door. In contrast, the six year old child sits low enough in the seat that his head is below the door window opening and, therefore, impacts the padded door so that his injury measures are quite low.

4. The standard seat locations provided in the Ford Pinto are adequate in providing sufficient stroking room to bring all passenger sizes safety to rest in 50-mph frontal impacts.

   This conclusion is based upon the 95th percentile male in the aftmost seat position having approximately 4 to 6 inches stroking room remaining, the 50th percentile male having approximately 10 to 12 inches remaining from the midseat adjustment position, and the 5th percentile female and six year old child having even greater amounts of available stroking room remaining from any seat position.

5. The standard Pinto anchor points with which we began the program were judged to be inefficient from a stroke efficiency standpoint. We found the angle from horizontal to the line of action of the belt to be too high to provide a major decelerative force to the passenger

in the initial stroking stages of the crash event. We therefore changed the belt anchor locations to obtain a more stroke efficient system (Figure 5.3). This change also substantially reduced the belt forces required to adequately restrain the passenger due to the more favorable belt angles.

6. Both the 2-point and 3-point airbelt restraint systems were capable of meeting the injury criteria. However, the 2-point system was very sensitive to the placement of the belt on the dummy. If the torso belt were not placed on the dummy exactly the same way every time, the dummy would move erratically during the crash -- sometimes rotating almost completely out of the restraint. Since the 3-point system did not exhibit this instability, we judged the 3-point system to be superior to the 2-point system.

7. The finalized airbelt restraint system is entirely producible in quantity by conventional mass production techniques. We base this conclusion on the fact that the components comprising the system are either off-the-shelf items themselves or are of very simple, easily fabricated construction.

8. The energy-absorbing belt anchors (force limiters) attenuate the g levels that otherwise would be transmitted to the passenger through the compartment. G amplification to the passenger through the restraint is very low, with the force limiters acting as filters to prevent crash pulse functions and spurious "g spikes" from reaching the passenger.

   This amplification factor, i.e., the ratio of torso acceleration level to vehicle compartment acceleration level, varies with restraint mass, relative velocity of the driver with respect to the impacted restraint, and the effective spring rate for the airbelt restraint. It is this effective spring rate of the restraint that is reduced by the addition of the force limiters.

9. The restraint system is relatively insensitive to variations in crash pulse. We base this conclusion on the fact that in the frontal sled tests, the oblique sled tests, and the three car crash tests in which different crash pulses were obtained, the restraint system performed very consistently with very similar injury levels measured in these tests (Figures 2.3 through 2.7).

3.2 Recommendations

1. Additional sled testing with some force limiter adjustments are required to lower the injury levels for the six year old child, while maintaining the overall low injury levels for the larger passenger sizes. By increasing the length of the low force regime of the force limiter, it should be possible to meet this objective within a few sled tests.

2. The force-limited, but not inflated, 3-point belt will meet the injury criteria at 50-mph frontal impact (Figure 5.5 of the technical volume), but head injury levels and contact pressures are higher with this system than for the airbelt. However, since this version is less expensive than the airbelt, a favorable benefit-cost relationship may be possible. We therefore recommend that a study be initiated to determine which of these two belt systems will result in the greatest overall safety payoff (benefit minus cost) for society.

3. Although the 3-point airbelt is entirely producible on a mass production basis just as it is, we feel there are certain areas where the belt system can be made even more producible. Some of these are:

   A. Force limiting methods, besides the type-roller mechanism described in this report, should be investigated to ascertain whether the desired force-stroke relationships can be obtained with an even simpler mass producible system.

B. The passive version of the 3-point airbelt should be tested by a statistical sample of people to ascertain:

1. How well they like the system.
2. How well the system accommodates the anthropometric size range of passengers (we did some work on this, but more work should be done).
3. The potential usage rates.
4. Their suggested improvements.

C. The inflator performs the function of filling the belt with the proper amount of gas in the required time; however, we recommend that additional testing outside the scope of this contract be conducted to verify performance of the inflator in other areas such as:

1. Stability of performance in a variety of environmental conditions.
2. Statistical probability of reproducible performance.
3. Shelf life.

In addition, the inflators used in this program were "work horse" inflators that could be reloaded a number of times. In the interest of making the system less massive and cheaper to produce, a new lightweight, non-reloadable case should be designed.

4.0 FINALIZED AIRBELT RESTRAINT SYSTEM

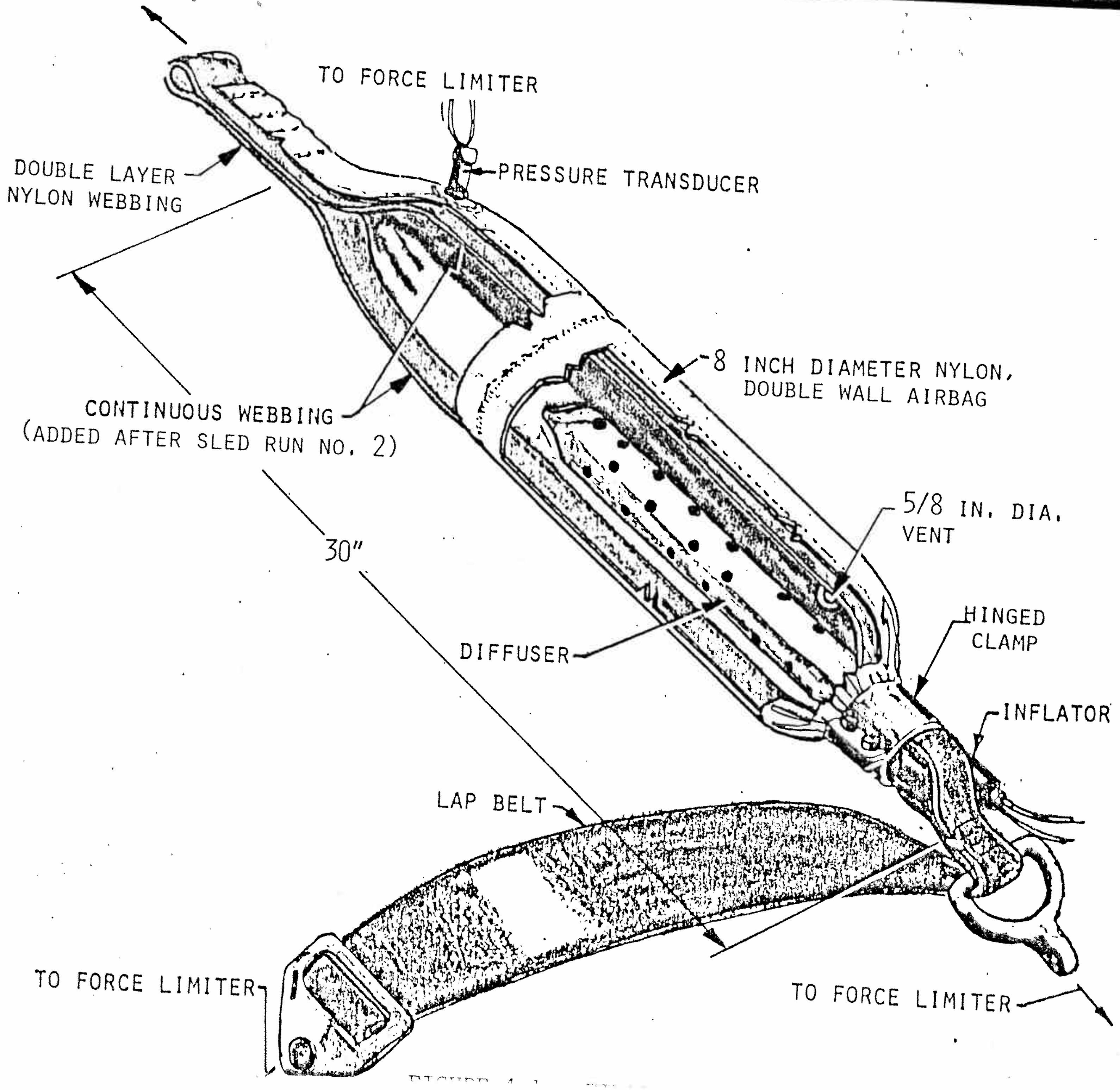
4.1 The Airbag

The airbag portion of the airbelt is that portion that inflates upon impact. In the case of the finalized version of the Minicars' airbelt design, only the torso belt inflates. This inflated section is 30 inches long by 8 inches in diameter and is constructed of two layers of nylon material. Figure 4.1 shows a schematic of the airbag portion of the airbelt. Running longitudinally along two sides of the inflated cylinder are strips of conventional seat belt webbing. This webbing is continuous, as shown in the figure, and eventually joins and is sewn together as a double layer to form the lap belt and the connecting webbing to the upper force limiter and belt anchor.

Located in the airbag portion of the airbelt is a 5/8-inch diameter vent which attenuates rebound by dissipating a portion of the stored compressive energy in the gas. Inside the airbag and attached to the inflator is a diffuser. The purpose of the diffuser is, of course, to distribute the incoming gas to various areas of the bag in order to prevent a large local hot gas jet from burning a hole in the bag. The diffuser is constructed of radiator hose, 1-3/4 inches inside diameter and 16-1/2 inches long with 3/8 inch diameter holes punched on 2-inch centers. One end of the hose fits over the inflator nozzles, while the other end is pinched with a rivet so that two holes are formed in the end of the tube.

4.2 The Inflator

The inflator selected for use in this program was a pryotechnic inflator as opposed to a stored gas inflator. The reason for this selection was discussed extensively in the proposal Minicars prepared prior to the award of this contract.


TO FORCE LIMITER
DOUBLE LAYER NYLON WEBBING
PRESSURE TRANSDUCER
CONTINUOUS WEBBING (ADDED AFTER SLED RUN NO. 2)
8 INCH DIAMETER NYLON, DOUBLE WALL AIRBAG
30"
5/8 IN. DIA. VENT
DIFFUSER
HINGED CLAMP
INFLATOR
LAP BELT
TO FORCE LIMITER
TO FORCE LIMITER

Very briefly, the reasons were twofold. First, a stored gas system is prone to gas leakage, especially so since the required gas pressures are so high (approximately 4,500 psig). Second, the combined effect of the inflator's high pressure and low volume make the flow duration of a stored gas system very short. In fact, approximately 10 milliseconds after the initiation of gas flow, the gas flow rate has already decreased to practically nothing. After this time, the gas is venting from the bag with no additional flow coming in so that the bag contains less and less total gas. This effect reduces the gas available for supporting the head when the head begins to rotate forward significantly at approximately 50 to 60 milliseconds into the crash event. Thus, for a stored gas system, the flow into the bag is not phased well since there is no gas flow when the gas is actually needed.

In contrast, the pyrotechnic system reaches its maximum rate of gas flow later in the event when the gas pressure in the inflator case reaches its maximum value. For the inflator and propellant chosen for the airbelt in this contract, this occurs approximately 40 milliseconds after squib initiation. Therefore, the pyrotechnic inflator gas flow is more nearly synchronized with the passenger requirements than is the case with a purely "blowdown" system, i.e., the stored gas inflator.

Figure 4.2 shows a photograph of the inflator. The inflator itself is 4 inches long and 1-3/4 inches in diameter, containing 60 grams of propellant.

4.3 Force Limiters

The primary energy absorbers in the restraint system are the force limiters -- one at each of the three belt anchor positions. Figure 4.3 shows a general sketch of the force limiters, while Figure 4.4 shows the dimensions of the three energy absorbing metal tapes that are matched with the appropriate force limiter at each anchor position. The roller diameters for the lap belt force limiters are 5/8 inch, while the roller diameter for the upper anchor is 3/4 inch. There are three rollers in each of the three force limiters.

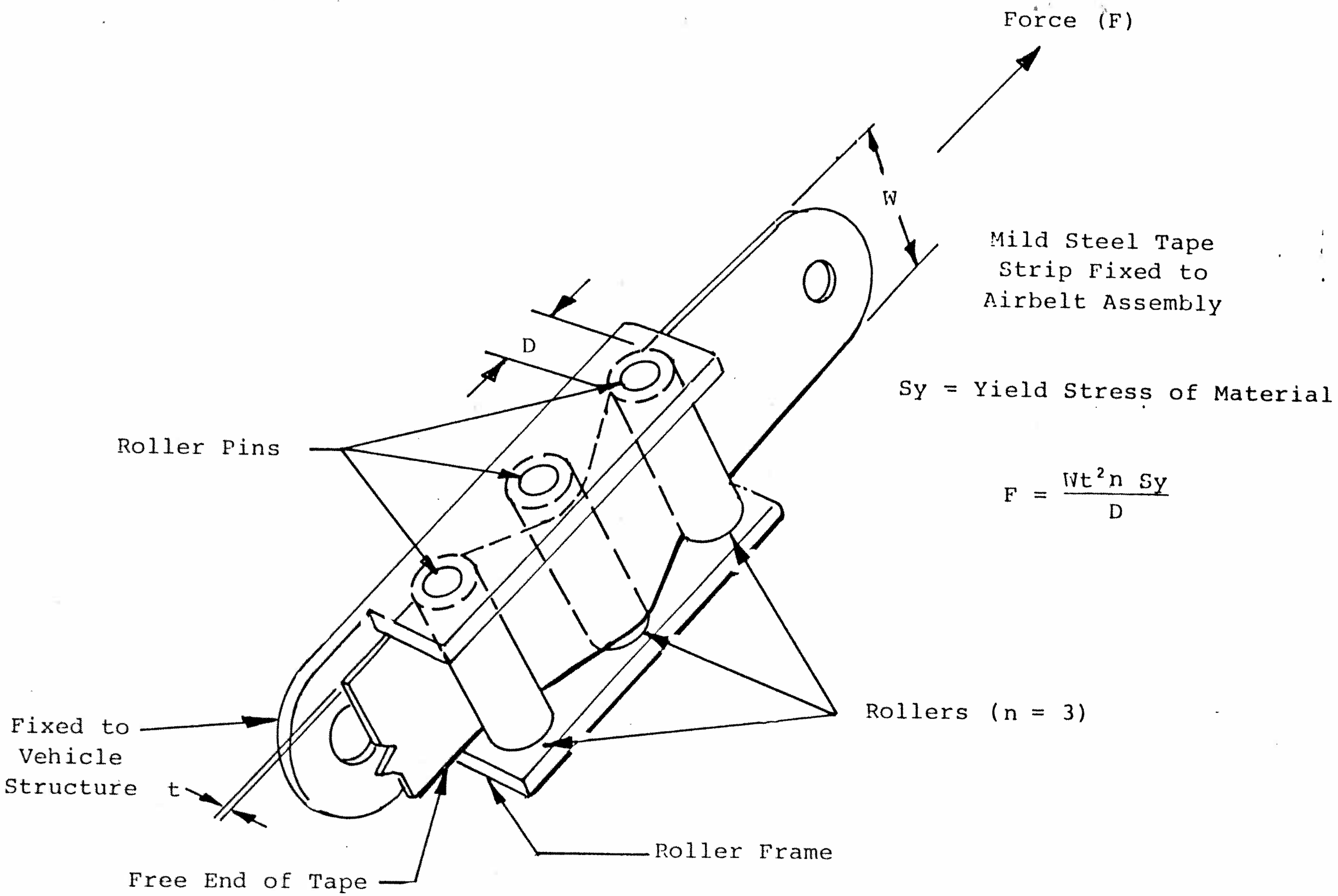
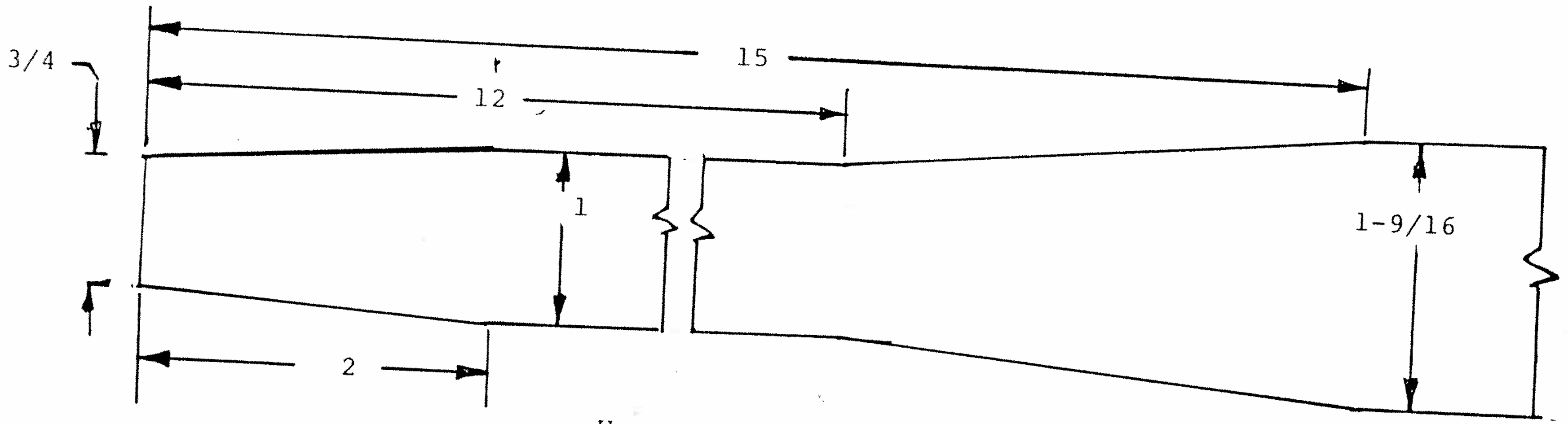


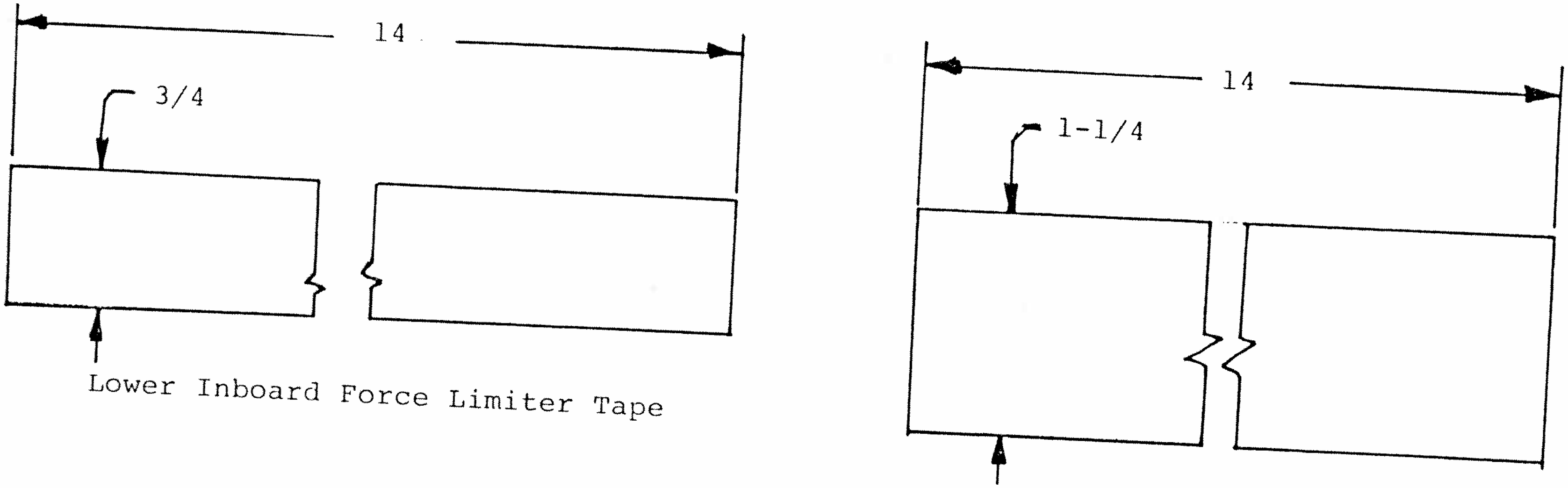
FIGURE 4.3 FORCE LIMITER

FIGURE 5.7 AIRBELT INFLATOR



Upper Force Limiter Tape

Note: All three tapes are .075 inches thick.



Lower Inboard Force Limiter Tape

Lower Outboard Force Limiter Tape

FIGURE 4.4 FORCE LIMITER METAL TAPES

The force-stroke properties of the finalized force limiters are shown in Figures 4.5 through 4.7. The reason the force at the lower outboard location is higher than the force at the lower inboard location is due to the fact that the lower outboard force limiter must react not only a portion of the lap belt load, but also the force transmitted through the lower part of the torso belt.

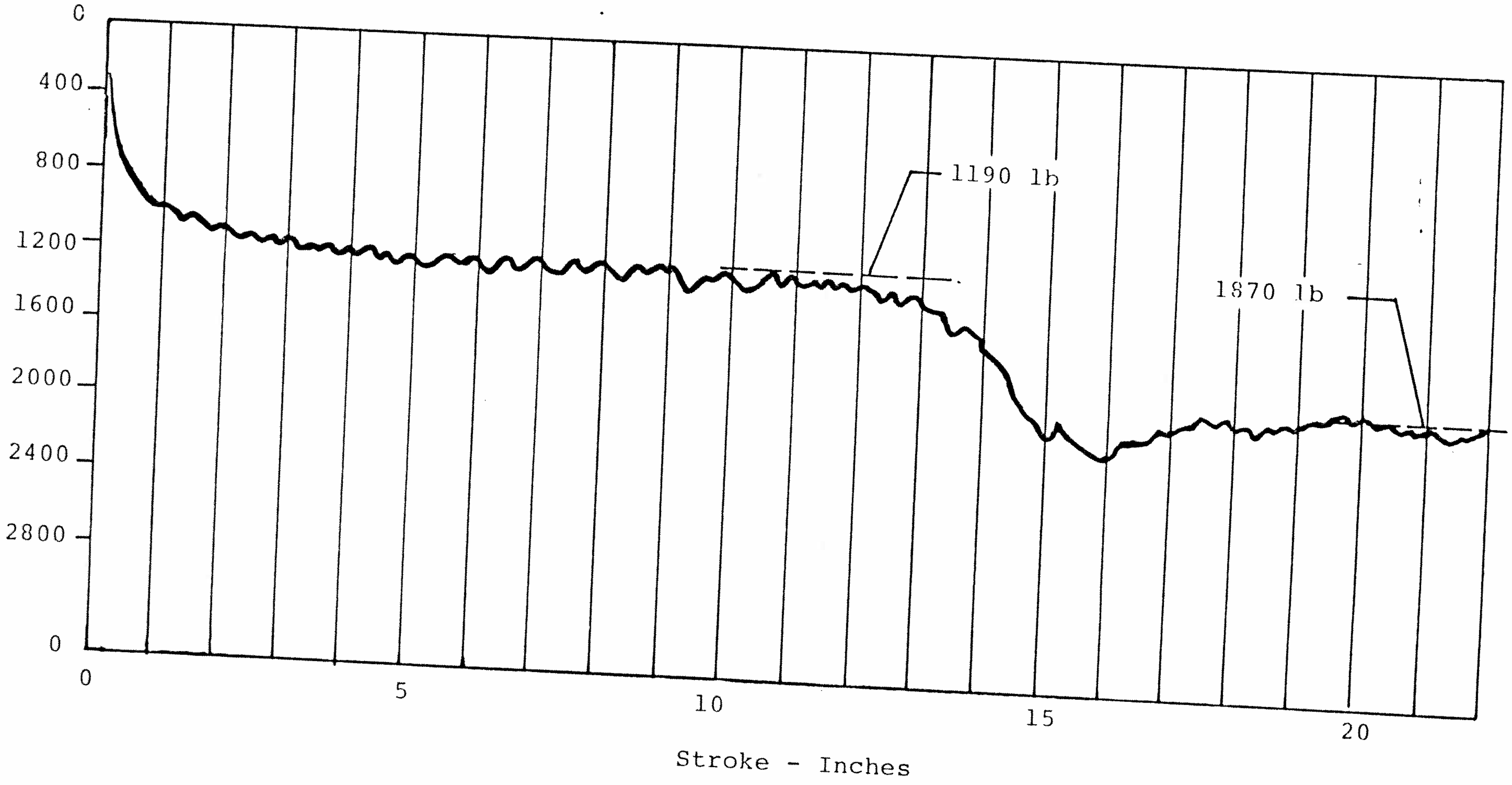


FIGURE 4.5 FORCE-STROKE CHARACTERISTIC - UPPER FORCE LIMITER

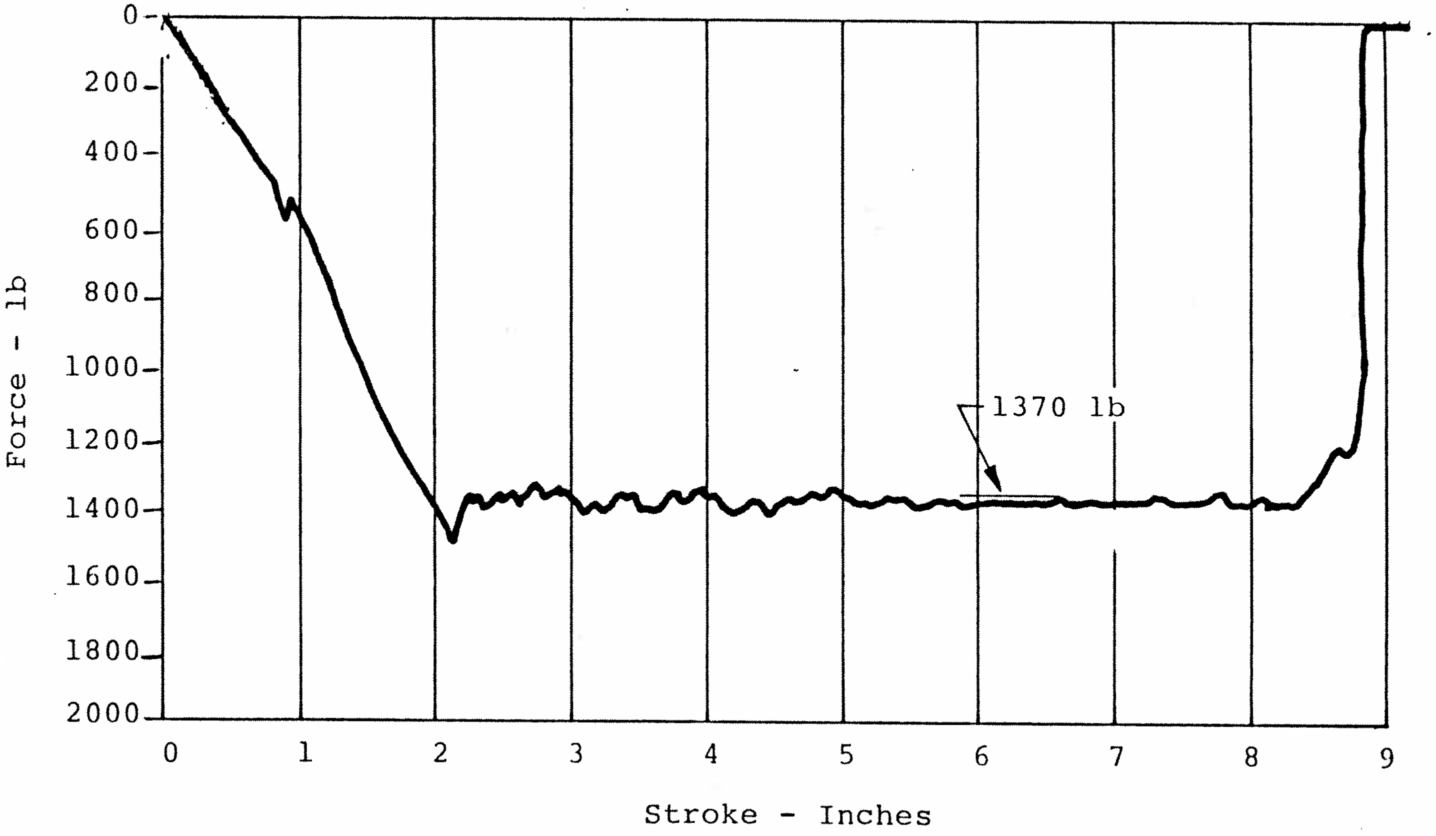


FIGURE 4.6 FORCE-STROKE CHARACTERISTIC - LOWER OUTBOARD FORCE LIMITER

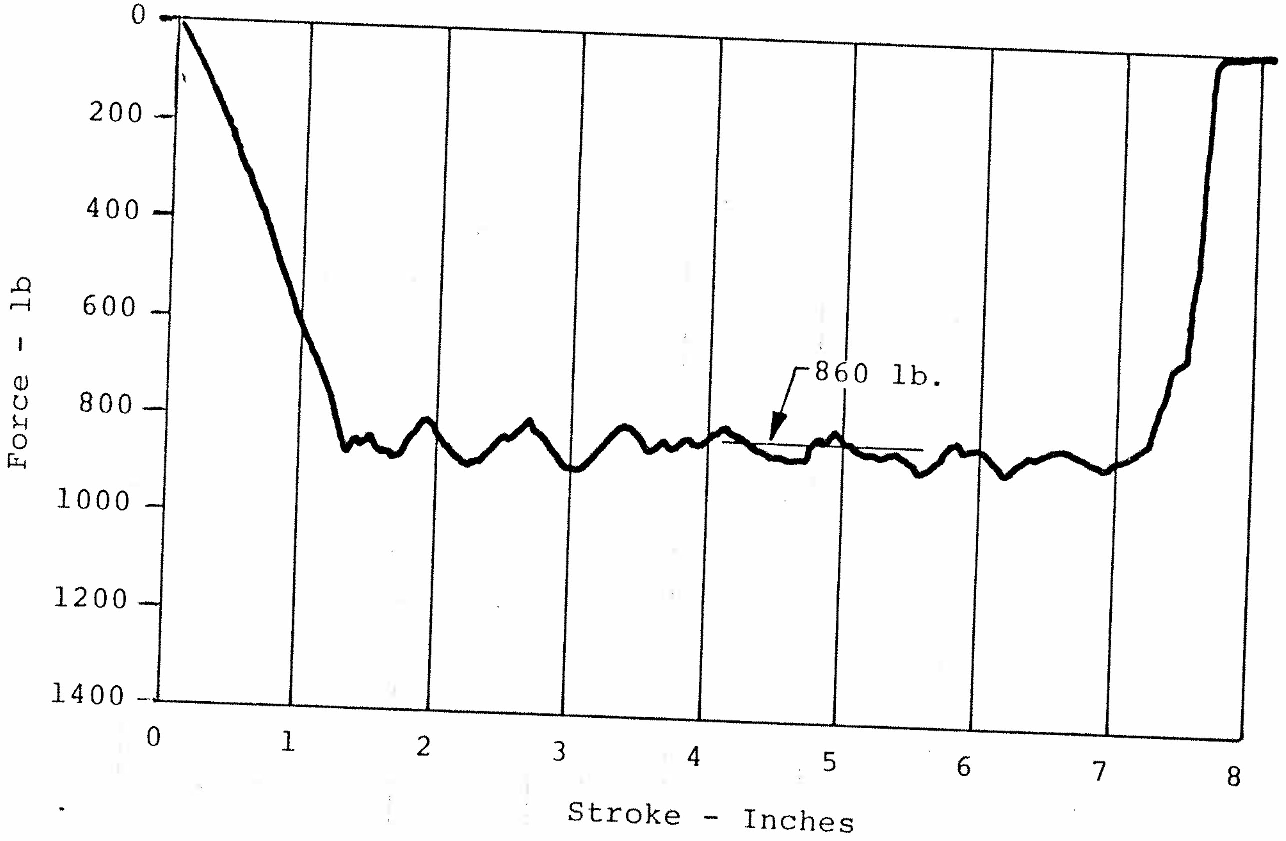


FIGURE 4.7   FORCE-STROKE CHARACTERISTIC - LOWER INBOARD FORCE LIMITER