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INFLATABLE RESTRAINT CONCEPT FOR GENERAL
AVIATION AIRCRAFT

BETA INDUSTRIES, INCORPORATED

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MAY 1973

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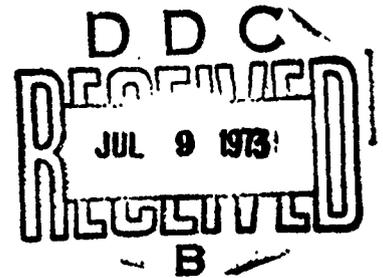
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INFLATABLE RESTRAINT CONCEPT FOR GENERAL AVIATION AIRCRAFT

Richard W. Carr
Norman S. Phillips



MAY 1973



FINAL REPORT

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INTRODUCTION

Inflatable occupant restraint systems have been investigated with great intensity over the past few years due to their tremendous potential in protecting vehicle occupants during an accident or crash situation. The inflatable restraint or airbag has the advantage of being a passive system since it does not require the occupant to engage any hardware devices, and it also has the capability of providing more protection than conventional restraint harnesses. By furnishing a greater surface area over which to apply a restraining force, the injury potential to the seated occupant is reduced and greater protection is afforded him in severe crash environments.

Much of the data and information currently available on airbag systems pertains to their application as an automotive restraint system. However, several test programs have been conducted by NASA and the FAA which investigated the use of inflatable restraint systems as occupant protection devices in aircraft crash environments. The results of these tests indicate a considerable potential for airbag restraint systems and the need for more engineering development and study. A series of tests recently conducted by the FAA (Ref 1) using an automotive airbag system installed in a general aviation fuselage, indicated such improvements in crash survivability and energy absorption capability that the FAA felt it essential to continue the development of an inflatable restraint system for use in general aviation aircraft. Therefore, a program was initiated to investigate inflatable restraint systems and develop a concept for use in general aviation aircraft.

The objectives of this program were

- ... to conduct a literature search for crash test reports and define a survivable crash profile for general aviation aircraft.
- ... to investigate all inflatable restraint systems presently available and being developed to determine each system's advantages and disadvantages.

- ... to conduct a literature search on studies to determine the optimum energy absorption characteristics for attenuation for both longitudinal and vertical crash loads.
- ... to determine design goals for an inflatable restraint system for general aviation aircraft.
- ... to develop a concept of an inflatable restraint system that will meet the design goals, not interfere with any operational requirement of the aircraft, and have a minimum of maintenance and deployment difficulties.

The program conducted to meet these objectives required three phases of effort. These were data collection, establishment of design goals, and concept development. The first phase consisted of collecting data on crash acceleration profiles, inflatable restraints, energy attenuation criteria, and airframe dimensions. With this information and available human tolerance data, it was possible to determine design goals for inflatable occupant restraints that could be used in general aviation aircraft. Once the design goals were established, airplane cabin dimensions and inflatable system performance specifications were used to develop an airbag restraint concept for general aviation aircraft.

The approach used in developing this concept was to study inflatable restraint systems and their interaction with a seated occupant, restrained by a lap belt, in a general aviation crash environment. The dynamic response of the occupant-inflatable restraint system was theoretically calculated and used to determine the best characteristics for an airbag restraint system and the feasibility of using this type of restraint in general aviation aircraft. The results indicate that inflatable restraints would adequately protect a seated occupant in a general aviation aircraft from a very severe crash load. This substantiates the findings of previous investigators such as R. G. Snyder

(Ref 2) who found "The overall evaluation of the airbag concept suggests that it offers potentially far greater protection than that provided by other systems tested" and C. C. Clark (Ref 3) who concludes "Analytical examination and experimental crashes in aircraft and crash simulator devices indicate excellent additional protection would be provided by the airstop restraint".

An inflatable restraint system offers the general aviation occupant the following advantages.

It reduces the restraint loads.

It is passive; it requires no decision on the part of the occupant.

It is an energy absorption device.

It is a versatile restraint mechanism; many airbag geometries are possible.

The use of an airbag restraint requires that noise level, gas toxicity and cabin pressure not be injurious to the occupants. The results of numerous tests of each of these parameters indicate that levels below human tolerances can be obtained. However, for a particular inflatable restraint these parameters should be measured in an actual operating environment to insure that human tolerance levels are not exceeded.

It should also be mentioned that apparent disadvantages of airbag restraints such as cost, complexity and weight are not unique to an inflatable system. If aircraft occupants are going to be protected from severe crash loads, then energy absorption devices of some kind are required and the addition of these devices in a general aviation aircraft is going to increase cost, complexity and weight. In fact, mechanical devices may increase these factors by a greater amount than an airbag restraint system.

DISCUSSION

LITERATURE SEARCHES

Crash Profiles

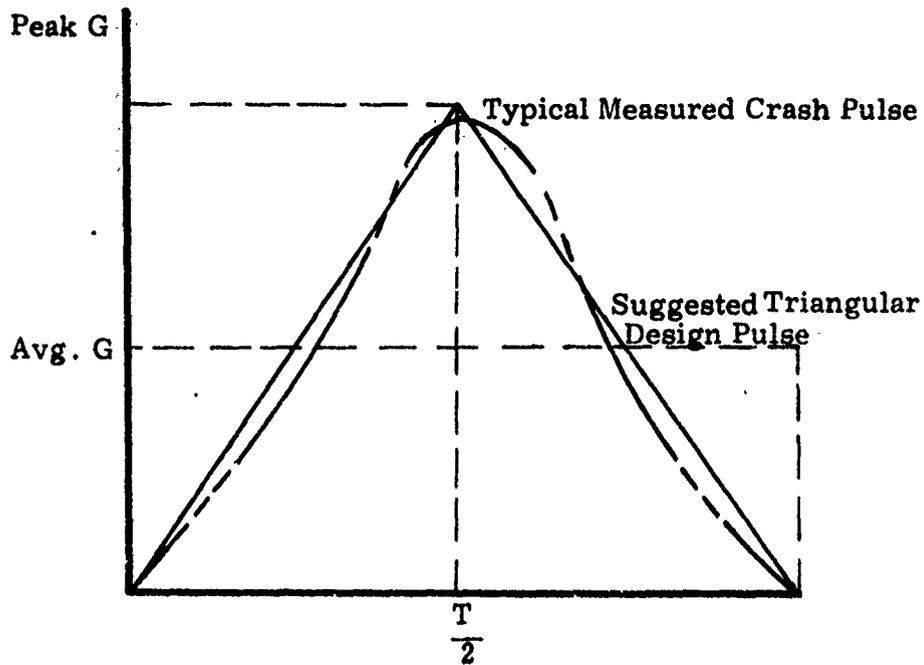
In recent years several studies have been conducted to define the crash environments experienced by aircraft on impact. The results of some crash tests and accident investigations that pertain to general aviation aircraft are contained in the following reports:

"Crash Survival Design Guide" USAAMRDL-TR-71-22, U. S. Army Air Mobility Research and Development Laboratory, Ft. Eustis, Virginia, Oct 1971.

"A Summary of Crashworthiness Information for Small Airplanes," FAA No. FS-70-592-120A, Flight Standards Technical Division, Federal Aviation Administration, Oklahoma City, Okla., Feb 1973.

In addition to these reports numerous other publications which contained related information were examined. All of the reports studied on this program are listed in the Bibliography.

The "Crash Survival Design Guide" (USAAMRDL-TR-71-22) has compiled existing crash data and determined the statistical distribution of crash accelerations for light fixed wing aircraft. The vertical and longitudinal design pulses for the 95th percentile accident for light fixed wing aircraft are shown in Figure 1. Crash acceleration waveforms from full scale crash tests of light aircraft are given in the "Crashworthiness Design Handbook". The longitudinal and vertical accelerations from the highest velocity impacts are shown in Figures 2 and 3. A comparison between the design crash pulses and the crash acceleration waveforms indicated the triangular design pulse was at least as severe as the measured accelerations. The design crash pulses also have a known frequency of occurrence and represent a general



95th Percentile Crash Accelerations				
Impact Direction	Velocity Change (fps)	Peak G	Average G	Pulse Duration "T" Second
Longitudinal	50	30	15	0.104
Vertical	42	48	24	0.054

Figure 1. Design Crash Pulses for General Aviation Aircraft

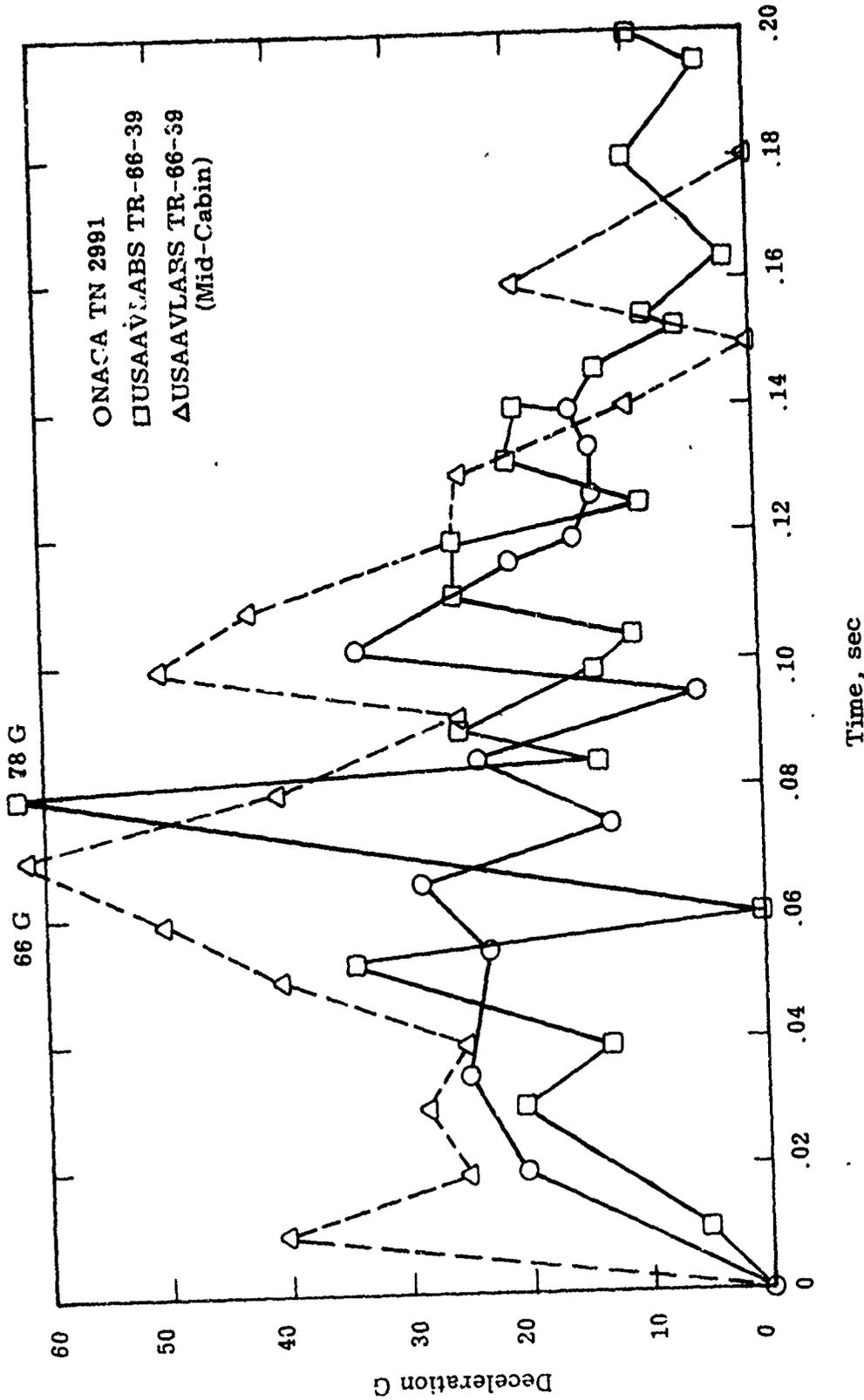


Figure 2. Longitudinal Crash Decelerations

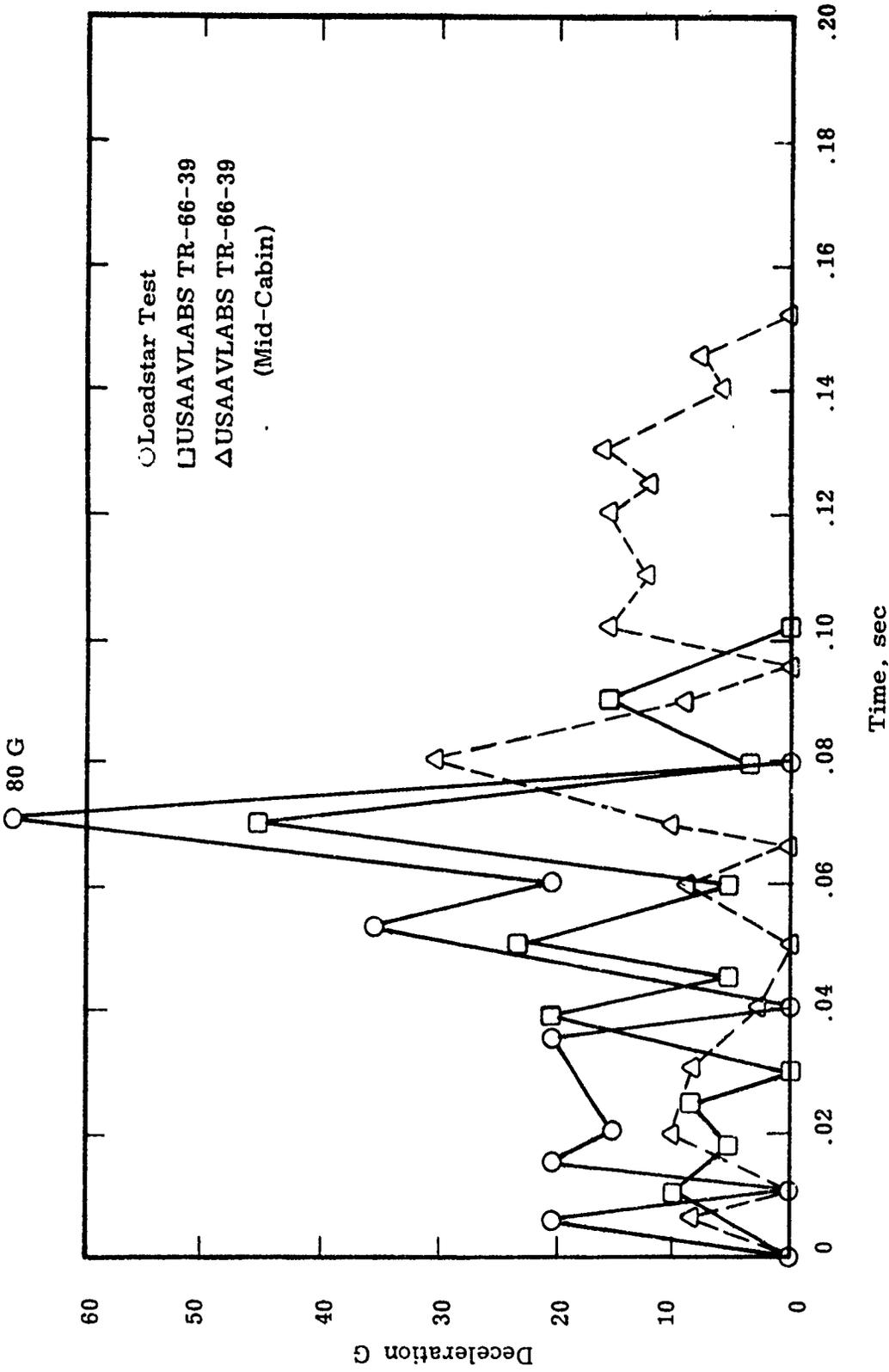


Figure 3. Vertical Crash Decelerations

crash condition which can be easily described mathematically. For these reasons the design crash pulses given in Figure 1 were chosen as the input accelerations for the vertical and longitudinal directions.

Crash Pulse Shape Effects

The triangular waveform of the design crash accelerations was chosen as a representative pulse shape for the major impact in small aircraft accidents. Since aircraft crashes do not generate pure triangular pulses, the effects of pulse shape and high frequency structural ringing on the response of the seated man system should be mentioned.

Previous investigations (Ref 4 & 5) have shown that the restrained seated occupant responds to an impact in the longitudinal and vertical direction as a linear single degree of freedom system. The equation of motion for a single degree of freedom system subjected to an acceleration input is:

$$\ddot{X}_r + 2\zeta\omega_n\dot{X}_r + \omega_n^2 X_r = -A(t) \quad (1)$$

where X_r = relative displacement

ζ = damping ratio

ω_n = natural frequency

$A(t)$ = input acceleration

This is the differential equation of motion for a damped linear system. The response of this system to a unit impulse, $A(t) = \zeta(t)$, is:

$$X_r(t) = \frac{e^{-\zeta\omega_n t}}{\omega_d} \sin\omega_d t \quad (2)$$

where $\omega_d = \omega_n \sqrt{1-\zeta^2}$

For the seated restrained occupant it has been found (Ref 4 & 5) that:

$$\zeta = 0.3$$

$$\omega_n = 62.8 \text{ rad/sec}$$

If the damping term is neglected ($\zeta = 0$), equation (1) becomes:

$$\ddot{X}_r + \omega_n^2 \cdot X_r = -A(t) \quad (3)$$

This equation describes the motion of an undamped linear system whose impulse response is given by:

$$X_r(t) = \frac{1}{\omega_n} \sin \omega_n t \quad (4)$$

Examination of equation (2) and (4) indicates the undamped systems response will be a slightly higher frequency and will not have an exponentially decaying amplitude. Since the change in frequency is small (5%) and the increased amplitude will not influence the comparative analysis, the response of the undamped system was used to investigate the effects of pulse shape variation.

The pulses examined were symmetrical pulses of rectangular, half-sine, versed-sine and triangular shapes. The analytical expression for these inputs and their responses are given in Appendix A.

The basis for comparison of the different pulses was to assume that all pulses had equal time duration and area. For an airplane crash the input acceleration applied to the seated occupant is primarily a function of the impact surface and the structural response of the aircraft. Since the aircraft's structural response depends on the natural frequency of the fuselage, it appears that the pulse duration of the input should be a function of the particular airplane. The shape of the acceleration pulse would depend on the deformation characteristics of the impact surface. The assumption that all pulses have equal area means that the velocity changes for all inputs are the same.

The normalized time responses of the four pulses for different $\frac{\tau}{T}$ ratios are given in Figure 4 (Ref 6)

τ = time duration of input pulse

T = natural period of system

The responses shown in Figure 4 indicate that the relation between τ and T influences the system's response to different pulse shapes. If the time duration of the input is long in comparison to the systems natural period ($\frac{\tau}{T} \geq 1$), then the effect of pulse shape variation is quite noticeable. However, if $\frac{\tau}{T}$ is small ($\frac{\tau}{T} \leq \frac{1}{2}$) the effect of variation in pulse shape become negligible. For the two design crash accelerations previously selected the pulse widths are:

longitudinal 104 msec

vertical 54 msec

This results in $\frac{\tau}{T} \approx 1$ for the longitudinal direction and $\frac{\tau}{T} = \frac{1}{2}$ for the vertical direction which means that the shape of pulse will influence the longitudinal response but will not have much effect on the vertical response.

Examination of the crash data in Figures 2 and 3 indicates that there is high frequency structural oscillations riding on top of a basic acceleration pulse. The effects of these high frequency oscillations can be determined by looking at the magnitude of the frequency response of a linear single degree of freedom system. The frequency response of a linear system can be defined as the complex magnitude of the transfer function evaluated over the frequency range of interest. The transfer function for a single degree of freedom linear damped system is (Ref 7)

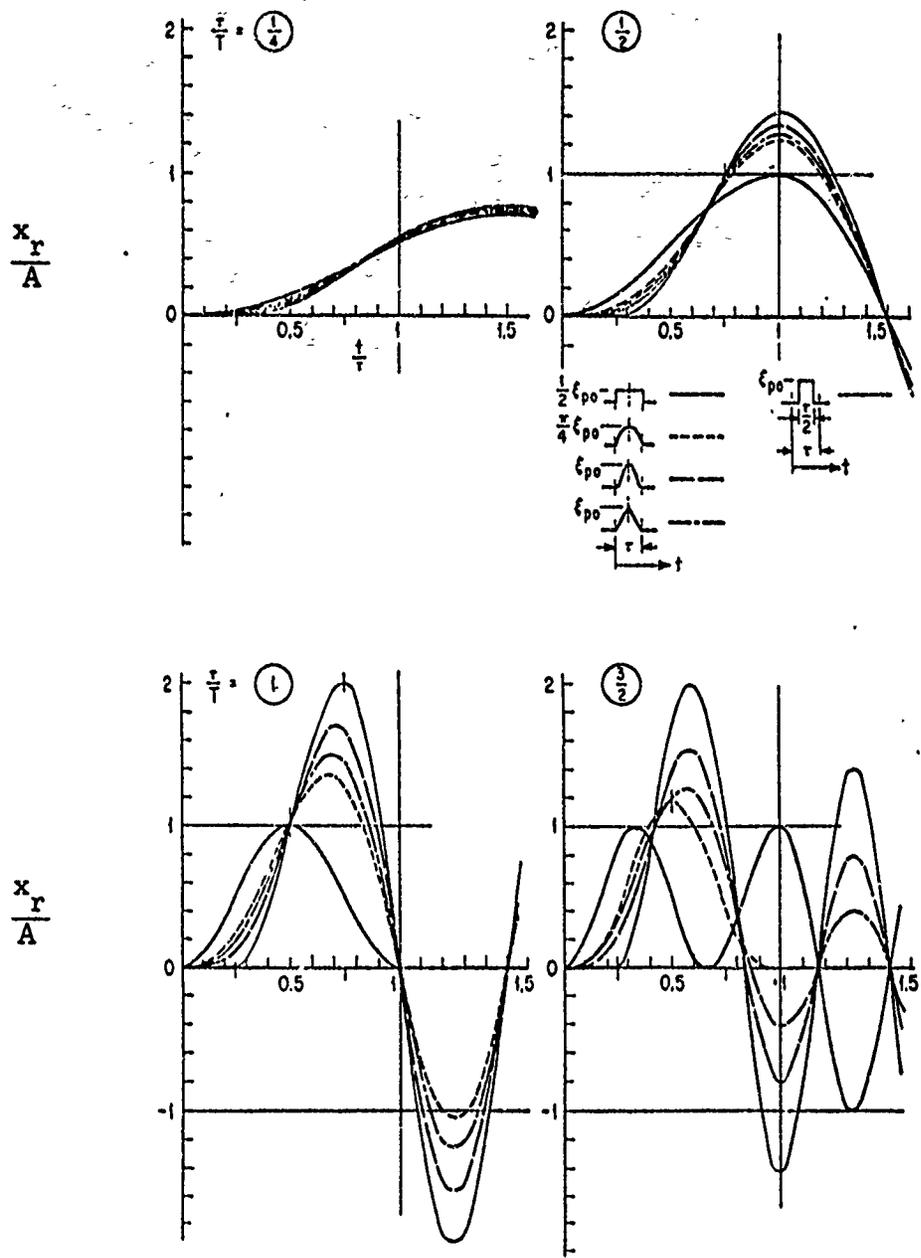
$$G(j\omega) = \left[(j\omega)^2 + 2\zeta\omega_n (j\omega) + \omega_n^2 \right]^{-1}$$

where ω = variable frequency

$$j = \sqrt{-1}$$

By defining the log magnitude (Lm) of $G(j\omega)$ as

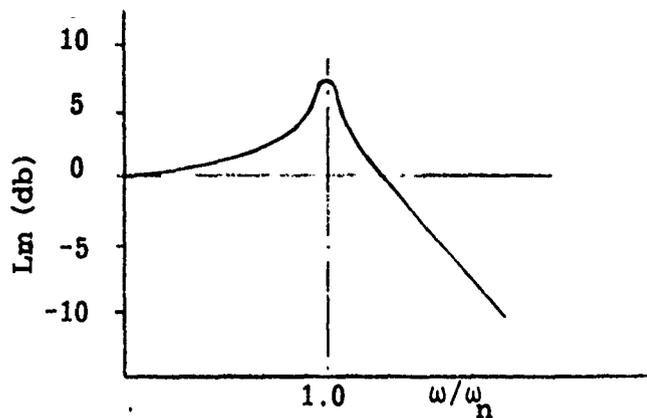
$$Lm G(j\omega) = 20 \log G(j\omega) \text{ db}$$



(Reproduced from Ref. 6)

Figure 4. Time Responses to Symmetrical Pulses

and plotting this as a function of frequency a frequency response curve, such as that shown below, can be determined.



From the crash data, it appears that the structural oscillations have a frequency of approximately 100 Hz. Since ω_n for the seated occupant is 10 Hz it can be shown (Ref 7) that the log magnitude at 100 Hz can be approximated by

$$L_m = -40 \log \frac{\omega}{\omega_n} \text{ db}$$

For $\omega = 100 \text{ Hz}$ $L_m = -40 \text{ db}$ which means that the amplitude of the high frequency oscillations has been reduced by a factor of 10^2 . If the frequency of these oscillations were 50 Hz their amplitude would still be down 28 db. In other words, the high frequency structural ringing will have little or no effect on the seated occupant.

Inflatable Restraint System

A survey of available reports and publications on airbag systems was conducted and those documents which contained relevant information were collected. Abstracting sources (DDC, STAR, etc.) were reviewed for current reports related to inflatable restraint system operation. A report bibliography was requested and received from DDC. Also a large amount of in-house literature was examined in areas pertaining to airbag systems. All of the reports collected and received are listed in the Bibliography.

Several of the publications listed in the Bibliography contained information and data that was directly applicable to this program and are listed below with a short summary.

Trosien, K. R., and Patrick, L. M., "Steering Wheel Airbag Collision Performance", Wayne State Univ., SAE 710020, Society of Automotive Engineers, New York, N. Y., Jan. 1971.

An experimental test program for steering wheel restraint systems was conducted using a barrier impact facility. The following conclusions were drawn from the test results.

1. The airbag can be triggered and inflated after collision initiation in time (40-50 ms) to provide driver protection.
2. The airbag cushions the face and abdomen at velocities up to 30 m.p.h., and prevents injurious concentrated loads when the impact is centered.
3. The efficacy of the steering wheel airbag installation in mitigating injury is increased by lap belt usage.
4. Head accelerations were below the 80g/3 ms injury criterion in all cases of impact to the bag.
5. Rebound velocities up to 9 m.p.h. appear satisfactory and achievable at impact velocities up to 30 m.p.h. barrier equivalent.
6. Velocities up to 86 m.p.h. were imparted by the inflating airbag to the arm initially across the steering wheel. No fractures or head accelerations in excess of 80g/3 ms injury criteria resulted from arm and hand impact to the head under these conditions.

7. The steering column should not rotate (bend) upward during frontal impact to expose the lower rim to abdominal impact. Also, column bending inhibits collapse of the column.
8. Bag shape, size, and pressure blow-out valve should be designed to cause column collapse prior to bag collapse.
9. Bag and column should operate together to achieve maximum driver decelerating distance--the airbag does not eliminate the need for energy absorbing column.
10. Provision for protection from off-center (and oblique) impacts is necessary and can be attained by using a large bag to prevent the driver from wedging between the steering wheel and the door.

Pflug, J. A., "Dynamic Problems with an Air Bag Restraint System", Ford Motor Co., SAE 710021, Society of Automotive Engineers, New York, N. Y., Jan. 1971.

Crash testing has revealed dynamic problems with present designs for airbag passive restraints which must be resolved. Out-of-position occupants can restrict deployment of the airbag or affect its restraint action. In rollover and side impact accidents, today's airbag offers only minimal restraint. Accordingly, it appears essential to use lap belt, in combination with airbags, to achieve an improved restraint system over current systems when usage rates and effectiveness are considered. The noise level created by airbag actuation may exceed tolerance levels in some humans. Inadvertent deployment of airbags could compromise the driver's control of the vehicle. These and other technical problems listed below must be resolved before such systems are furnished in automobiles to be sold to the public.

1. Out-of-position occupants would not have the intended protection from the airbag.

2. Braking prior to impact pitches the occupant forward which could restrict bag deployment and result in the occupant being lifted so that his head would impact the vehicle.
3. The out-of-position child may be particularly vulnerable to injury caused by the inflating airbag.
4. In rollover, the airbag would provide little restraint to the lateral movement of the occupants and seat belts appear to continue to be necessary.
5. In side impacts, intrusion would occur before bag inflation could be achieved and protection in the form of vehicle structure and padding would be required.
6. Noise level and pressure buildup produced by airbag actuation may exceed human tolerance levels.
7. Protection below 10 m.p.h. where serious injury can still occur must be achieved by means other than the airbag, such as padding and seat belts.
8. The unavoidable small number of inadvertent actuations of the airbag can have serious consequences.

The airbag passive restraint system has the potential to be greatly effective in specific crash conditions. But, there is much evidence that leads to the conclusion that the lap belt should remain a part of the total restraint system. It will control the original occupant position and restrain his movement during braking, low speed impact, and rollover. Early production installations of airbags will, with the retention of lap belts, contribute to additional safety in frontal collisions. However, there is continuing work to be done to optimize airbag shape, location, size, deployment time, and deflation rate.

Martin, D. E., "Theoretical Limits of Inflatable Restraint Performance", General Motors, International Conference on Passive Restraints, NATO, Midland, Mich., May 1970.

The theoretical limits of airbag performance were established using the assumption that the airbag force is constant and the Severity Index should not be greater than 1000. From this it was determined that, the distance available for stopping the occupant within a given time decreases as impact velocity increases, and the stopping distance required to prevent injury increases as the impact velocity increases. The intersection between these two regions determines the operational capability of an inflatable restraint system and is illustrated in Figure 5.

In addition to reviewing the literature, inflatable system and components manufacturers were asked to supply data and information on airbag restraints that are currently available. The companies listed below were contacted:

Allied Chemical
Automotive Products Division
Mt. Clemons, Michigan

Atlantic Research Corporation
Alexandria, Virginia

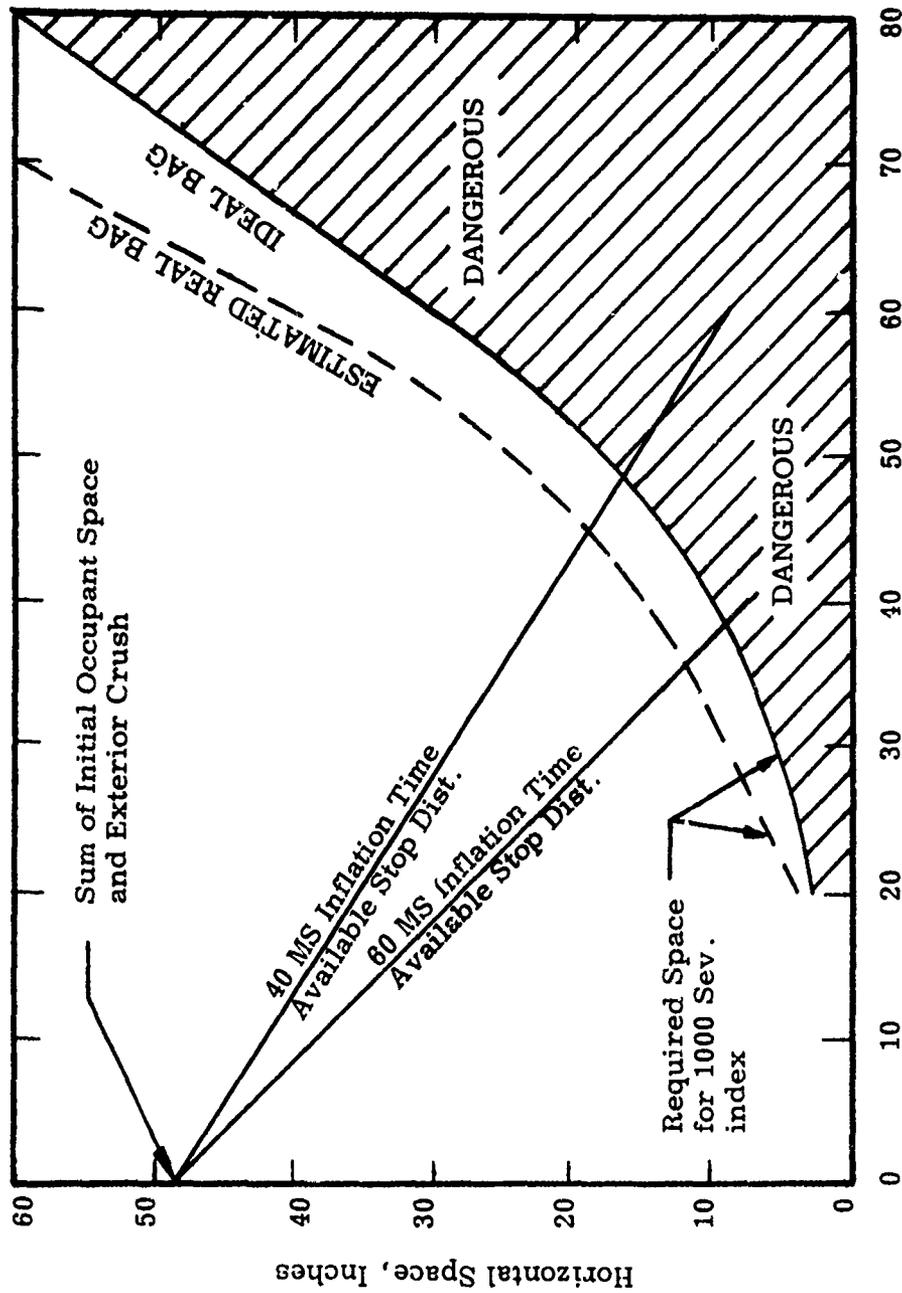
B. F. Goodrich
Akron, Ohio

Eaton Corporation
Auto Cepter Division
Troy, Michigan

Ensign & Bickford Co.
Space Ordinance Division
Simsbury, Conn.

General Motors
Inland Manufacturing Division
Dayton, Ohio

Goodyear
Akron, Ohio



Barrier Impact Speed in Miles Per Hour

Figure 5. Theoretical Limits of Inflatable Restraints

Olin
Energy Systems Division
East Alton, Illinois

Rocket Research
Redmond, Washington

Sargent Industries
Pico Division
San Francisco, California

Talley Industries, Inc.
Mesa, Arizona

Thiokol Chemical Corporation
Wasatch Division
Brigham City, Utah

Uniroyal, Inc.
Mishawaka, Inc.

Irvin Air Chute, Ltd.
Fort Erie, Ont., Canada

From the response to this request, data on the following inflatable systems were tabulated:

Olin
Energy Systems Division
Safe-T-flate

Rocket Research Corp.
All-Solid Inflator
Aspirator Inflator

Talley Industries, Inc.
Cool Gas Generator

Thiokol Chemical Corp.
Wasatch Division
Gas Generator

Performance values data and hardware information data on these systems are presented in Tables I and II. From these tables, the capability of current airbag systems was determined.

Performance Data	Olin Safe-T-Flate	Olin General	R. R. C. Solid Inflator	R. R. C. Talley Aspirator Cool Gas	Thiokol
Bag Volume (cu ft)	10	2-14	1.75	7-10 .67-14	1.4-8
Bag Inflation Time (msec)	30	25-80	2^~25	35 20	20-30
Bag Pressure (psig)		0-8	0	4	2-4
Inflator Pressure (psig)	2400 psi Augmented Sys.	3000 psi		2000-4000	
Bag Surface Temp. (°F)		120		120-solid cool amb. - freon	180
Bag Deployment Velocity	Safe	Safe			100-500 ft/sec
Ignition Delay (msec)	20	5		4.5-5	1.5-4
Deployment Noise Level (db)		164 db	140 db	110-135	155
Gas Toxicity		Safe	Safe	Safe	Safe
Reliability	Good	.99999 @ 55%		High	.99999

Table I. Inflatable Systems - Performance Data

<u>Hardware Data</u>	<u>Olin Safe-T-Flate</u>	<u>Olin General</u>	<u>R. R. C. Solid Inflator</u>	<u>R. R. C. Aspirator</u>	<u>Talley Cool Gas</u>	<u>Thiokol</u>
System Weight (lb)	15	7*	2.7	12-14	3*	2
Storage Volume (cu/in.)	710 (4.5 x 7.5 x 21)	30-85*		570 (3.25 x 6.25 x 28)	25*	20-90*
Mounting Configuration			Base			
Inflation Mechanism	Augmented Air System	Hybrid	Solid Propellant	Aspirator	Solid Propellant freon & solid cool	Pyrotechnic Gas Generator
Bag Material		Nylon--neoprene or uerthane coated			Nylon coated & uncoated	Nylon neoprene
Bag Configuration	Tear Drop	Tear Drop				
Sensor Type		Mechanical Rolamite			Inertial	
		*Inflator			*Inflator	*Inflator

Table II. Inflatable Systems - Hardware Data

Inflatable Restraint Performance Parameters Data

Performance Data

Bag Volume	.67-14 cu ft
Bag Inflation Time	20-35 msec
Bag Pressure	1-8 psig
Inflator pressure	2000-4000 psig
Bag Surface Temperature	120-180 ^o F
Ignition Delay	5 msec
Deployment Noise Level	110-164 db
Gas Toxicity	Safe
Reliability	.99999

Hardware Data

Weight	2-15 lb
Storage Volume (inflator)	20-90 cu in.
Inflation Mechanism	Hybrid, Aspirator, Gas Generator
Bag Material	Nylon - neoprene coated
Operating Temperature Range	-20-220 ^o F

Airframe Cabin Data

The development of inflatable restraints for general aviation aircraft required cabin dimensions and seat locations for various airplanes in the general aviation category. To obtain this information it was necessary to select specific aircraft and request cabin data from the manufacturers. The particular aircraft types were determined on the basis of popularity. Business and utility aircraft shipments for the first six months of 1971, as published in Aviation Week and Space Technology, were examined and the quantity of each aircraft shipped was determined. From this information a chart of cabin seats versus aircraft shipped and a chart of aircraft weight versus aircraft shipped were made. These two graphs are given in Figures 6 and 7. The data in the two graphs indicated that the majority of general aviation aircraft could be divided into two groups.

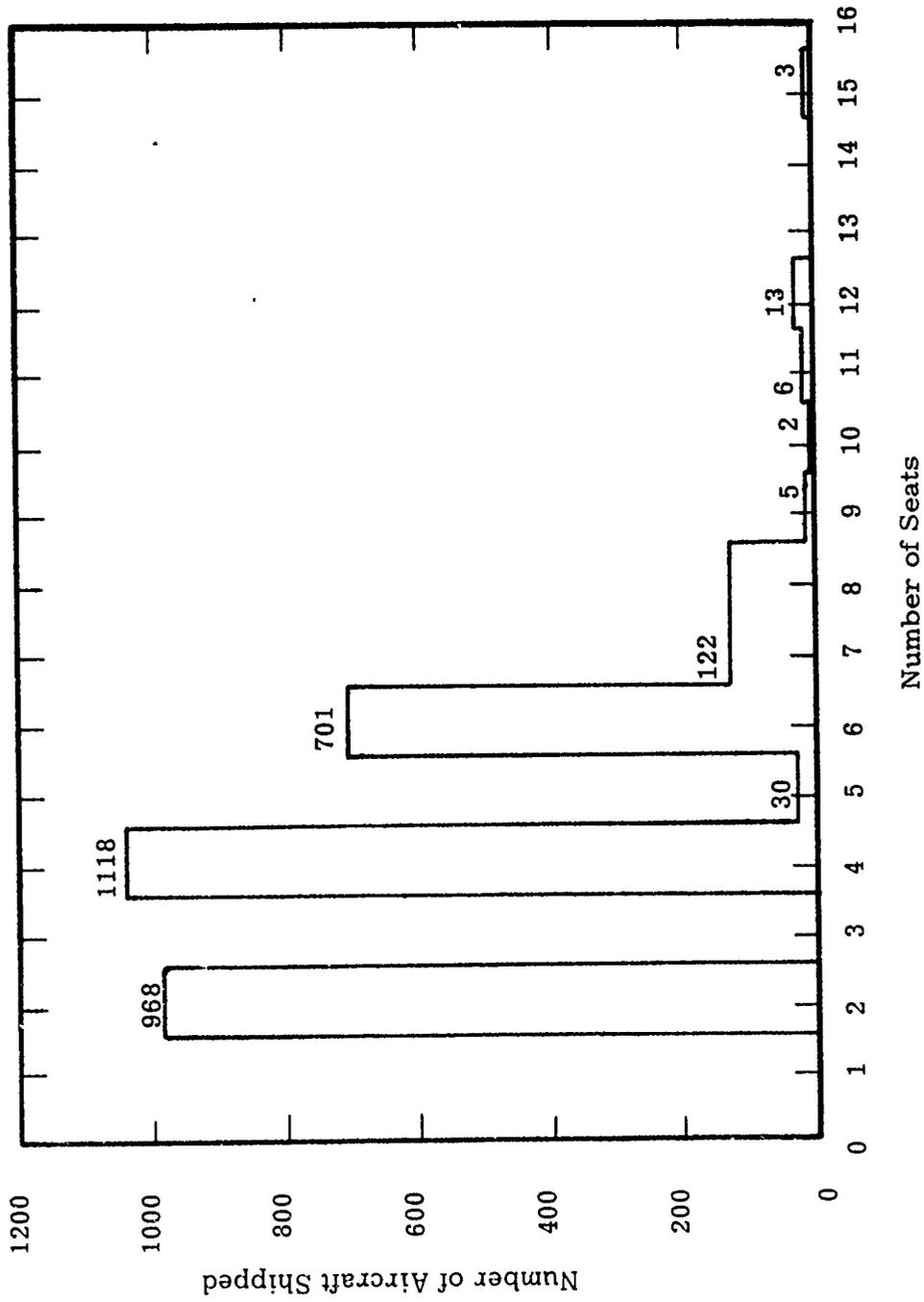


Figure 6. Cabin Seat Versus Aircraft Shipped

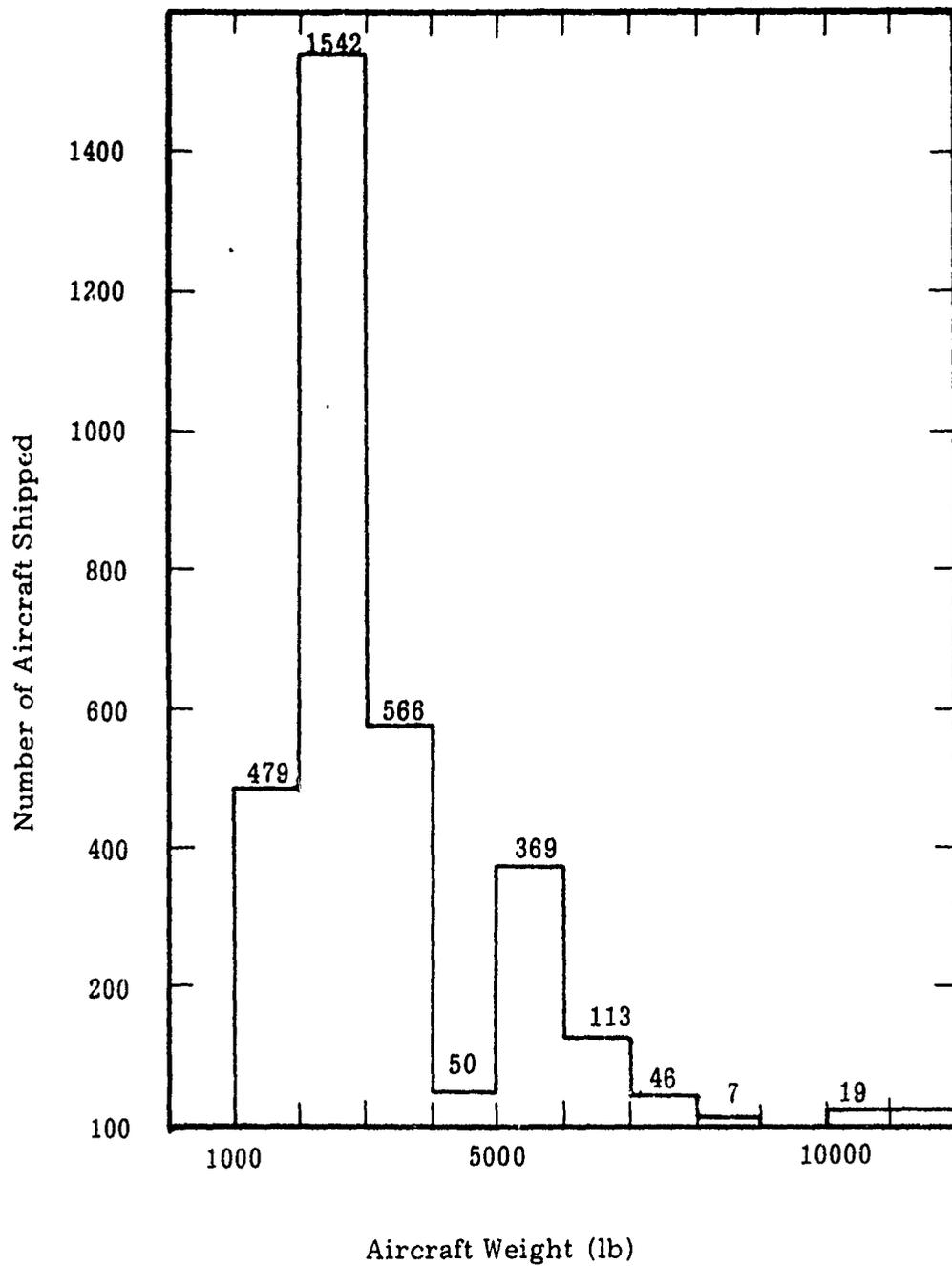


Figure 7. Aircraft Weight Versus Aircraft Shipped

Group 1 - Pleasure Aircraft

Passengers - 4-6

Gross Weight - 2000-4000 lbs

Group 2 - Business Aircraft

Passengers - 6-8

Gross Weight - 5000-8000 lbs

Airframe manufacturers who built airplanes falling in either or both of these groups were requested to supply cabin information on their aircraft. The companies contacted were:

Aerostar Aircraft Corp.
Kerrville, Texas

American Aviation Corp.
Cleveland, Ohio

Beech Aircraft Co.
Wichita, Kansas

Bellanca Aircraft Corp.
Alexandria, Minn.

Cessna Aircraft Co.
Wichita, Kansas

Lake Aircraft
Aerofab Division
Sanford, Maine

Maule Aircraft Corp.
Maultrie, Ga.

North American Rockwell
General Aviation Division
Bethany, Oklahoma

North American Rockwell
Aero Commander Division
Albany, Ga.

Piper Aircraft Corp.
Vero Beach, Florida

Piper Aircraft Corp.
Lock Haven, Pa.

From the response to this request and from inspections of the actual aircraft, layout drawings, showing interior cabin configurations, were made for the following aircraft.

Beech Musketeer Custom
Cessna Skyhawk
Piper Cherokee 180
Beech King Air
Piper Navajo

These drawings were used in a latter phase of the program to develop inflatable restraint concepts.

Energy Absorber Criteria

Energy attenuation characteristics for optimum protection of the seated occupant in the vertical direction were recently investigated and defined in the following report:

Carr, R. W. and Phillips, N. S., "Definition of Design Criteria for Energy Absorption Systems", NADC-AC-7010 Naval Air Development Center, Warminster, Pa., June 1970.

This study investigated the dynamic response of the seated man energy absorber system, shown in Figure 8, and determined the force deflection characteristics of an optimum energy absorber. The physical response system used a seated man model which consisted of a single degree-of-freedom, spring mass damper system with a natural frequency of 10 Hz, a damping ratio of 0.3, and a mass equal to that of the man. Placing this model

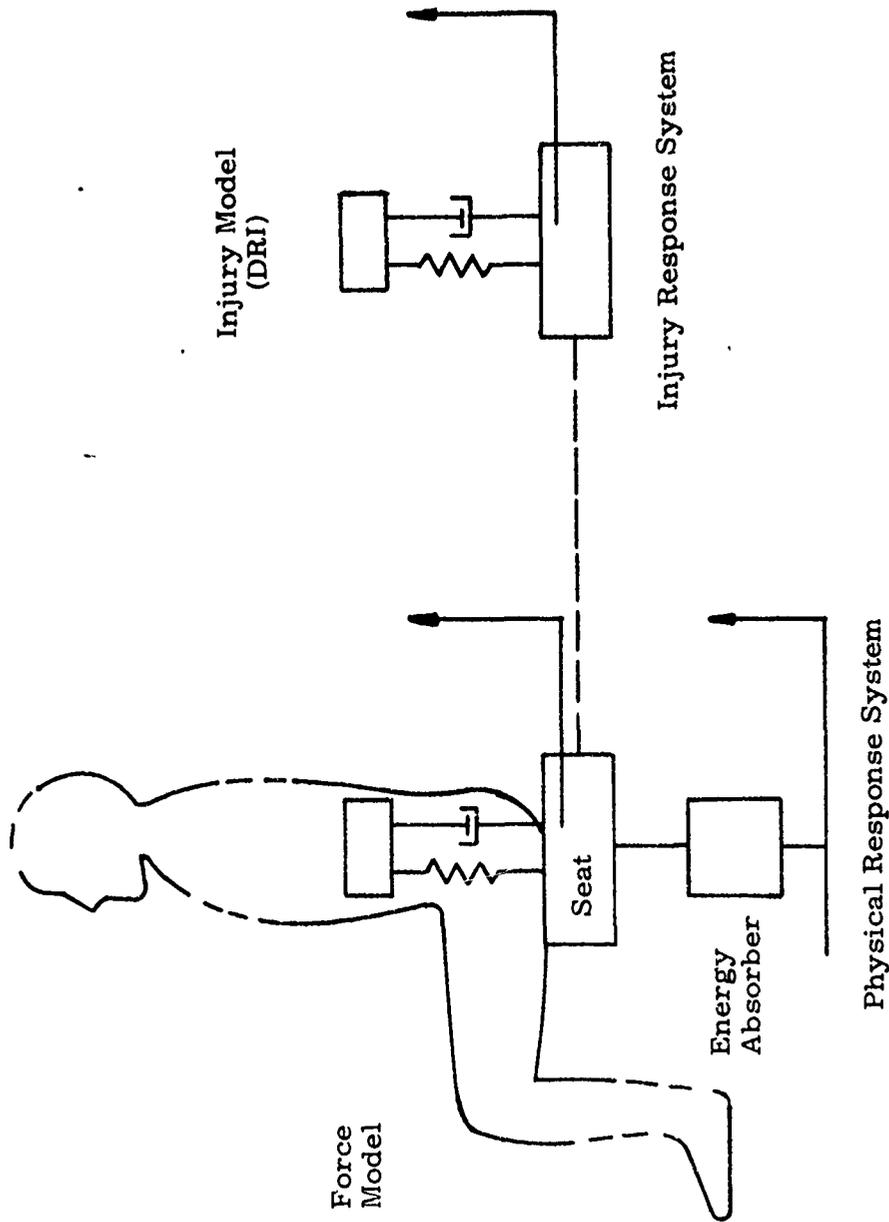


Figure 8. Seated Man Energy Absorber System

on a simple model of the seat and energy absorber, the equations of motion for the system were found. Crash accelerations were applied as an input and a computer program was used to solve for the seat acceleration. This acceleration was then used as an input to the injury response model whose output is a Dynamic Response Index (DRI) which provides a measure of spinal injury probability. By adjusting the force deflection characteristics of the energy absorber, a seat acceleration was found which generated an ideal DRI response.

DRI is defined as:

$$\text{DRI} = \frac{\omega_n^2 \cdot \delta \text{ max} = K \cdot \delta \text{ max}}{g}$$

where ω_n = natural frequency

δ = compression of spring

g = gravitational acceleration

The ideal DRI response is one which reaches and holds a certain value of $\delta \text{ max}$ in the shortest time and the force displacement curve which generated this type of response was defined as an optimum energy absorber characteristic. The wave shape of this force-deflection curve deviated from those of conventional energy absorbers and is shown in Figure 9.

Energy attenuation characteristics in the longitudinal direction have not been as well defined as those in the vertical direction. Investigations in this area have been primarily with respect to the motions of the upper torso and restraint forces imposed on the upper torso. None of the reports surveyed during this program studied or defined the energy absorption characteristics required to attenuate the horizontal load vector. However, an optimum force-deflection curve for the longitudinal direction can be theoretically determined using the severity index (Ref 8) and the initial velocity of the upper torso.

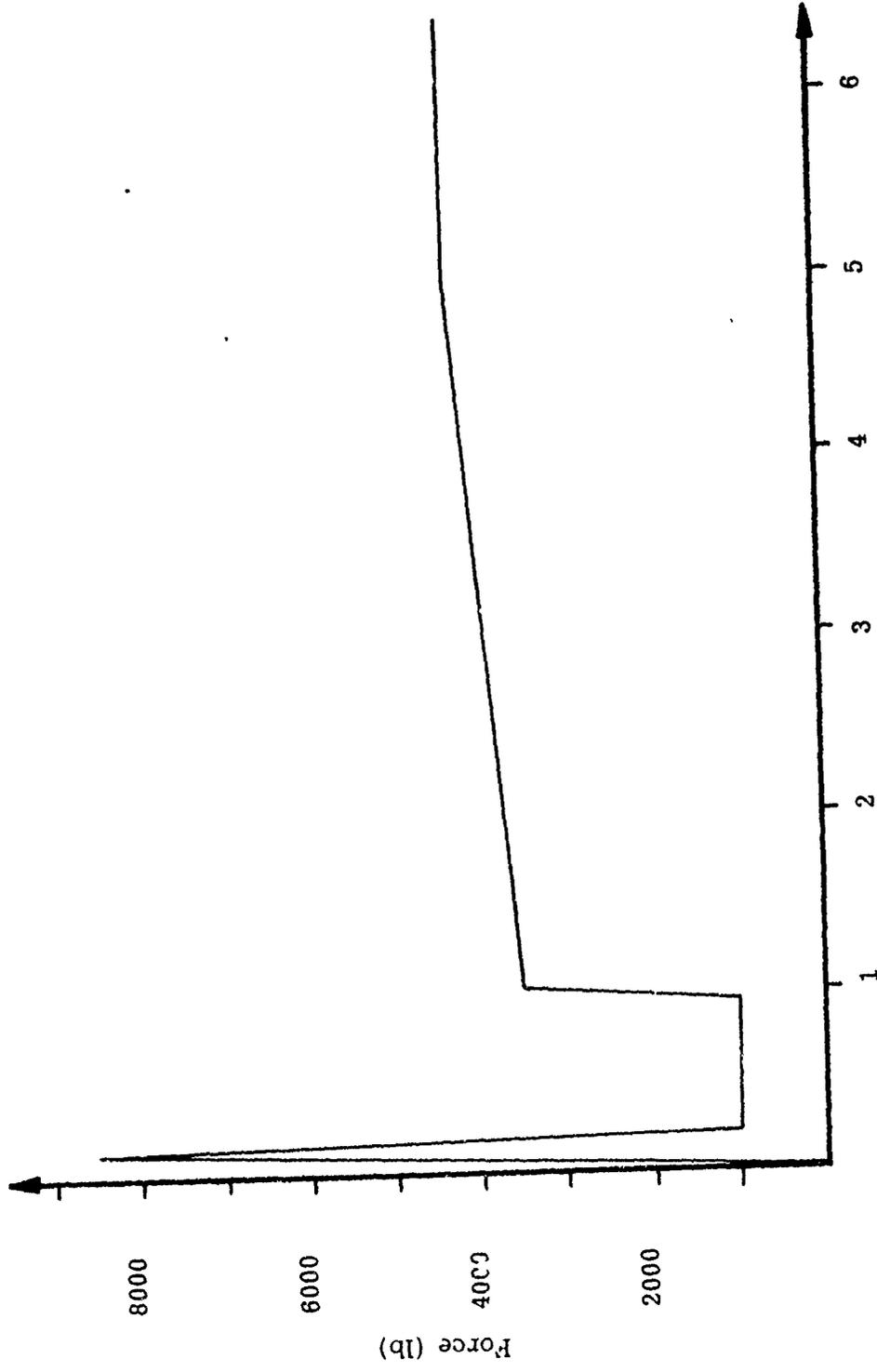


Figure 9. Optimum Energy Absorber Waveform

Severity index is defined as

$$S.I. = \int_{t_0}^{t_1} a^{2.5} dt$$

where a = acceleration of the head

t_0 = initial time

t_1 = final time

Since the severity index is to be minimized, and it is defined in the Lagrange Variational form, calculus of variations can be used to determine the optimum acceleration

$$\text{Minimum S.I.} = \int_{t_0}^{t_1} a^{2.5} dt$$

subject to the isoperametric constraint

$$\text{Velocity Change } \Delta V = \int_{t_0}^{t_1} a dt$$

The augmented functional then becomes

$$(S.I.)_a = \int_{t_0}^{t_1} (a^{2.5} + ha) dt$$

where h = Lagrange multiplier

from the Euler-Lagrange equation

$$a^{3/2} = \frac{h}{2.5}$$

$$a = \left(\frac{h}{2.5} \right)^{2/3}$$

substituting into the velocity equation.

$$\Delta V = \int_{t_0}^{t_1} \left(\frac{h}{2.5} \right)^{2/3} dt$$

$$\Delta V = \left(\frac{h}{2.5}\right)^{2/3} (t_1 - t_0)$$

$$h^{2/3} = \frac{(2.5)^{2/3} \Delta V}{t_1 - t_0}$$

Substituting this into the equation defining acceleration.

$$a = \frac{\Delta V}{t_1 - t_0}$$

This equation says that for a given velocity change, the optimum head acceleration is constant whose value depends on the time interval $(t_1 - t_0)$. If the acceleration of the head is to be constant then the force exerted on the head to restraint motion must also be constant. This implies that for optimum energy attenuation in the longitudinal direction a constant force or square wave device should be used.

DESIGN GOALS

Inflatable Restraint Model

A model of an airbag system was developed to assist in defining the design goals for an inflatable restraint system. The airbag model has the characteristics shown schematically in Figure 10. The model is basically a thermodynamic system with an associated dynamics problem within. As the high pressure bottle exhausts, energy is added into an expanding bag. The bag has inertia by virtue of its mass, and a retarding force due to aerodynamic drag. Additionally, as the bag expands, work is done against the atmosphere in displacing the volume of the bag. The air entering the bag is the thermodynamic system in that it has a certain amount of energy as it enters the bag, it does work, and the loss of energy results in an equilibrium between bag size, gas temperature, and bag strain.

The dynamic system is the bag configuration as defined by its size and weight. A configuration was chosen such that a volume and displacement

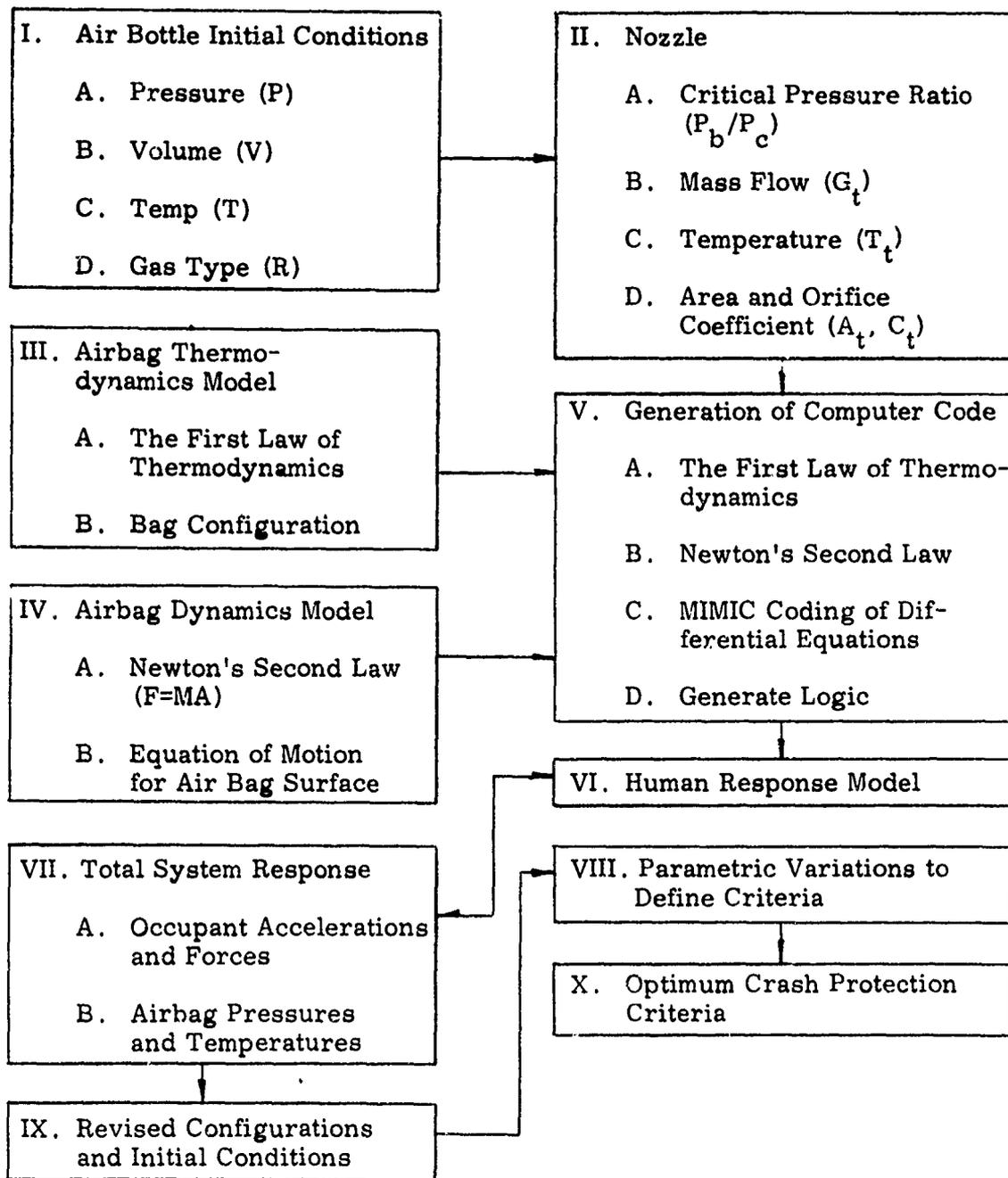


Figure 10. Airbag Model Flow Chart

relation could be established. That is, as the bag is forced away from its attachment points, there must be some method of relating volume that exists as the bag surface advances. It could be hemispherical, rectangular, or any arbitrary choice. As the outer surface accelerates it must do so because it is a mass acted upon by the internal pressure of the gas, retarded by drag, inertia and the elastic action of the bag.

The airbag model developed is not a fixed pressure, fixed volume model that only examines the response after steady state inflation exists. Rather it is a model that examines the total response of the bag during inflation and during impact. The system solved generates the response as a function of time that reflects the thermodynamics and dynamics of the gas and the bag.

Air Bottle

The air bottle is the energy source of the system. It is a high pressure bottle specified by particular values of pressure, volume and temperature. For this program nitrogen was used since enthalpy curves were easily available from existing data. The bottle is assumed to be an adiabatic control volume bottle. The exhausting of the gas is an isentropic process.

Nozzle

The nozzle is described by an area and nozzle coefficient. These and the bag and bottle pressures dictate the mass flow into the bag. The type of flow is dictated by the pressure ratio across the nozzle. For nitrogen there is a critical pressure ratio defined by the ratio of specific heats, K . If the pressure ratio across the nozzle is less than the critical, the flow is supersonic and the mass flow is only a function of the properties of the gas in the bottle. If the ratio is greater than critical, the flow is subsonic and the

mass flow is a function of the pressure ratio across the nozzle. Hence, the pressure ratio is monitored in the program to insure that the flow is calculated according to the correct supersonic or subsonic equations.

Thermodynamics Equations

As mentioned, the thermodynamics balance must be calculated for the gas that enters the bag, expands within the bag, and exits through a blowout patch. The equation is

$$\Delta Q - \Delta W = \Delta E .$$

which is the deceptively simple equation indicating that if heat is added to the gas, and work extracted; then the temperature changes accordingly. The next step is to isolate the elements of the equation.

Energy Values

The energy that enters the bag is

$$\Delta E = \int \left(h(T) + \frac{V^2(T)}{2g} \right) \cdot m(t) dt$$

where $h(T)$ is the specific enthalpy (BTU per pound)

V is the velocity (feet per second)

g is the gravitational constant (feet per second square)

m is the mass flow (pound-second square per sec square)

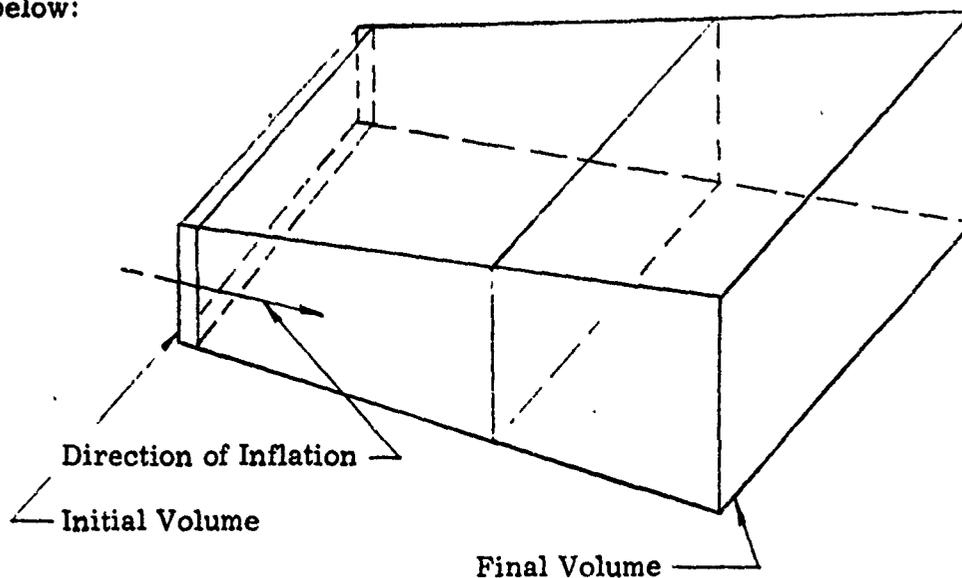
The energy is calculated knowing the temperature and mass flow at the nozzle. The specific enthalpy is known from a chart or table giving the value of enthalpy as a function of temperature (Ref 9). Hence ΔE is the number of BTU's transferred from bottle to bag.

The energy lost through a blowout patch is calculated by the same relations. The flow through a patch is analytically identical to that through a nozzle.

There is no other energy transfer. This is because of the definitions that are consistent with the First Law of Thermodynamics. Energy is carried into and out of the control volume and does not cross the boundaries.

Work Values

The bag inflation given requires work to be taken from the gas. The first example is that of bag inertia. The bag configuration assumed is shown below:



The bag inflates as the frustrum of a pyramid. The dimensions are arbitrary so that any size bag can be used. As the bag inflates, the volume is developed by having the material unfurl along the framework shown. As this happens the end plate increases in area as do the sides and tops, according to the dimensions fed into the program.

The work required to do this is the integral of force times velocity. That is,

$$\Delta W = \int (F \cdot V) dt$$

where F is the force generated (pounds)

V is the velocity (inches per second)

As an example, the force generated by the end of the bag is

$$F = m\ddot{x}$$

where m is the mass of the end

\ddot{x} is the acceleration of the end.

The mass is surface area times areal density, and hence the work can be written:

$$\Delta W = \int (A \cdot \rho \cdot \ddot{x} \cdot \dot{x}) dt$$

This indicates that the work (thermodynamic) is related to the displacement of the bag (dynamics). The work of the sides, top and bottom are similar except that the accelerations and velocities used are functions of the end displacement. This is because the center of gravity of the side does not travel at the same acceleration and velocity as does the end. However, the relations were evaluated as function of bag and cap displacement.

Atmospheric work is the most easily recognized because it is simply

$$\Delta W = \int p dv$$

where p is the differential pressure (pounds per inch square)

v is the volume (cubic inches)

The work against bag stretch was incorporated because of data available from Rocket Research Corporation. It was known empirically that previous bag inflations have followed the equation

$$\frac{v_p}{v_0} = 1 + 0.1p^{0.623}$$

where v_p is the pressurized volume

v_0 is the volume at zero gauge pressure

This was used to calculate bag stretch work as

$$\Delta W = \int p dv$$

Aerodynamic drag creates work according to the equation

$$\Delta W = \int F \cdot v dt$$

where F is aerodynamic drag as described by

$$F = \frac{1}{2} \rho V^2 S C_D$$

where ρ is atmospheric density

V is the bag velocity

S is the surface area

C_D is the drag coefficient

Hence the aerodynamic work is again a function of the bag dynamics since it is:

$$\Delta W = \left(\frac{1}{2} \rho \dot{x}^2 A(x) C_D \cdot \dot{x} \right) dt$$

Dynamics Equations

As the bag accelerates outward the motion is described basically by

$$F = m\ddot{x}$$

The bag has a certain mass and is acted upon by a pressure over the end cap area. The equation of motion for the end cap is

$$m\ddot{x} = p \cdot A - \text{Drag} - \text{Elastic Restraining Force}$$

The mass of the end cap was established as was the area and drag. The elastic force was evaluated by assuming that the strain over the bag surface

is uniform. That is, the bag dimensions elongate by some incremental amount to create a volumetric change. This results in the expression

$$\Delta V = WH + L\Delta W + H\Delta L$$

where W is the width of the bag

H is the height

L is the length

for uniform strain $\epsilon = \frac{\Delta L}{L} = \frac{\Delta H}{H} = \frac{\Delta W}{W}$

This results in

$$\Delta V = V_0 \epsilon$$

where V_0 is the volume at zero gauge pressure.

Therefore the elastic restraining force is calculated by

$$F_e = E \cdot \epsilon (2W + 2H) Th$$

where E is Youngs Modulus for the material (pounds per inch square)

ϵ is the strain (inches/inch)

$(2W + 2H)$ is the peripheral length

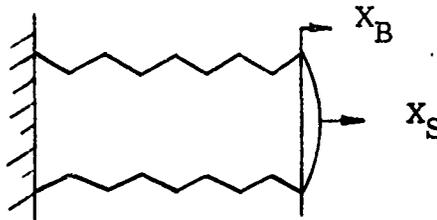
Th is the material thickness

An additional feature was necessary to calculate the bag motion. As described above, the bag should accelerate outward as pressure is generated within the bag and gradually be retarded by drag, inertia and elasticity.

Unfortunately this was not correctly interpreted either theoretically or realistically. Because of the small mass of the bag, the acceleration of the end cap was extremely large and therefore so was the initial velocity.

In fact the velocity was so great that the drag calculated generated forces sufficient to analytically shove the bag back into the bottle. This uncovered the problem that indicates the true motion of the bag.

The end surface with the initial burst of pressure deforms as a membrane and elongates pulling the bag out of its container. Hence the true velocity of the bag through the air is something less than the motion of the center of the end cap. This was accounted for by analytically incorporating a diaphragm into the end of the bag. The equations for a membrane are well known and were used to calculate the displacement as a function of pressure. This was used to calculate the response of the bag as a two-body problem.



The bag surface X_S moves according to Newton's Law as a mass accelerated by the bag pressure and restrained by the elasticity of the membrane. The remainder of the bag is then accelerated by the elastic force of the membrane. This creates a system whereby the initial burst of pressure causes the bag to deform at the surface, but the drag is dictated by the motion of the bag, X_B , out from the reference line.

Program Operation and Logic

A computer program was written which solved the dynamic and thermodynamic equation. A listing of this program is given in Appendix B. The program functions in the following manner. The high pressure nitrogen expands through the nozzle and into the bag. As it does so it carries energy into the bag and the pressure acts to move it away from its reference. In moving the bag works on the atmosphere against drag and inertia to create a volume. The work subtracted from the input energy dictates an amount of energy that establishes the temperature. Since the volume, mass and temperature are known, the pressure is

evaluated and the cycle repeated. The equations are both differential and thermodynamic and the computer routine uses iterative techniques to solve them. The solution determines the particular combination of variables that permit the pressures that exist across the nozzle, to agree with the pressure in the bag that has created the bag volume and system work.

The program recognizes the supersonic and subsonic flow conditions for the system. It also recognizes that the blowout patch cannot actuate without having the bag unfurled. The patch is established as a particular pressure level patch. A 20 psi patch will "blowout" when the pressure exceeds 20 psi per gauge. However, as seen in the data, the airbag pressure has a large spike initially when it is not realistic for the patch to release. To overcome this it is established that until the bag reaches its zero psi gauge level volume, the patch will not release.

Longitudinal Response Model

A lumped parameter model of a seated occupant was developed on this program to determine the design goals for the longitudinal inflatable restrain system. Two previous models of a seated human (Ref 10 and 11) were studied and applicable features of each one incorporated into the model shown in Figure 11. The model consists of two masses: M_u representing the upper torso and head; M_l representing the lower torso. These two masses are tied together at a pivot point P which is the axis about which M_u rotates. Point P is also the attachment point for the lap belt. B_{lb} and K_{lb} are the damping and stiffness coefficients for the lap belt, while B_{th} and K_{th} are the rotational damping and stiffness coefficients for the upper torso. Two restraining forces are used in the model. F_a is the force exerted on the upper torso by the airbag and F_f is the frictional force between the lower torso and the seat.

The equations of motion for the longitudinal response model are

$$M_t \ddot{X}_1 = M_u \cdot R_t \cdot \cos \theta \cdot \ddot{\theta} + M_u \cdot R_t \cdot \sin \theta \cdot \dot{\theta}^2 - F_a \cdot \cos \theta - F_{lb} - F_f$$

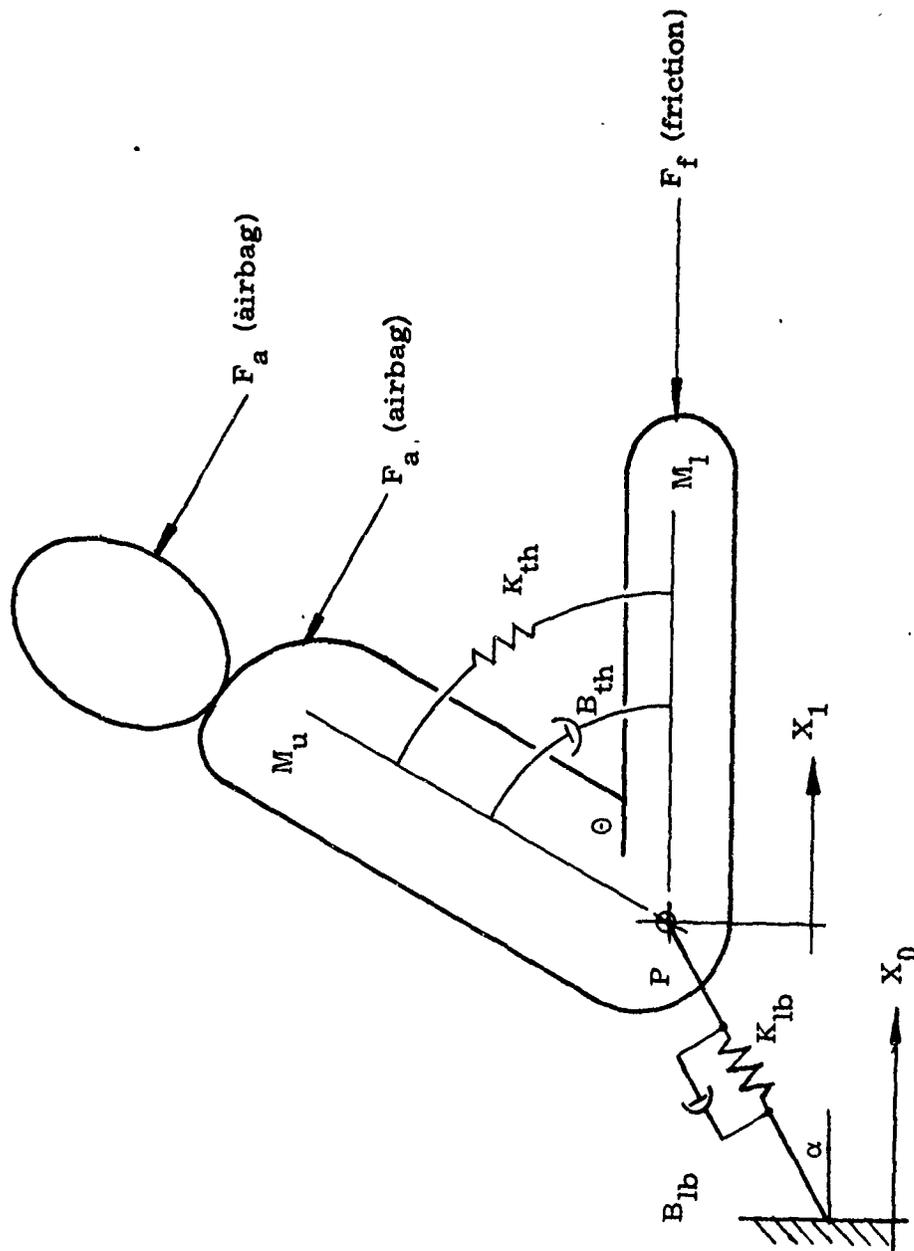


Figure 11. Longitudinal Response Model

$$I_t \ddot{\theta} = M_u \cdot R_t \cdot \sin\theta \cdot g - M_u \cdot R_t \cdot \cos\theta \cdot \ddot{x}_1 - B_{th} \dot{\theta} - K_{th} \theta - F_f R_s$$

where $M_t = M_u + M_1$
 R_t = radius of torso c.g.
 F_{lb} = lap belt force
 I_t = upper torso inertia
 R_s = radius of shoulder
 F_f = frictional force

Anthropometric data used to determine the parameter values were obtained from the Bioastronautics Data Handbook (Ref 12). The mass terms (M_u , M_1 and I_t) were determined from the weight of the occupant by multiplying body weight by an appropriate constant.

$$M_u = \frac{(.225) WB}{g}$$

$$M_1 = \frac{(.275) WB}{g}$$

$$I_t = M_u \cdot (R_t)^2$$

where WB = occupant weight
 $g = 32.2 \text{ ft/sec}^2$

The linear distances that determine the location of the torso c.g. (R_t), shoulder height (R_s), and head c.g. (R_h) also depend on the occupant's size. By examining the distribution of these values as a function of occupant weight, a linear approximation for each distance was determined.

$$R_t = .0546 \cdot WB + 9.24$$

$$R_s = .0546 \cdot WB + 14.24$$

$$R_h = .0625 \cdot WB + 21.2$$

With these equations, all the anthropometric values required to find the motion of the model can be computed by just knowing the occupant's weight.

Lap belt forces (F_{lb}) were determined from load elongation characteristics of restraint harness materials. Previous studies of the dynamic properties of nylon and dacron webbing (Ref 13) indicate that the load elongation curves for these materials is almost linear under impact conditions and that the slope is about 55,000 lb/ft. This value was used as an elongation constant and the lap belt force was calculated as a function of belt elongation and the relative velocity between the occupant and seat. The equation for calculating lap belt force was

$$F_{lb} = K_{lb} \cdot Elg + B_{lb} \cdot V_r$$

where Elg = belt elongation

V_r = relative velocity

The airbag force (F_a) was modeled as a constant force applied at the shoulder of the occupant. The shoulder was selected as the midpoint of the airbag contact surface and therefore was the application point of the resultant airbag force. The seat friction force F_f was determined from the occupant's weight and the vertical component of the lap belt force. The equation used to calculate the seat friction force was

$$F_f = \mu \cdot (WB + F_{lb} \sin \alpha)$$

where μ = coefficient of friction

The equations of motion, the anthropometric equations, the lap belt force, airbag force, and frictional force equations were programmed for solution on a digital computer using MIMIC (Ref 14). A listing of this computer program is given in Appendix C. The results generated by this program were compared with data from sled tests conducted on human subjects restrained by a seat belt and/or airbag (Ref 15) to accurately determine the

model's coefficients. The lap belt stiffness coefficient (K_{lb}) was selected from dynamic test data for dacron webbing (Ref 13). Lap belt damping (B_{lb}), body masses (M_u and M_1), and the friction coefficient (μ) were adjusted until the linear displacement of the whole body and the lap belt forces were close to the measured data. Once these values were chosen, the rotational coefficients (K_{th} and B_{th}) were selected to match the measured displacement time profile of the head. Following this procedure, the final values for these coefficients gave the results shown below:

	<u>Model</u>	<u>Data</u>
Body Displacement	0.9 in	1.0 in
Lap Belt Force	758#	703#
Head Angular Displacement	82°	85°
Time to Peak (head Angular Displacement)	220 ms	230 ms

A comparison of the measured and calculated head angular displacement is shown in Figure 12. Since the model's response compared favorably with measured data, the refinement of the coefficients was terminated and model was used to investigate crash input accelerations.

Vertical Response Model

A previously developed biodynamic model of the seated occupant (Ref 16) shown in Figure 8 was used to determine the inflatable restraint criteria for the vertical direction. The program was slightly modified to accept the general aviation crash input and the seat weights. It was then used to find the energy absorption characteristics that produced the minimum probability of injury.

Inflatable Restraint Design Criteria

An airbag restraint system for general aviation aircraft should be designed to provide the maximum protection for the greatest range of occupants. For design considerations this means keeping the injury potential for the

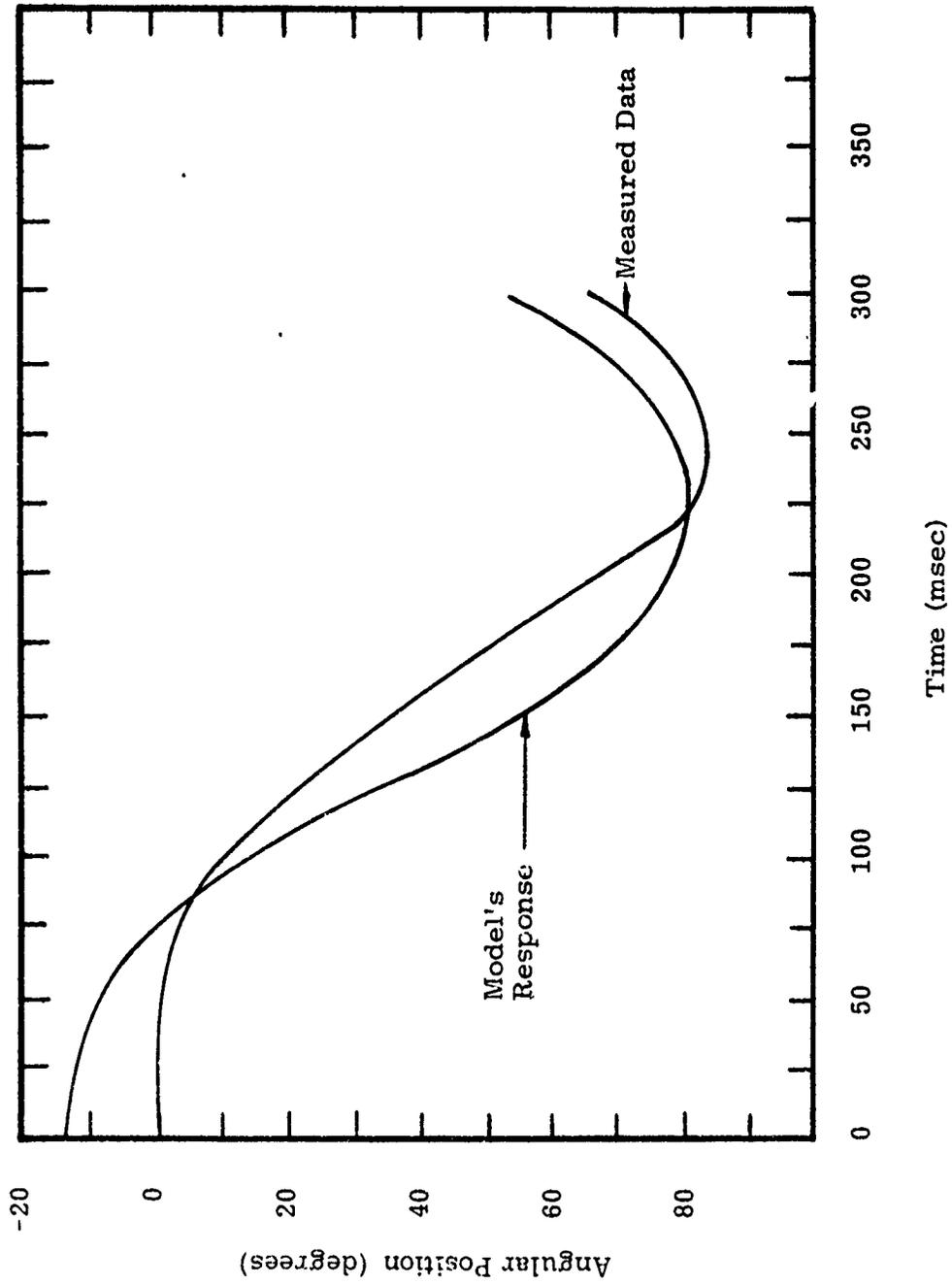


Figure 12. Model Response and Measured Data Comparison

heaviest occupant subjected to the highest level crash loads within the design goals. The injury potential design goals for the two restraint systems investigated during this program were:

Vertical Restraint System - DRI = 18

Longitudinal Restraint System - Severity Index = 1000

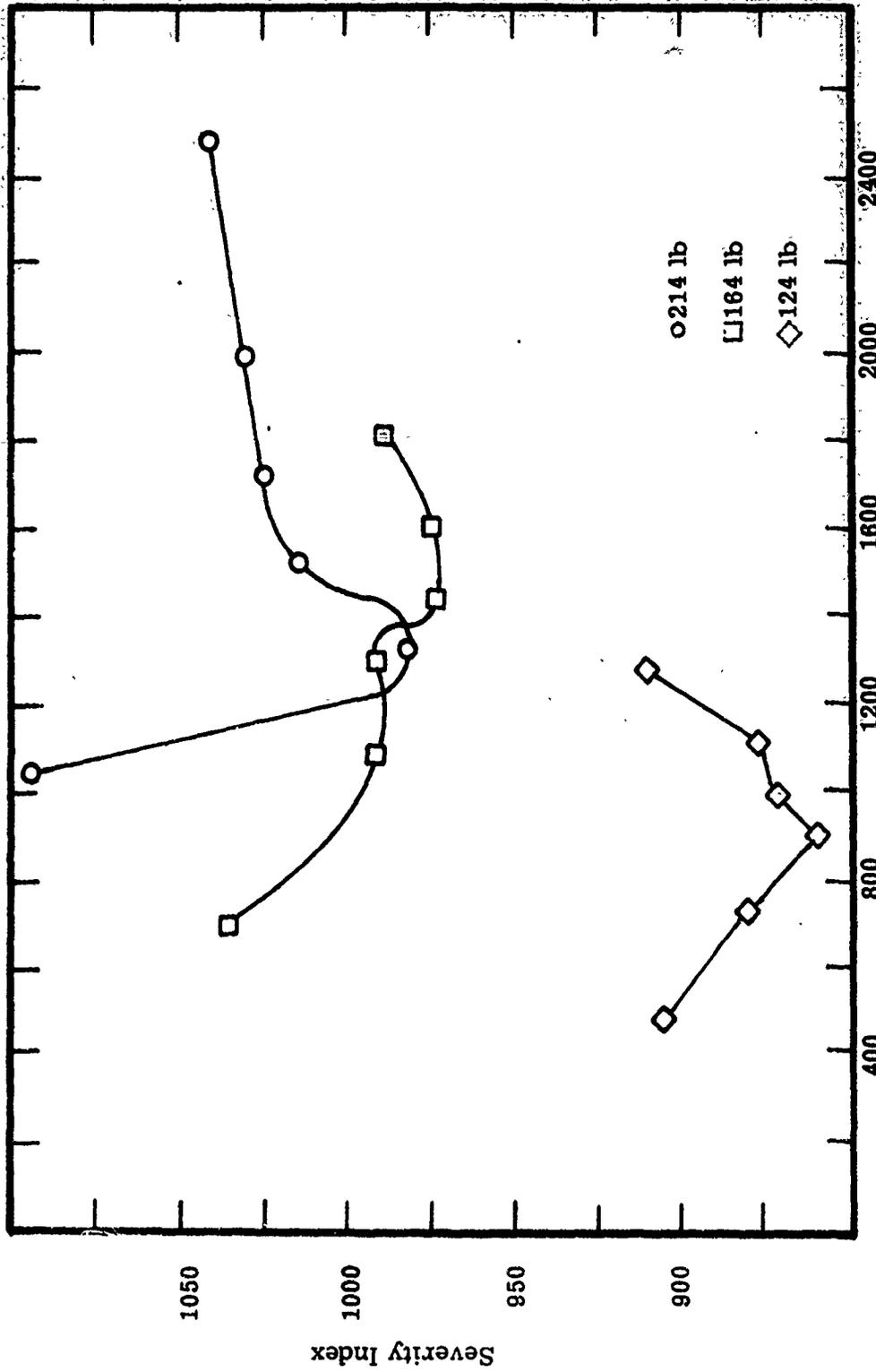
The crash loads used were the 95th percentile design crash pulses for light fixed wing aircraft (Ref 17). The occupant weights were obtained from the male weight distribution for the flying public (Ref 18). Since a design based on the heaviest occupant in the case of dynamic systems might prove potentially dangerous to lesser weights, three occupant weights (95th, 50th and 5th percentile) were used for design parameters.

95th percentile	214 lbs
50th percentile	164 lbs
5th percentile	124 lbs

The initial goals treat the longitudinal and vertical airbag restraints as separate systems. Therefore, the design specification was determined for two independent systems; vertical and longitudinal. The design specification was developed by using the occupant and airbag models previously mentioned.

Longitudinal Airbag Restraint System

The airbag restraint system for the longitudinal direction must restrain the upper torso from impacting the control console during a crash environment. The crash pulse for this environment is the longitudinal acceleration defined in Figure 1. The airbag system must restrain the upper torso so that the Severity Index is less than 1000. The first item to determine is the restraining force the airbag should exert on the upper torso. Using the longitudinal response model different force levels were investigated and the results are presented in Figures 13 and 14.



Airbag Force (lb)

Figure 13. Non Vented Airbag Force Effects on Severity Index

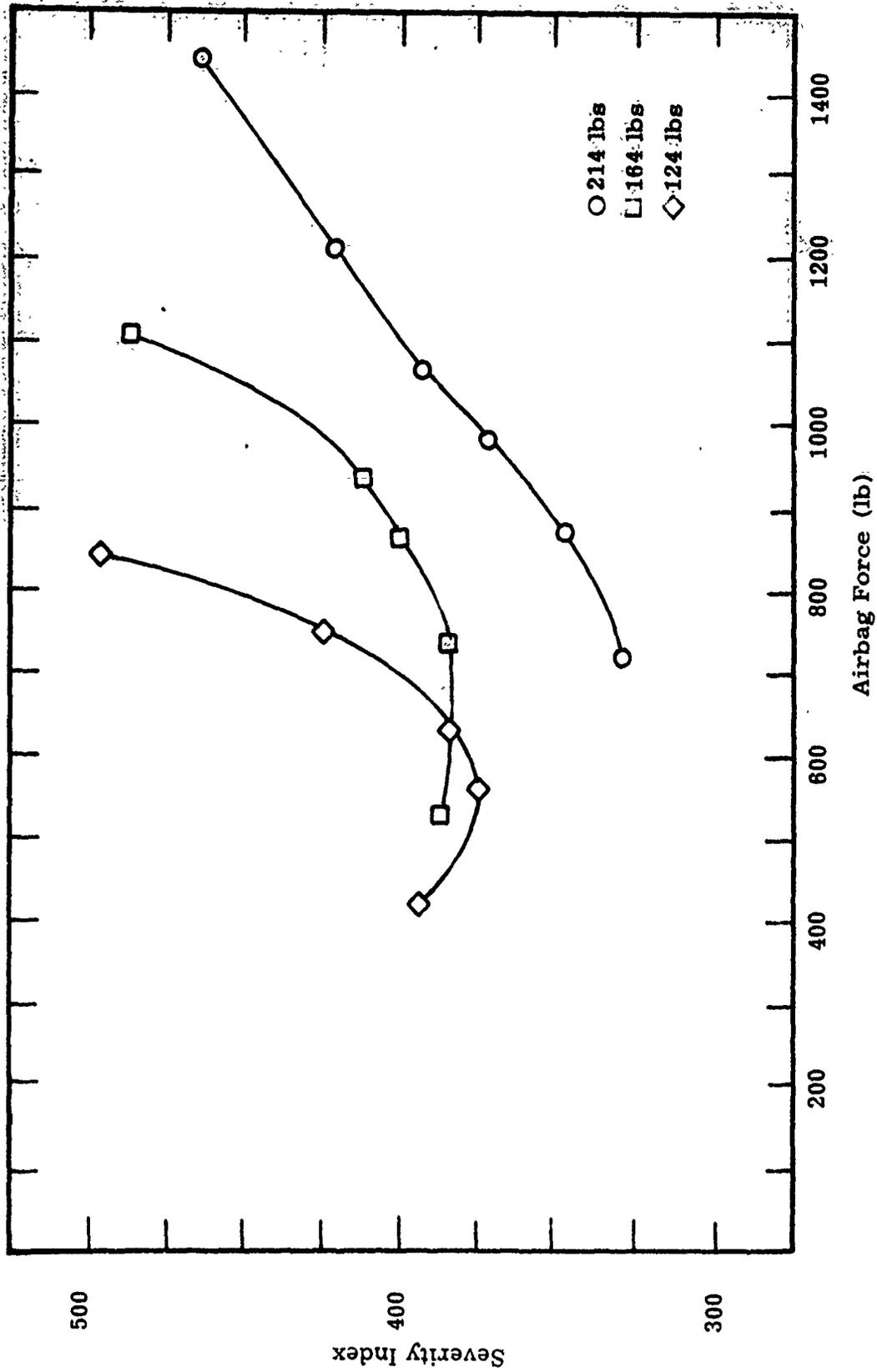


Figure 14. Vented Airbag Force Effects on Severity Index

The data points in Figure 13 were from computed responses that assumed the airbag force was applied to the occupant the entire time he was in contact with the airbag. The airbag force acts as a decelerating force as the occupant rotates forward and as an accelerating force when the occupant rotates backward. The airbag stops the occupant from impacting against the control panel and then "throws" him back into the seat. In Figure 14 the data points were obtained from responses which assumed the airbag force was only applied as a restraining force during the time the occupant was rotating forward. As the occupant rotates forward the airbag deflates in a manner that applies a constant force to the upper torso. When the occupants forward motion has been stopped, the airbag is completely deflated and the occupant returns to his original position unassisted by any airbag force. From the severity indices computed for these two cases, the latter one appears much more desirable. Therefore, the airbag force for each occupant weight was initially selected from Figure 14.

Once the airbag force has been found the pressure can be determined from the contact area between the upper torso and the airbag. The contact areas for each of the three occupant weights are given in Appendix D and the corresponding bag pressures are given in the first rows of Table III. The Severity Index was determined from Figures 13 and 14. From this data it appears that a bag pressure around 2.75 psig would provide adequate protection for all weights. The effects on Severity Index of bag pressures 3.0, 2.75 and 2.5 psig are given in Table III with a bag pressure of 2.75 psig having the lowest Severity Index for all weights.

After finding the pressure for the airbag restraint, the volume can be determined from the work done in stopping the upper torso. This work is equal to the torque applied to the upper torso multiplied by the displacement

$$W = T \cdot \theta$$

Weight lbs.	Contact Area sq in.	Airbag Pressure psig	Airbag Force lbs	Severity Index (1) (Figure 13)	Severity Index (2) (Figure 14)
214	313	2.77	867	981	340
164	264	3.5	923	972	380
124	218	2.94	642	858	360
214	313	3.	940	1010	350
164	264	3.	792	990	360
124	218	3.	654	860	360
214	313	2.75	860	981	335
164	264	2.75	725	990	355
124	218	2.75	600	870	350
214	313	2.5	784	1020	330
164	264	2.5	680	995	365
124	218	2.5	545	880	350

Table III. Airbag Pressure Effects on Severity Index

For the 214 lb occupant this work is $W = 24345 (.737)$
 $W = 17950 \text{ in.}\cdot\text{lb}$

Knowing the pressure and work, the volume of the airbag can be found.

$$W = \int_{v_i}^{v_f} p \, dv$$

where p = pressure
 v = volume of airbag

Since p is a constant

$$W = p \int_{v_i}^{v_f} dv$$

$$W = p (v_f - v_i)$$

$$\text{or } v_f - v_i = \frac{W}{p}$$
$$= \frac{17950}{2.75} = 6500 \text{ in.}^3$$

Other criteria for the longitudinal airbag were determined from general aviation cabin dimensions, the longitudinal response model, and current airbag system specifications. The displacement was determined from the minimum distance available in a general aviation aircraft. The time required for the occupant to reach an upright position was used as the deployment time. The initial angular position of the occupant was reclined 13 degrees. Surface temperature, noise, and toxicity were determined from manufacturers performance data.

Vertical Airbag Restraint System

The vertical airbag restraint system must function in a manner that prevents the seat acceleration from exceeding human tolerance levels. This can be accomplished if the seat support structure (i.e. legs) collapses in a controlled fashion. From a previous study (Ref 16) an optimum force-deflection curve for seat collapse has the form shown in Figure 9.

In general aviation aircraft seats, the support structure is generally rigid and does not collapse. This results in dangerous accelerations transmitted to the seated occupant in a crash environment. Therefore, a vertical airbag system must contain a method of collapsing the seat legs. If the legs collapse at the proper time, the collapse mechanism and the airbag system will create the optimum force deflection curve for the seat. The force "spike" at the beginning of the force displacement curve can be generated by the rigid seat legs initially remaining in place. When the peak force is reached, the legs are released and the seat is supported by the airbag. This should create the "notch" and plateau of the optimum waveform. There are numerous techniques that could be used for collapsing the seat.

The optimum force displacement curves for general aviation aircraft were determined using the Vertical Response Model and the vertical crash pulse shown in Figure 1. From these curves the vertical airbag specifications were found. Since the force displacement curve is a function of occupant weight, three optimum waveforms were determined. These curves are shown in Figure 15 and correspond to occupant weights of 124, 164, and 214 pounds. The seat weight used was 25 pounds. The optimum force deflection characteristics for the 214 pound occupant were used to determine the vertical airbag criteria since they represent the worst conditions (i.e. highest force and longest stroke).

The inflatable restraint system pressure was found using an airbag force of 3406 lb and assuming a contact area of 324 in.² (18 x 18).

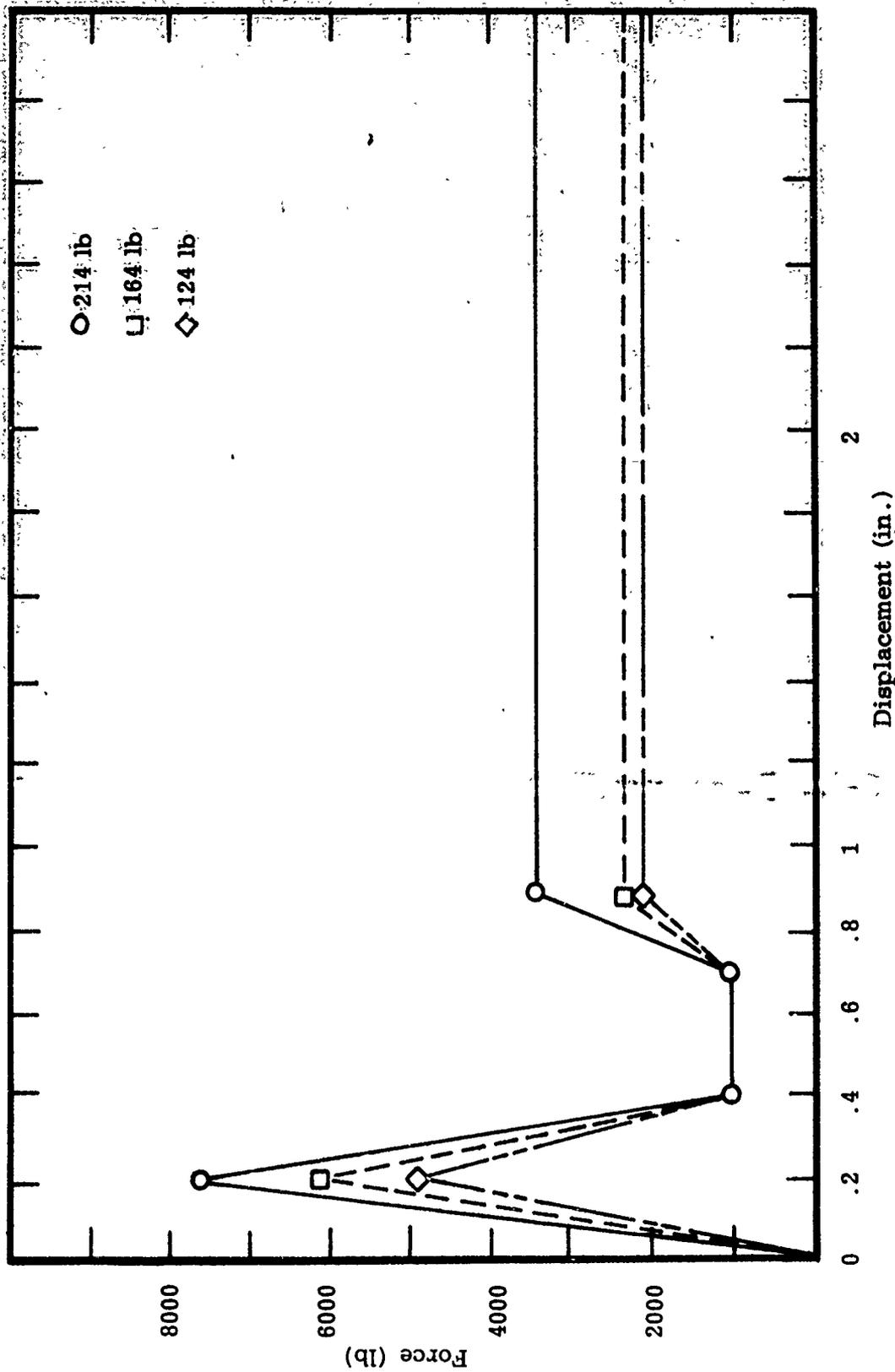


Figure 15. Force Displacement Curves for Vertical Airbag

$$\text{Pressure} = \frac{3406}{324} = 10.5 \text{ psig}$$

The area under the force deflection curve is equal to the work that has to be done by the airbag and for this case was 41,720 in.-lb. From the pressure and work, the volume of the bag was found.

$$\begin{aligned} v_f - v_i &= W/p \\ &= \frac{41,720}{10.5} = 3970 \text{ in.}^3 \end{aligned}$$

The vertical displacement required is 12.5 in. This distance is necessary to dissipate the energy of the seat and occupant. The inflation time for the airbag was determined from the time it takes the force to reach the initial peak and manufacturer's performance data was used to define values for the surface temperature, noise, and toxicity.

Inflatable Restraint Design Goals

Two sets of design goals for the vertical and longitudinal airbag restraint systems were defined using the results from previous phases of the program. Computed responses of the occupant and airbag models and performance data on current airbag systems were used to determine the goals listed below:

	<u>Longitudinal Airbag System</u>	<u>Vertical Airbag System</u>
Pressure (psig)	2.75	10.5
Displacement (in.)	19	12.5
Surface Area (in. ²)	313	324
Volume (in. ³)	9750	5950
Deployment Time (msec)	40-50	25-30
Bag Surface Temperature (°F)	125 ^o	125 ^o
Deployment Noise (db)	100	100
Weight (lb)	5	3
Toxicity (Ref 19)	emergency unit less than unity	emergency unit less than unity
Overpressure (psig)	< 3 psig	< 3 psig

INFLATABLE RESTRAINT SYSTEM CONCEPTS

Airbag restraint system concepts for general aviation aircraft were developed using the preliminary inflatable restraint design goals, airbag system hardware data, and interior cabin dimensions of general aviation aircraft.

Aircraft Cabin Dimensions

Layout drawings of general aviation cabin interiors were made which depicted seating arrangements, control locations, instrument panels, and possible mounting surfaces for inflatable restraints. These drawings illustrated the similarity between cabin interiors in different aircraft and were used to develop a composite interior for a general aviation aircraft. From this generalized cabin interior and airbag manufacturers hardware data, four preliminary inflatable restraint concepts for general aviation aircraft were developed.

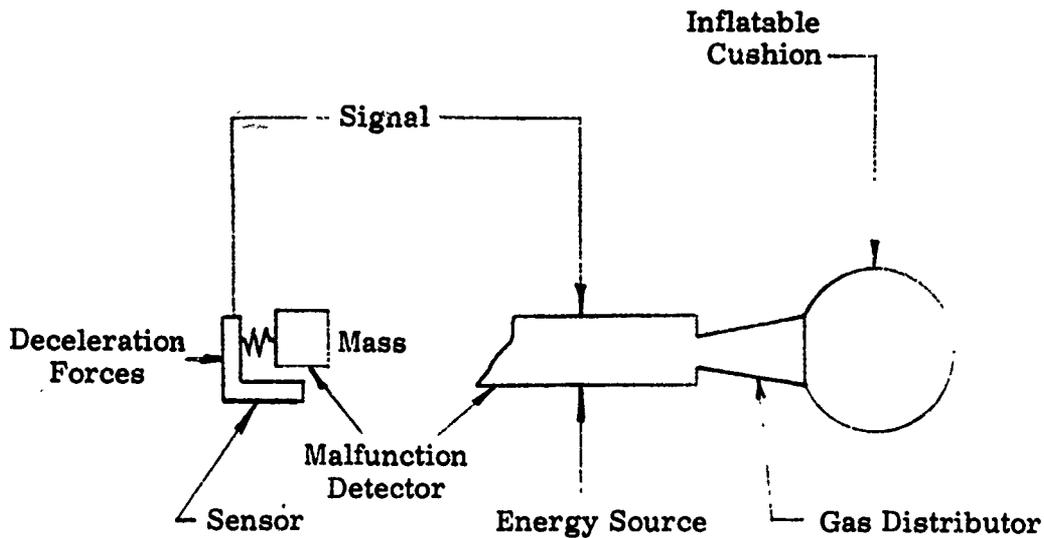
Airbag System Selection

The selection of the type of airbag system used in the four concepts was based on a study of the requirements for a general aviation inflatable restraint and current inflatable system technology.

General Description - The airbag system that is to be used as an inflatable occupant restraint for general aviation aircraft is one that deploys and restrains the occupants automatically in the event of an accident or crash. This system should consist of the following components.

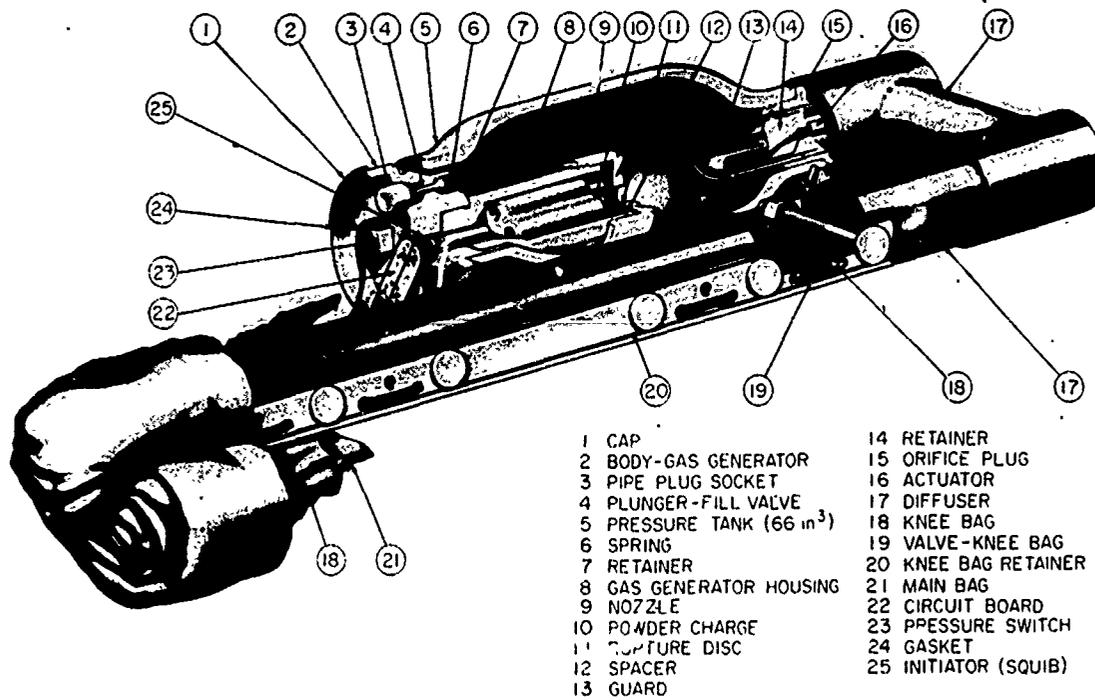
1. Crash Sensor
2. Inflator (Energy Source)
3. Inflatable Cushion
4. System Readiness and Diagnostic Indicator

A pictorial diagram of an airbag system illustrating the configuration of these components is shown on the following page.



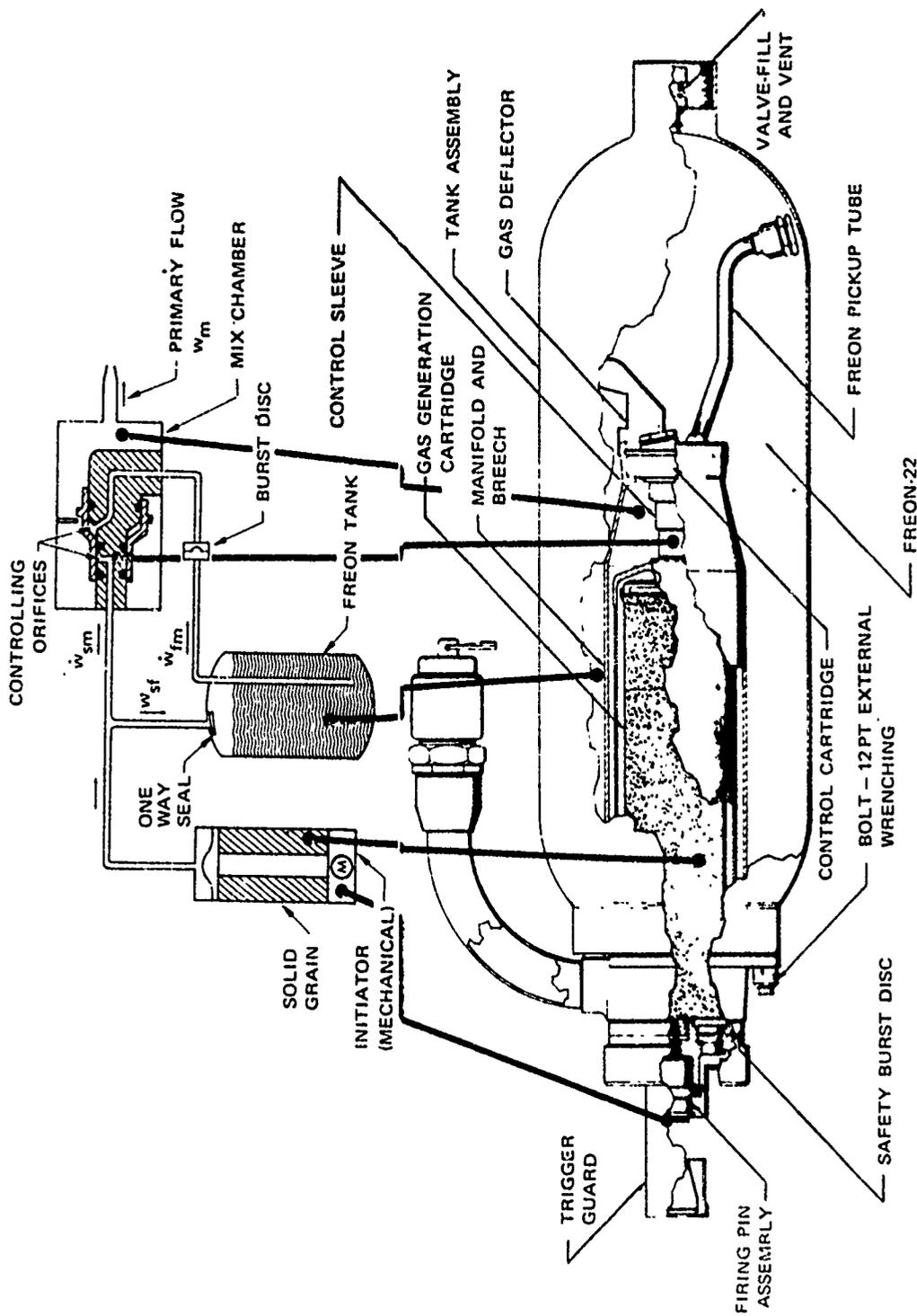
The sensor detects that a crash condition exists and activates the energy source. Gas from the energy source flows through the gas distributor (i.e. manifold and diffuser) and fills the inflatable cushion which restrains the occupant and protects him from the deceleration forces. The system readiness and diagnostic indicator detects the failure of a critical component of the system and displays a warning signal to the occupant. In the event that no components have failed, a signal indicating the operating status of the system is displayed. A cut-away view of a hybrid (stored gas and gas generator) airbag system developed for automotive use is shown in Fig 16. Two other types of energy sources for inflatable systems are shown in Figures 17 and 18.

Crash Sensor Selection - The Sensor is the element that detects a crash situation and supplies an initiating signal to the inflator. This signal is normally obtained by just a contact closure that ignites a squib in a gas generator or opens an orifice in a gas bottle. The development of crash sensors to date has been almost exclusively oriented toward automotive passive restraint systems. However, it appears that the technology and techniques developed for



[Reproduced from: Automotive Engineering February 1972]

Figure 16. Hybrid Airbag System



[Reproduced from: Ref 24]

Figure 17. Cool Gas Generator - Liquid Coolant

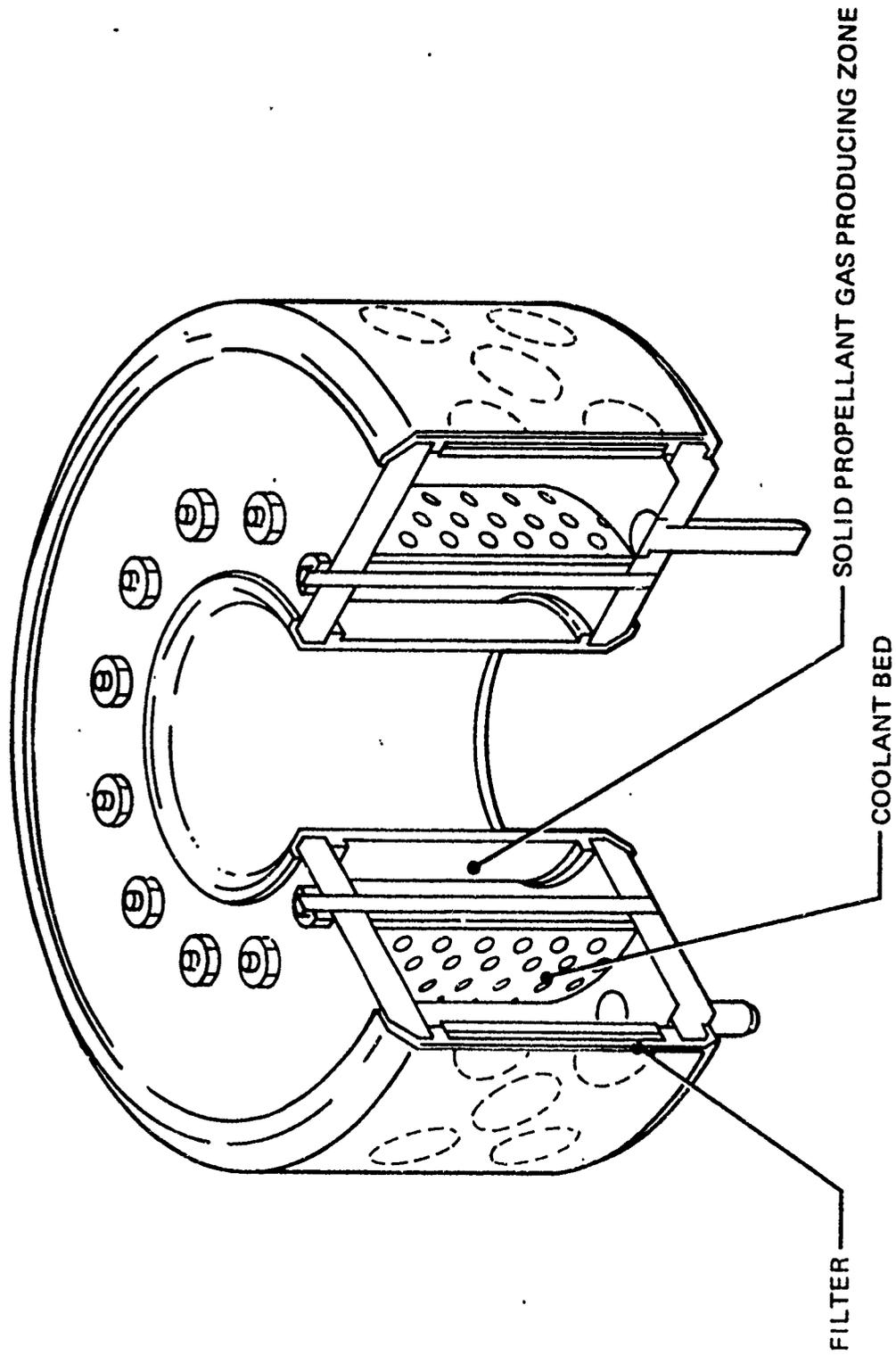


Figure 18. Cool Gas Generator - Solid Coolant

automotive use are compatible with the crash sensing requirements of a general aviation aircraft. Sensors for crash detection can be divided into two general categories.

- ... Impact Sensors
- ... Predictive Sensors

As the name implies, predictive sensors anticipate a crash situation and actuate before the impact occurs. These types of sensors usually employ one of the following principle.

- ... Acoustic Detection
- ... Optical Detection
- ... Radar

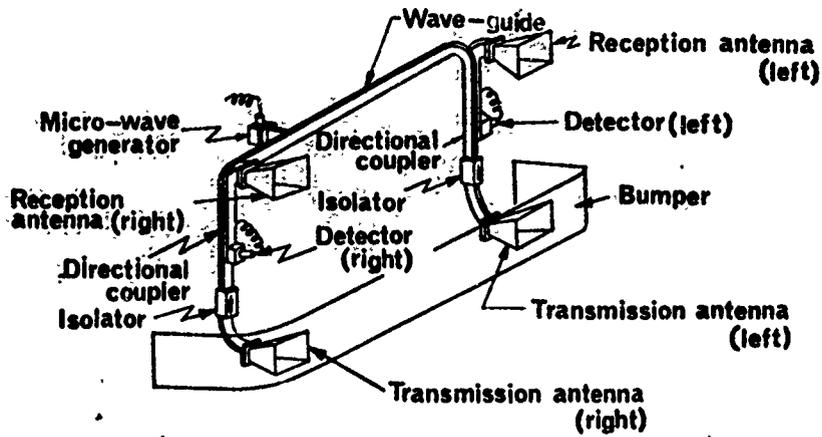
A comparison of these techniques is given in Table IV (Ref 20). Sensors using acoustic and optical techniques are currently being investigated in order to determine their feasibility as crash detectors, however, radar sensors have reached the stage where prototype units have been built and tested. A radar sensor developed by Toyota Motor Company (Ref 21) is shown in Figure 19.

Although radar sensors appear to be ideal from a crash detection standpoint, since they can sense an impact before it occurs, there are some inadequacies in using them for automotive crash detection. The biggest disadvantage to a radar sensor is its inability to identify obstacles as hazardous or non-hazardous (Ref 22). An automobile continuously has objects passing close to or in front of it which present little or no hazard, yet are detected as obstacles by radar sensors. Some of these objects are

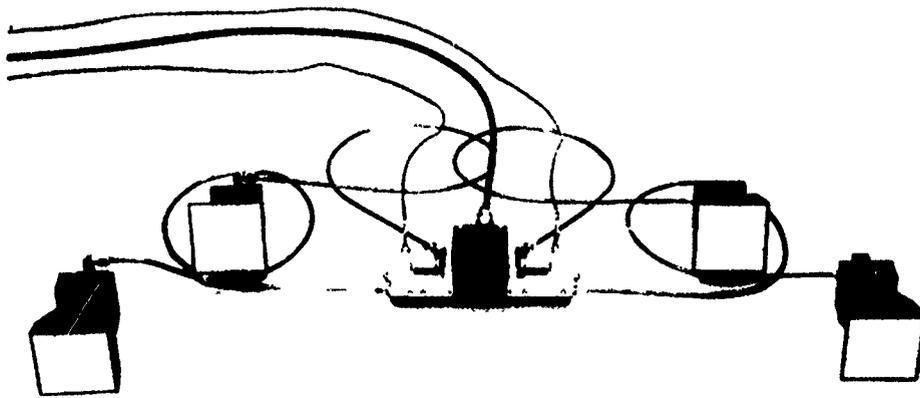
- ... small metal objects lying on roadway
- ... water spray from passing vehicles on wet roads
- ... animals running in front of car
- ... trees and metallic signs along roadside.

Acoustic (Ultrasonic; Sonic)	Optical (Laser, Infra-Red)	Radar (Microwave)
<p>Advantages</p> <p>Relatively easy signal processing due to lower frequencies (probably between 20 and 100 KHz); reflection coefficient depends on bulk modulus and density of obstacle; perhaps better correlation with mass can be expected when compared to microwaves; reduced vehicle-to-vehicle interference due to attenuation</p>	<p>Allows accurate determination of target position; and size relative velocity measurement possible; solid state sources available; potentially low cost in 5 years in large quantities.</p>	<p>Allows position and velocity measurement of obstacle relative to protected vehicle; solid state sources available; potentially low cost in 5 years in large quantities; negligible attenuation for distances involved; essentially unaffected by temperatures, humidity and precipitation; desired area of protection possible with some compromise.</p>
<p>Disadvantages</p> <p>Performance degraded by environment (ice, snow, mud, noise, debris); desired area of protection difficult to achieve; relatively high cost; much transducer development needed.</p>	<p>Performance degraded by foreign material in aperture - dust, fog, water, spray, snow, relatively high cost; desired area of protection difficult to achieve; inability to perform mass discrimination.</p>	<p>Radar echo may not be true indication of hazard posed by obstacle, i.e., poor crash discrimination; false alarm possibility due to intervehicle interference; no system action for certain impact configuration; relatively high cost; protection against vandalism may be difficult to achieve; inability to perform mass discrimination.</p>
<p>Remarks</p> <p>Ultrasonic system proposed by Sylvania, automatically flashes warning light when vehicle travels at least 35 mph and comes with 25 feet of protected car, operates at 100 MW power.</p>	<p>Robert Bosch Company found laser impractical for collision avoidance system.</p>	<p>X-Band, CW, Bistatic proposed by TSC to DOT; X-Band, CW proposed by Toyota; X-Band proposed by Bendix for braking; X-Band (10.5GHz) proposed by Bentley Associates; radar found as impractical for collision avoidance system by Robert Bosch Company.</p>

TABLE IV. COMPARISON OF CRASH SENSORS



Schematic Diagram (Reproduced from Ref 21)



Pictorial View (Reproduced from Ref 21)

Figure 19. Radar Crash Sensor

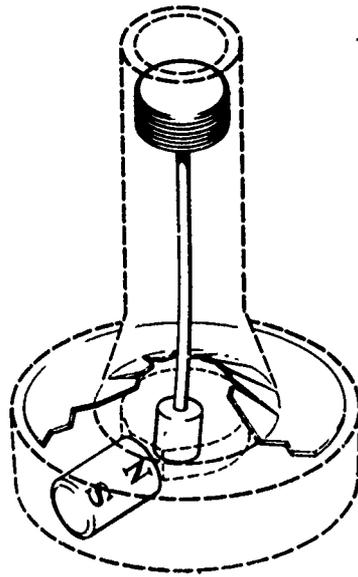
The reason a radar sensor detects non-hazardous objects is because it basically depends on the energy of the received signal to determine the size of an object. This return signal depends primarily on the reflective characteristics of the target and cannot be related to the physical mass of the object. This results in relatively small objects with large reflective surfaces, such as road signs, appearing as big as a full sized automobile or a tree to a radar sensor

The inability of radar sensors to differentiate or classify potential hazards is a distinct disadvantage in automotive applications, however, in a general aviation aircraft environment the differentiation of targets in the flight path of the vehicle would not be as critical. Anything in the flight path of an airplane, especially in a crash situation, is a hazard and therefore should be detected. This is particularly true in the case of aircraft crashes with large vertical decelerations. In this case, the vertical velocity of the aircraft exceeds that of an aircraft in a normal flight pattern. Detection of a higher than normal vertical velocity could be easily handled by a radar sensor such as the one shown in Figure 19. This sensor is typical of bistatic doppler radar systems that generally operate between 10 and 35 GHz. The term bistatic means that separate transmitting and receiving antennas are used, and ranging is accomplished through an overlay of the antenna patterns. The movement of a reflecting object relative to the transmitting antenna in the radar's field of view (overlay region) results in frequency modulation of the received signal (doppler effect). This signal is usually detected by a simple mixer which uses a sample of the transmitted signal for the local oscillator. A sensor of this type could be adjusted to detect the earth's surface and the relative velocity between the aircraft and the ground. Since the earth's surface is the only obstacle that needs to be detected in the vertical direction and since it has a large reflective surface, target discrimination would not be as big a problem for aircraft as it is for automobiles. This implies that present state-of-the-art radar anticipatory crash sensors could be modified for use as a general aviation crash sensor although the ramifications of practical use of such a device should be further investigated.

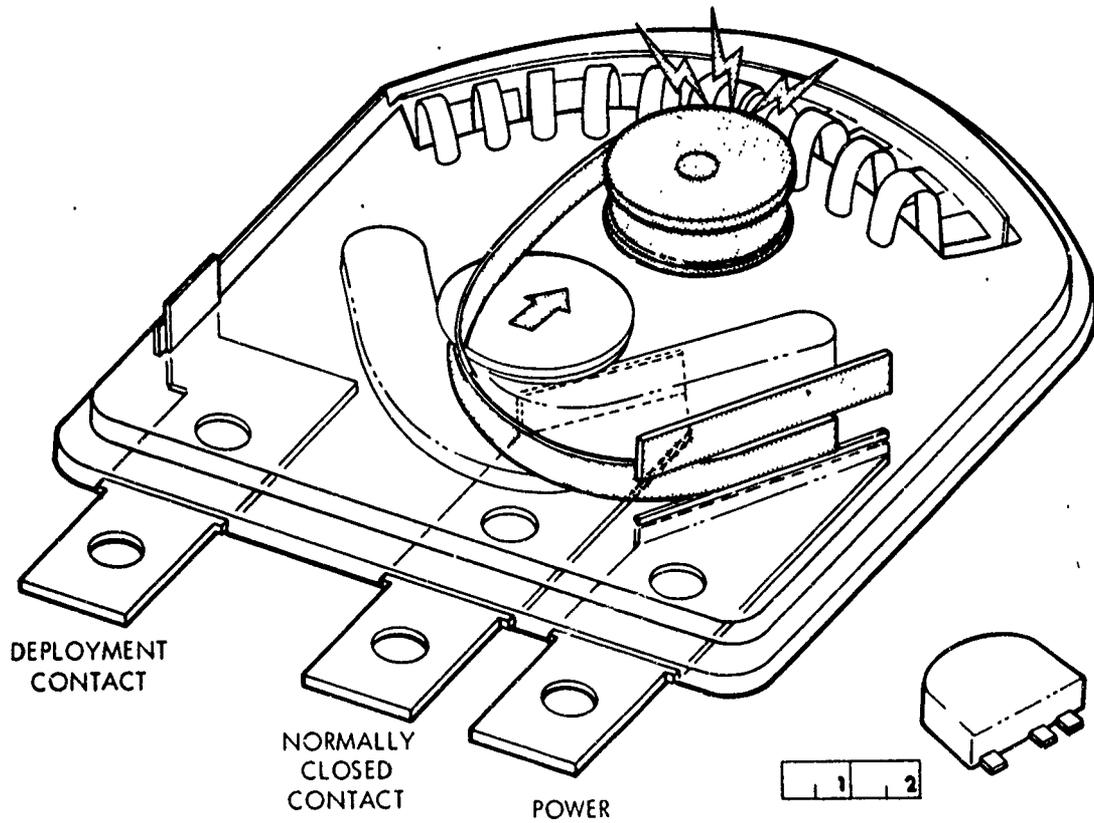
Impact sensors detect a crash situation by direct measurement of the vehicle's acceleration and/or velocity change after the initial contact has occurred. For this reason they are called post crash sensors. Crash sensors of this type generally consist of an inertial mass restrained by a spring mechanism or a piezoelectric transducer and operate on a principle that allows them to detect the magnitude and pulse duration of a crash signal. In the inertia sensor when an impact occurs, a mass moves away from a neutral position with sufficient velocity to make contact with a metal terminal. The stiffness of the spring restraining the mass plus its travel distance determine the amount of energy required to detect a crash situation and actuate the sensor. Piezoelectric sensors consist of a mass pressing against a piezoelectric transducer and electronic circuitry that measures the force and duration of an impact. If a crash acceleration of sufficient amplitude and duration is detected, the sensor provides an output signal to initiate an inflatable restraint system. Illustrations of several impact sensors are shown in Figures 20 and 21.

Both types of inertia sensors have similar response characteristics and are generally designed to sense critical acceleration wave forms but not respond to accelerations which are less severe.

Another variable which determines a sensors response is the time required to sense critical acceleration. Two sensors can have similar waveform detection characteristics, but one sensor might take twice as long as the other to detect a critical acceleration. The determining parameter for response time is the closure distance, the distance the sensor mass has to move to make the contact that provides an actuation signal. The longer this distance is, the more time it takes to sense an input acceleration. By specifying this reponse time and the critical acceleration waveform an inertia sensor can be designed and its response characteristics determined by theoretical analysis or testing. Since most aircraft crashes do not occur as pure longitudinal or vertical impacts, an impact angle over which the sensor must operate is another parameter that should be specified. This angle gives the number of degrees off center a critical acceleration can be applied and still be detected.

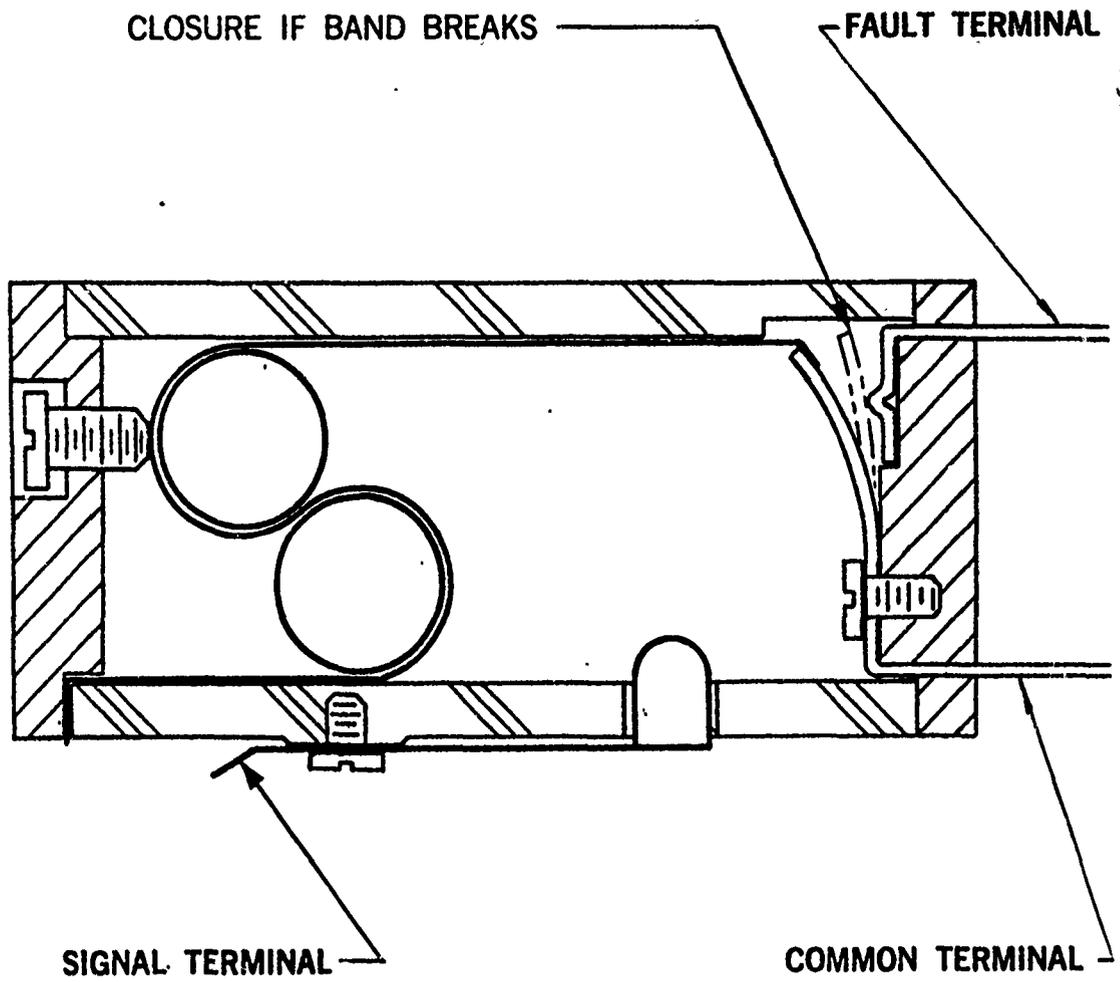


CRASH SITUATION



(Reproduced from Ref 20)

Figure 20. Impact Sensors - Wide Angle



[Reproduced from: Ref 27]

Figure 21. Impact Sensor - Directional

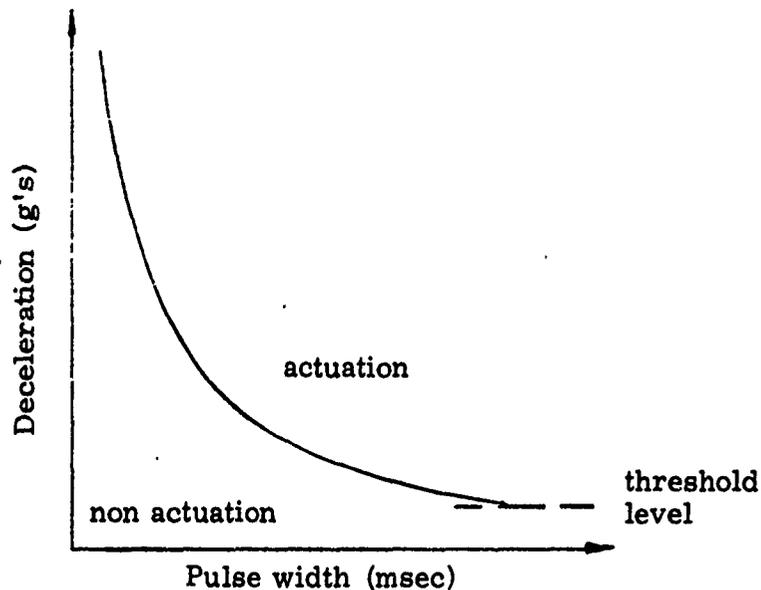
The selection of a crash sensor for an inflatable restraint system to be used in general aviation aircraft was based on the performance capabilities of existing crash sensors, the inflatable restraint design goals, and the crash design pulses for general aviation aircraft. The current technology of crash sensors indicates that inertia sensors can detect an aircraft crash condition and initiate deployment of an inflatable restraint system in approximately 5 milliseconds. This leaves 35-45 milliseconds for the longitudinal airbag to inflate and 20-25 milliseconds for the vertical airbag to inflate (see Inflatable Restraint Design Goals). Since these inflation times are within the capabilities of current airbag restraint systems, it appears that an inertia sensor could be used in an inflatable restraint system for general aviation aircraft. For this reason plus the ones listed below, inertia sensors were selected for use in both the longitudinal and vertical restraint systems instead of radar or anticipatory sensors.

Inertia sensors

- ... require a minimum of maintenance
- ... are inexpensive
- ... have no obstacle discrimination problems

A crash sensors function is to determine that a potentially dangerous impact is happening. To be able to accomplish this, a sensor must be capable of differentiating between severe and non severe crashes. This can be accomplished by specifying a critical crash acceleration profile, a minimum acceleration level, and an actuation time. The critical crash profile is an acceleration time waveform that is representative of a crash environment. It is a "typical" acceleration time history that is applied to the crash sensor during a potentially dangerous crash and an acceleration the sensor must detect. The minimum deceleration or threshold level is the value which determines the severe and non severe impacts. Crashes whose peak accelerations are above the threshold level will be detected provided their time duration is long enough and accelerations lower than the threshold will not actuate the sensor. High peak accelerations with very short pulse widths

and low velocity changes should not be detected since acceleration waveforms of this type can occur routinely during normal operation or maintenance of the aircraft. The range of accelerations and pulse widths that will or will not actuate the sensor can be obtained from the sensor's response curve which generally has the following form.



The actuation or response time of the sensor is the time it takes for the sensor to detect the critical crash profile. Since it is generally desirable to detect a crash as soon as possible, the response time can be the time required for the critical crash pulse to reach the threshold level.

From this discussion of sensor specifications it is apparent that the actual values depend a great deal on a particular acceleration waveform. Since it should not be expected that every crash will generate the same acceleration waveform, the effects of different waveforms should be considered.

Since inertia sensors can generally be modeled as a spring-mass-damper system (Ref 23) whose equation of motion is

$$\ddot{X}_R + 2\zeta\omega_n\dot{X}_R + \omega_n^2 X_R = -A(t)$$

This is the same second order differential equation described in the previous section on crash profiles. The response of this system with $\zeta = 0$ to various symmetrical pulses having equal area is shown in Figure 4. These responses indicate that for $\frac{\tau}{T} \leq 1$ a displacement exists which all responses reach at the same time. For instance, at $\frac{\tau}{T} = 1$ all responses reach a value of 1 at $\frac{t}{\tau} = 1$. This means the natural period of inertia sensor should be as long or longer than the crash pulse duration to insure that the effects of pulse shape are negligible.

This analysis of crash sensor response is based upon a linear model. Fabrication techniques and materials may prevent an actual crash sensor from responding in a linear fashion. Therefore, the conclusions reached should be regarded as approximations and may be revised when the non-linearities of a particular sensor have been defined.

Longitudinal Sensor

In the longitudinal direction, the design crash acceleration as given in Fig 1 is a triangular pulse with a peak of thirty g's and a time duration of 104 milliseconds. Since this is the crash input to be protected against, it is also the critical crash acceleration profile that is applied to the crash sensor. The minimum acceleration level can be determined from the load factor of the aircraft. Since the majority of general aviation aircraft have design load factors of 3 to 4 g's, an acceleration in excess of this indicates the aircraft is loaded beyond its normal capacity as would be the case in a crash situation. Therefore, an acceleration level of 5 g's was arbitrarily selected as the acceleration that would indicate a crash condition existed. In the longitudinal direction an acceleration level of 5 g's is reached in about 9 milliseconds, which is the response time required for the sensor. The maximum natural frequency of the sensor required to minimize pulse shape effects can be determined from the critical acceleration pulse. The ratio of the input pulse width to natural period of the sensor should be less than or equal to one, which means the natural frequency of the sensor should be less than or equal to 10 Hz. Another factor

to take into account is the impact angle the aircraft might have in a crash environment. How many degrees from the longitudinal axis of the aircraft can a critical acceleration be detected by the sensor? Based on the capability of current sensors and because of a lack of data or other criteria, the impact angle was arbitrarily set at $\pm 25^{\circ}$. This results in the sensor requirements for the longitudinal direction being those given below.

critical acceleration pulse: symmetrical triangular pulse with
30 g peak and duration of 104 milliseconds

impact angle: $\pm 25^{\circ}$

response time: 9 milliseconds

natural frequency: ≤ 10 Hz

The location of the longitudinal sensor should be as far forward in the aircraft as possible. This will provide for the earliest possible detection of a crash situation. On a single engine aircraft, the sensor should be mounted in the forward area of the engine compartment and in multi-engine aircraft the sensor should be mounted in the nose.

Vertical Sensor

The vertical crash acceleration, also given in Figure 1, is a symmetrical triangular pulse with a peak acceleration of 58 g's and a pulse width of 54 milliseconds. This pulse is similar to the longitudinal acceleration except that it has a shorter time and a higher peak. This means a different sensor will be required for the vertical airbag system. Using the same criteria that was used for the longitudinal sensor, the requirements for the vertical direction were determined.

critical acceleration pulse: symmetrical triangular pulse with
48 g peak and duration of 54 milliseconds

impact angle: $\pm 25^{\circ}$

response time: 3 milliseconds

natural frequency: ≤ 20 Hz

The mounting location for the vertical sensor should be approximately 14 inches below the cabin floor of the aircraft. This distance is required to insure that the critical acceleration pulse can be detected quickly enough to inflate the vertical airbag system. The activation signal from the vertical sensor should also be used to initiate the longitudinal airbag system and visa verse. Inflating both restraint systems in the event only one sensor detects a crash situation will provide the airplane occupant with maximum possible protection during an accident.

Inflator Selection

The inflator or energy source is the component of an airbag system that supplies the gas to inflate the cushion after an actuation signal from the crash sensor has been received. Energy sources for inflatable restraint systems must supply a rapid flow of gas and provide some initial control of that energy. The sensor signal either ignites a propellant which generates the gas or it releases a previously stored high pressure gas. Once the gas is released it is directed into the cushion through a gas distribution mechanism. This device consists of a manifold, filter, and diffuser which direct the flow of gas for proper airbag inflation and pressure distribution (Ref 24). Inflators used in current air cushion restraint systems can be separated into four general catagories.

- ... Stored Gas Inflators
- ... Cool Gas Generators
- ... Hybrid Inflators
- ... Aspirated Inflators

Stored Gas Inflators (Ref 24 and 25)

Stored or bottled gas inflators provide a relatively efficient energy source and are generally used for applications where minimal weight and storage volume are not required. These inflators usually have a compressed gas (at pressures up to 5000 psi) stored in a pressure vessel and release it upon

command by a valve attached to the bottle. This release valve consists of a diaphragm or rupture disk that normally maintains the high pressure gas storage. Upon receiving a signal from the sensor a detonator is ignited which ruptures the release valve and initiates the gas flow. In addition to the release valve, there may be another valve that controls the flow of gas into the cushion. The purpose of this valve is to provide even pressure distribution during release of the gas so that the initial forces of the inflating bag are reduced.

As the gas exits through the release valve, its temperature will either increase or decrease depending on the Joule-Kelvin coefficient of the gas. Helium will exhibit an increase in temperature during expansion while nitrogen will cool to approximately -200°F when expanded from a pressure vessel initially at 5000 psi and 60°F . If the particular application of the stored gas inflator cannot tolerate the heating or cooling effects, there are techniques available which will limit the change in temperature to more reasonable ranges.

A typical stored gas inflator is shown in Figure 22 and the characteristics of this type of inflator are given below.

- ... low temperature gas
- ... low toxicity
- ... low flexibility (bag volume and inflation time)
- ... temperature and pressure sensitive
- ... high weight and storage volume
- ... high pressure gas storage required

Cool Gas Generator (Ref 24 and 25)

A gas generator is an inflator that generates the gas required to fill the air cushion by burning a solid propellant. For restraint system application, this type inflator functions when an igniting squib is energized by a sensor. This action ignites a propellant which contains an oxidizing agent that supports the

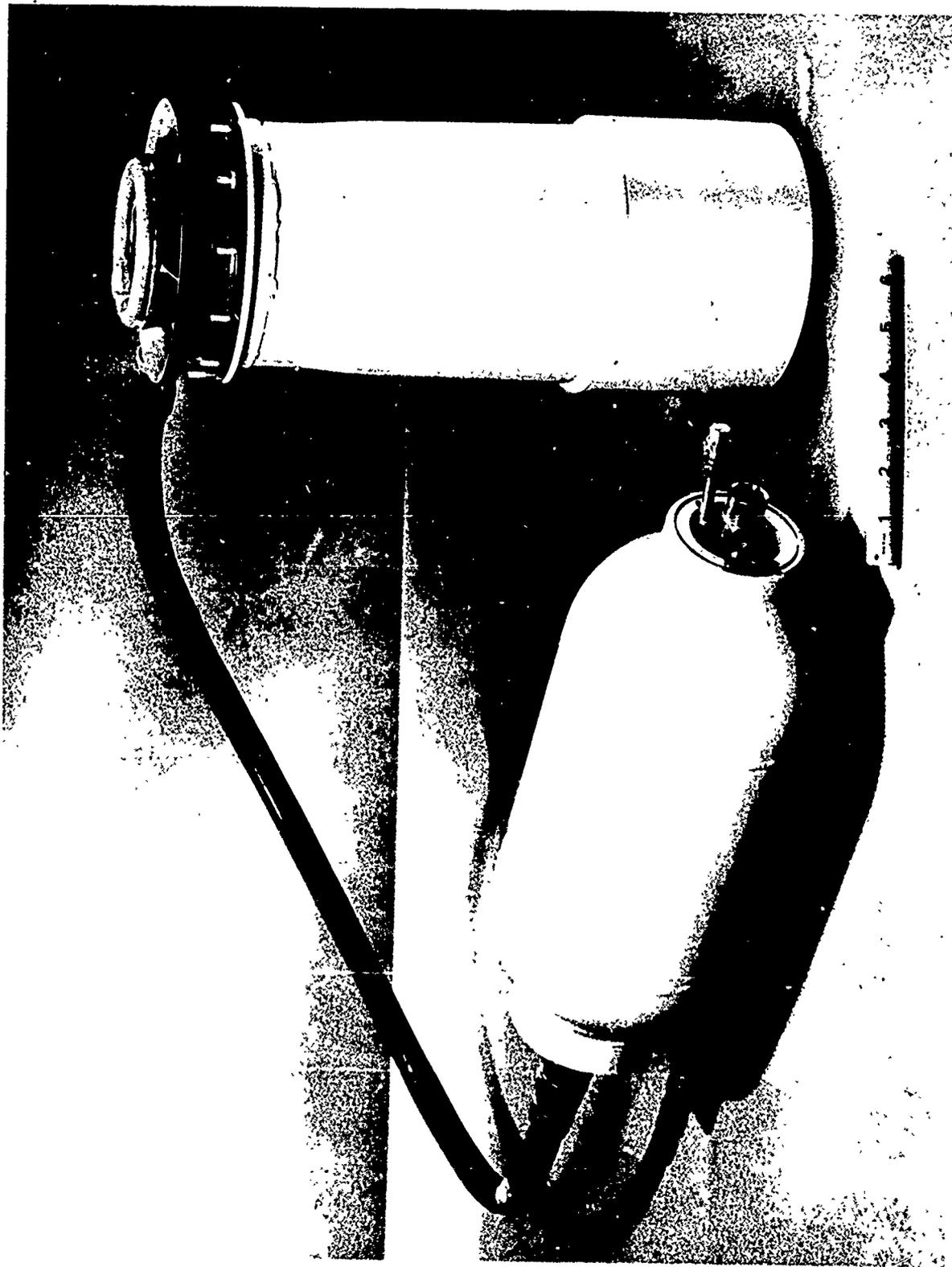


Figure 22. Stored Gas Inflator

reaction once it is started. The propellant burns rapidly producing hot gas which is cooled as it passes through a liquid, solid, or gaseous refrigerant. After being cooled by the refrigerant the gas passes through a filter that traps solid particles and diffuses the gas as it fills the attached airbag.

Cool gas generators can be designed to operate over a wide temperature range and deliver almost any quantity of gas at any temperature or pressure. Typical performance parameters for this type of inflator are:

- ... Operating time: 20 to 30 milliseconds
- ... Operating pressure: 500 to 5000 psi
- ... Delivery pressure: 10 to 3000 psi
- ... Delivery temperature: -40 to +4000^oF
- ... Operating temperature: -65 to +220^oF

To obtain this wide variation of performance parameters, a variety of propellant-refrigerant combinations can be utilized, depending on the output gas required. Some of the common refrigerants used in these inflators are water, ammonia, carbon dioxide and Freon components. The main advantage of the cool gas generator over a compressed gas inflator is a significant reduction in weight, size and storage pressure. Figures 17 and 18 illustrate two types of cool gas generators and typical operating characteristics for inflators of this kind are:

- ... low weight and storage volume
- ... no stored gas leakage
- ... low maintenance requirements
- ... high flexibility
- ... medium toxicity
- ... high gas temperatures

Hybrid Inflators (Ref 24)

A hybrid inflator provides the required volume of gas by combining the output of two types of inflators. The first source is a gas generator that produces

hot gases by burning a solid propellant. The second source is a stored gas which provides energy to the system quickly and cools down the hot gases from the gas generator.

The gas cooled hybrid inflator mixes the gases from a gas generator with a gas stored in a high pressure bottle to produce a cooler exit gas. The hybrid inflator reduces the volume of high pressure gas that must be stored and in some applications can be used as a dual level inflator. The high pressure gas can be released without igniting the gas generator to provide a low level output, or a high level output could be obtained by activating both energy sources.

A hybrid inflator consists of a high pressure vessel, a gas generator housing, a propellant, a squib and detonator, and a release valve. The pressure vessel contains a high pressure inert gas and the gas generator includes a solid propellant, an oxidizer, and a squib. The squib initiates the gas generator process by igniting the propellant, the generator housing directs the flow of hot gas and thereby controls the mixing of the gases. The detonator is used to rupture a diaphragm, thus releasing gas into the manifold. Gas flow rates can be regulated by controlling the surface area and composition of the propellant and the exit orifice. A representative hybrid inflator is shown in Figure 16 and operating characteristics for this type of device are as follows:

- ... low toxicity
- ... flexible gas thermodynamics
- ... medium weight and storage volumes
- ... medium gas temperatures
- ... temperature and pressure sensitive

Aspirated Inflators (Ref 19 and 25)

In applications where a low pressure, high volume gas supply is required, an aspirator or jet pump can be used with any of the previously discussed inflators to augment the gas supply. An aspirator is essentially a pump that utilizes the kinetic energy of one fluid to cause motion of another fluid. A primary high

velocity fluid is supplied to the aspirator and its kinetic energy includes motion of the ambient fluid near the inlet. These two fluids pass through a mixing section where a portion of the fluid's kinetic energy is converted into an increase in static pressure.

A generalized aspirator consisting of primary flow tube, an inlet area and a diffuser or flow channel is shown in Figure 23. At the inlet, the primary flow is a concentrated jet that contains most of the kinetic energy of the system. The shear area between the primary flow and the ambient area is highly turbulent which causes the two gas streams to mix. The gases travel down the flow channel and are progressively better mixed. The primary jet diffuses and transfers part of its kinetic energy to the secondary air. If the mixture section is not long enough, the gas streams will not be sufficiently mixed to attain maximum performance. This would be the case if the mixing tube were terminated at Plane 2. The optimum location for the exit is at Plane 3, where the two gas streams are evenly mixed. If the mixing section is too long (Plane 4), wall friction effects decrease the performance of the aspirator. The approximate shapes of the velocity profiles are shown to the right of the aspirator schematic. The parameter that describes an aspirator's mixing efficiency is the ratio of characteristic length (L) to flow channel diameter (d). For a simple aspirator which has only one primary flow nozzle, L/d is approximately 6. If envelope restrictions do not allow optimum ratios to be achieved, the performance of a shortened aspirator can be increased by using more than one primary flow nozzle. Better distribution of the primary fluid momentum across the inlet area is achieved and less length is required to attain complete mixing.

The performance of an aspirator is described by a pumping ratio, μ , which is defined as the ratio of secondary fluid mass to primary fluid mass.

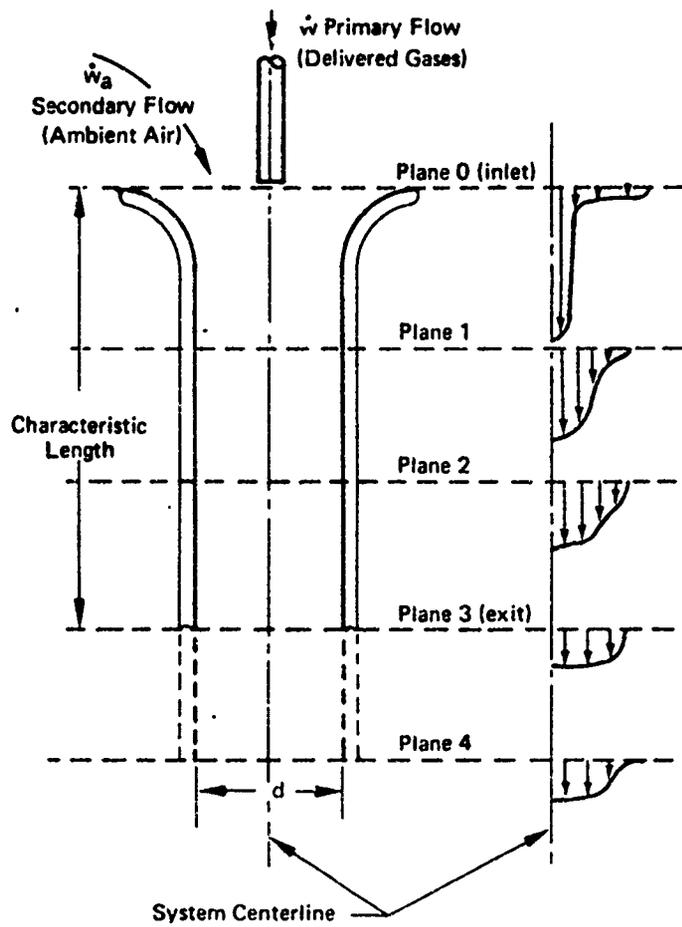
$$\mu = w_a / w$$

The pumping ratio is related to the aspirator geometry by the term A/w

A = throat cross sectional flow area

w = primary fluid mass flow rate

For low discharge pressures the relationship between the pumping ratio and A/w is approximately linear, the higher the value of A/w, the larger the



[Reproduced from: Ref 18]

Figure 23. Generalized Aspirator Flow

pumping ratio. However, the pumping ratio decreases as the discharge pressure is increased, and at some increased pressure, the aspirator reaches a stall condition. In this condition, no ambient fluid is being entrained, and the primary fluid is backflowing through the aspirator. The aspirator is essentially a fluidic check valve. It is obvious that an aspirator operates similar to a pump or fan because the performance is reduced with an increase in discharge pressure. To increase the capacities available from an aspirated inflator, units can be staged to produce a high volume-low pressure mode along with a low volume-high pressure mode. In Figure 24 the operation of an aspirated inflator is illustrated and typical characteristics of this kind of inflator are:

- ... reduced gas source requirements
- ... low noise
- ... low compartment overpressures
- ... low toxicity
- ... multiple impact capability
- ... medium gas temperatures

Inflator Evaluation

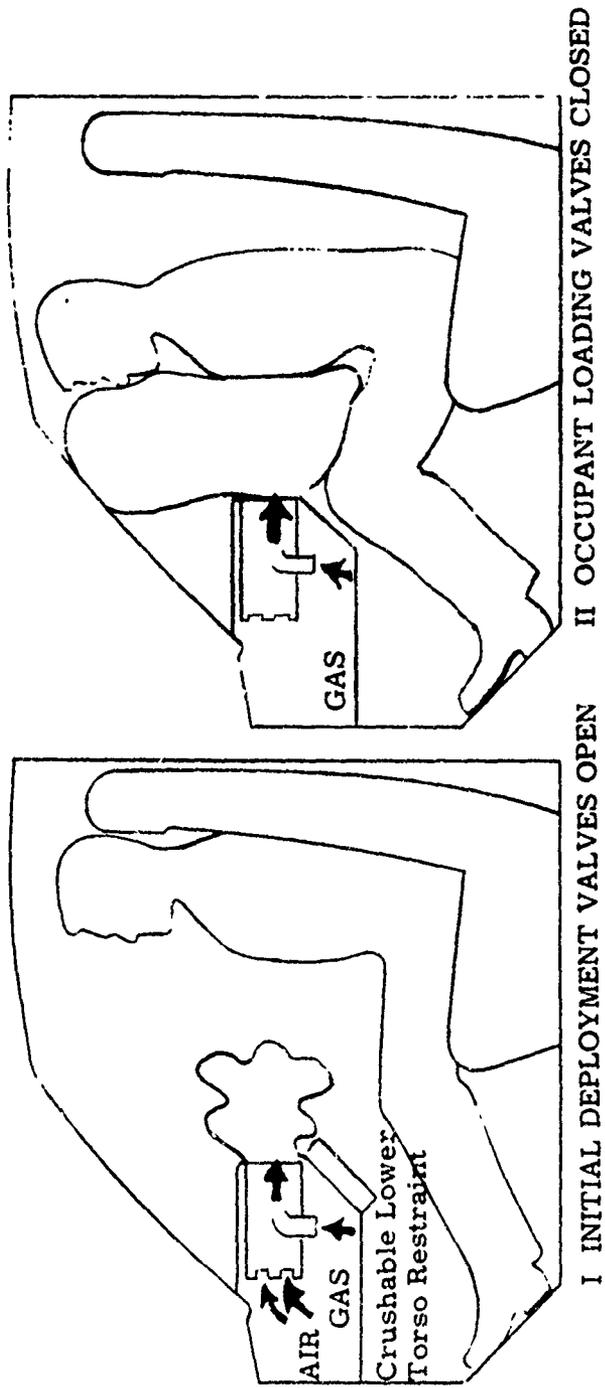
The selection of an inflator for a general aviation inflatable restraint system was made by comparing the characteristics of the different inflators with the design goals previously established for the vertical and longitudinal airbag restraints. The design goals were classified into two groups, dynamic requirements and operational requirements.

Dynamic requirements

- ... pressure
- ... volume
- ... inflation time
- ... displacement

Operational requirements

- ... bag surface temperature



(Reproduced from Ref 28)

Figure 24. Aspirated Inflator

- ... noise
- ... toxicity
- ... weight
- ... storage volume

The dynamic requirements for the vertical and longitudinal restraints are different and when compared with inflator characteristics resulted in the following evaluation .

Vertical Airbag Restraint Inflator

Acceptable

- ... Gas Generator
- ... Hybrid Inflator
- ... Store Gas Inflator

Unacceptable

- ... Aspirated Inflator

Longitudinal Airbag Restraint Inflator

Acceptable

- ... Aspirated Inflator
- ... Gas Generator
- ... Hybrid Inflator
- ... Stored Gas Inflator

All four types of inflators are capable of meeting the dynamic requirements of the longitudinal restraint but only three satisfy the vertical restraint's requirements. An aspirated inflator would not be practical because of the high bag pressure required.

Since the longitudinal and vertical inflatable restraints both have the same operational requirements, inflator characteristics were compared with only one set of requirements. This comparison is illustrated in Table V. Examination of the operational requirements indicated that an optimum inflator would minimize each parameter. Opposite these parameters, each inflator's relative characteristic was listed as low, medium, or high and the following values were assigned these designations:

	INFLATORS			
Operational Requirements	Stored Gas	Gas Generator	Hybrid	Aspirated
Gas Temperature	Low (1)	Med (2)	Med (2)	Med (2)
Noise	Med (2)	Med (2)	Med (2)	Low (1)
Gas Toxicity	Low (1)	High (3)	Med (2)	Med (2)
Weight	High (1)	Low (1)	Med (2)	Low (1)
Storage Volume	High (1)	Low (1)	Med (2)	Low (1)
Operational Cost	10	9	10	7

Table V. Inflator Comparison - Operational Requirements

- ... low - 1
- ... medium - 2
- ... high - 3

An operational cost was determined by summing the values for each inflator over all operational requirements. Since the lowest operational cost is indicative of the optimum inflator, the rank of inflators with respect to the operational requirements is

1. Aspirated Inflator
2. Gas Generator
3. Hybrid Inflator
4. Stored Gas Inflator

The evaluation of the inflators in comparison with the design goals resulted in an aspirated inflator selected for the longitudinal restraint and a gas generator for the vertical restraint. This can be summarized as shown below.

Longitudinal Inflator

- ... aspirated inflator (gas generator)
- ... meet longitudinal dynamic requirements
 - airbag pressure - 2.75
 - airbag volume - 6 cu ft
 - inflation time - 30 - 40 msec
 - displacement - 19 in.

Vertical Inflator

- ... gas generator
- ... meet vertical dynamic requirements
 - airbag pressure - 10.5 psig
 - airbag volume - 4 cu ft
 - inflation time - 20 - 25 msec
 - displacement - 12.5 in.

Inflatable Cushion (Ref 25)

The inflatable cushion is the component of an airbag restraint that inflates and restrains the occupant from impacting against the interior of the cabin. The cushion must be fabricated from a material that can withstand the inflation and occupant impact forces and yet not deteriorate when compressed for long periods of time in a small container. The material should also have a high strength to weight ratio. A recent study (Ref 25) investigated air cushion design criteria and outlined the factors that should be considered in the selection of materials and methods of fabrication. The materials and fabrication technique given below were chosen as the optimum for an inflatable cushion.

Fabric

Yarn - nylon 5.5 oz/sq yd

Weave - ripstop

Coating - neoprene 1.5 oz/sq yd

Fabrication

Vulcanized seams

Flat seams

Cushion Package

Material - ABS - vinyl/urethane foam composite

Fabrication - tear away seams

System Readiness and Diagnostic Indicator

The system readiness and diagnostic indicator electronically monitor critical parameters of inflatable system components, such as gas pressure, propellant condition, detonator and squib continuity, and crash sensor continuity (Ref 24). It also reports on the condition of electrical power required for operation. Information from the different monitoring stations, indicating the operating status of the system is displayed on a panel that is visible to the occupant. The operating characteristics of the readiness and diagnostic indicator depend primarily on the actual hardware components used in an

inflatable restraint system which implies that each indicator is unique and can only be used with a particular system. More research is needed to adequately define the operating criteria for an indicator used in a general aviation inflatable restraint, however, some general requirements can be determined now.

... provide visible and audible signal upon detection of vital component failure

... visibly indicate operational readiness of inflatable system

... protect against accidental operation

CONCEPT DEVELOPMENT AND SELECTION

Four inflatable restraint system concepts were developed utilizing the general aviation aircraft composite interior and airbag manufacturers hardware data. These concepts were designated as:

- ... Dual Cushion System
- ... Unit Cushion System
- ... Seat Back System
- ... Inflatable Belt System

The dual cushion system, shown in Figure 25, has separate airbags and inflators for the longitudinal and vertical system. The vertical inflatable restraint has the cushion mounted under the seat with the inflator mounted beneath the floor. The airbag inflates when a crash acceleration in the vertical axis is sensed. As the cushion inflates, it activates a release mechanism in the seat legs that allows the seat to collapse permitting the airbag to fully support the seat and absorb the energy. In the longitudinal direction the cushion is mounted on the control panel above all the indicators and the inflator is mounted directly behind the cushion pack. In the event of a crash, the occupant is thrown into the inflated cushion which provides a tolerable restraining force through which he displaces, thus dissipating the energy. A disadvantage to this concept is the possibility that the inflator may puncture the cabin floor and be pushed into the cabin interior in a vertical crash. If this event should occur the occupants would be prevented from coming in contact with the inflator by the seat pan and cushion; however, the intrusion of the inflator into the cabin space could reduce the allowable stroking distance of the seat pan. This would cause more energy to be transferred to the occupant and increase the probability of injury.

The unit cushion system, shown in Figure 26, has a single bag and inflator for restraints in both the vertical and longitudinal directions. The airbag and inflator are mounted under the seat. During the inflation sequence the lower section of the bag deploys underneath the seat, dissipating the vertical

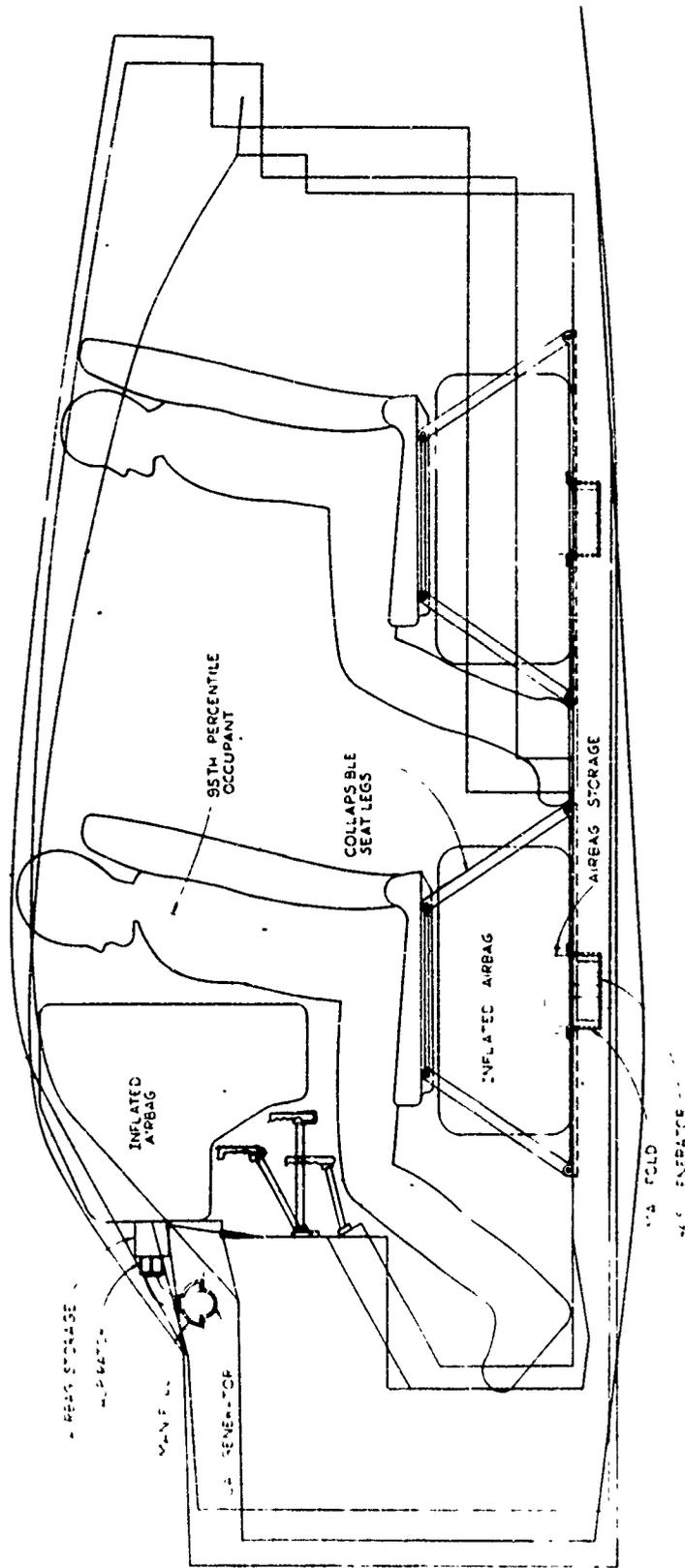


Figure 25a. Dual Cushion Inflatable Restraint System - Side View

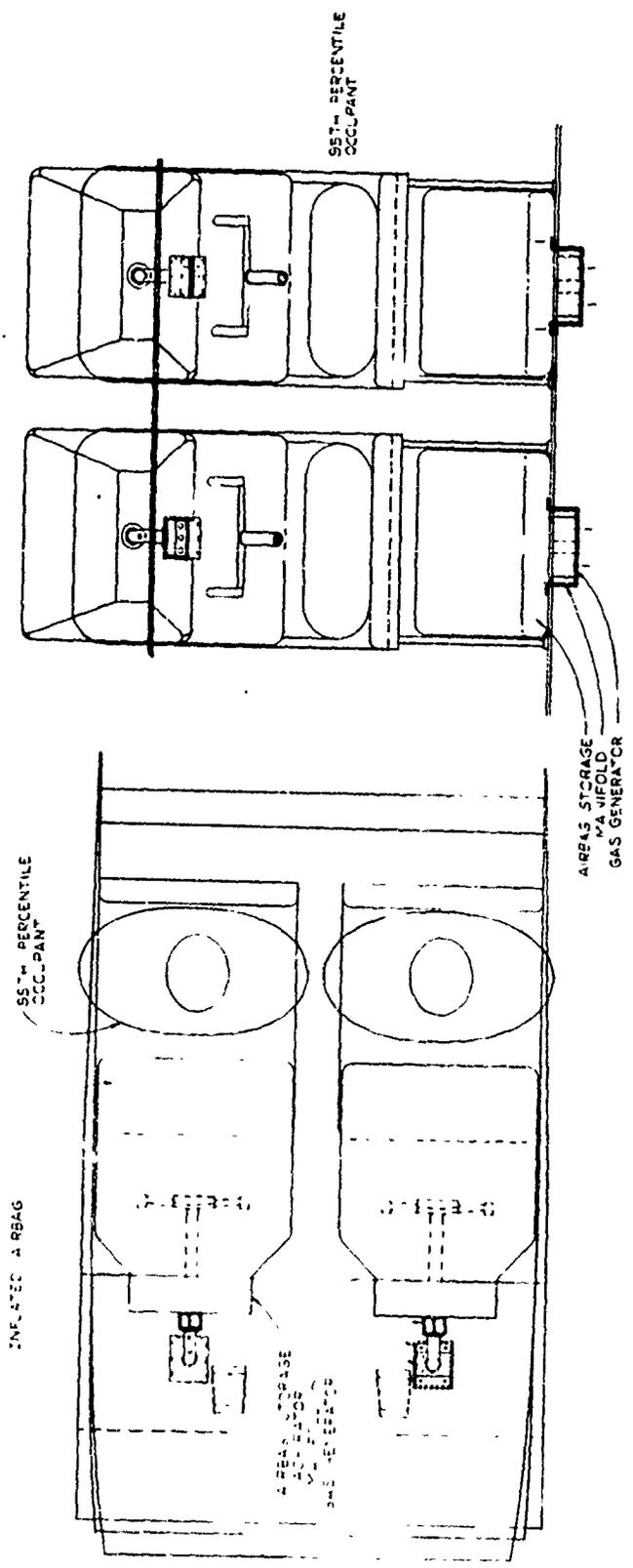


Figure 25t. Dual Cushion Inflatable Restraint System - Front and Top View

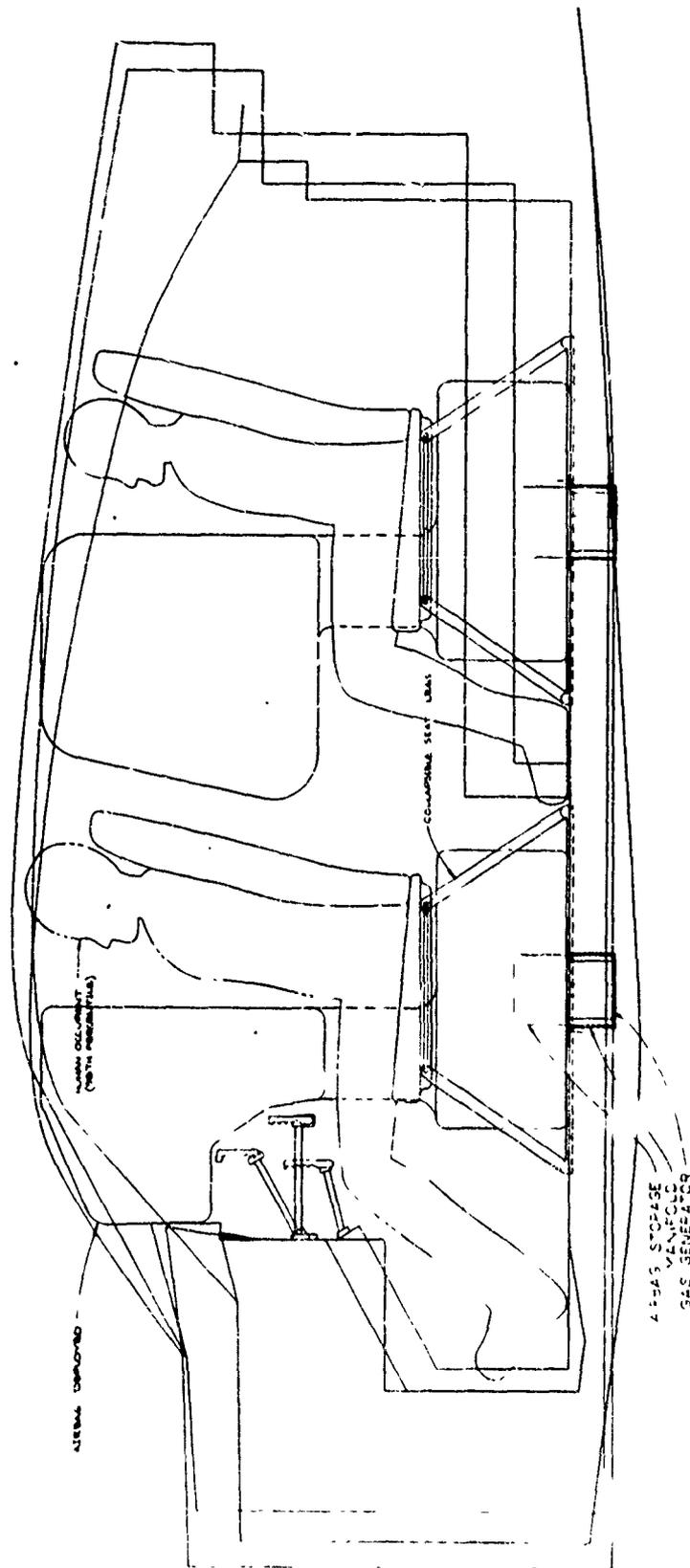


Figure 28a. Urit Cushion Inflatable Restraint System - Side View

energy as the seat collapses. The upper section comes up the side of the seat, inflates directly in front of the upper torso, and absorbs the longitudinal energy as the upper torso rotates forward. This concept also has the drawback of possibly having the inflator intrude into the cabin interior during a vertical crash thereby reducing the allowable displacement of the seat.

The seat back inflatable restraint system, shown in Figure 27, has two separate airbag systems, one for vertical restraint and one for longitudinal restraint. The restraint for the upper torso consists of two L shaped bags that come around the side of the occupant and hold him to the seat back. The seat back is hinged to an energy absorber which dissipates the longitudinal energy as the upper torso and seat back rotate. The vertical airbag is mounted on the aft section of the seat pan and deploys underneath the seat in a crash environment. The inflators for both the upper torso and vertical restraint are mounted on the seat back.

The inflatable belt system, shown in Figure 28, also has two separate inflatable restraint systems with the vertical airbag system the same as the one in the previous concept. The longitudinal restraint system is an integral part of the seat belt. In a crash situation, the bag inflates and fills the space between the upper torso and control panel. As the occupant's upper torso rotates forward it compresses the airbag and dissipates the energy. The inflator for this airbag is mounted on the back of the seat and the gas is supplied to the airbag through hoses mounted in the seat belt.

Concept Selection

The selection of a particular concept was made by comparing each concept with the evaluation criteria listed below.

- ... normal operation of aircraft's controls
- ... no interference with control panel after two seconds
- ... no impairment of visibility after two seconds

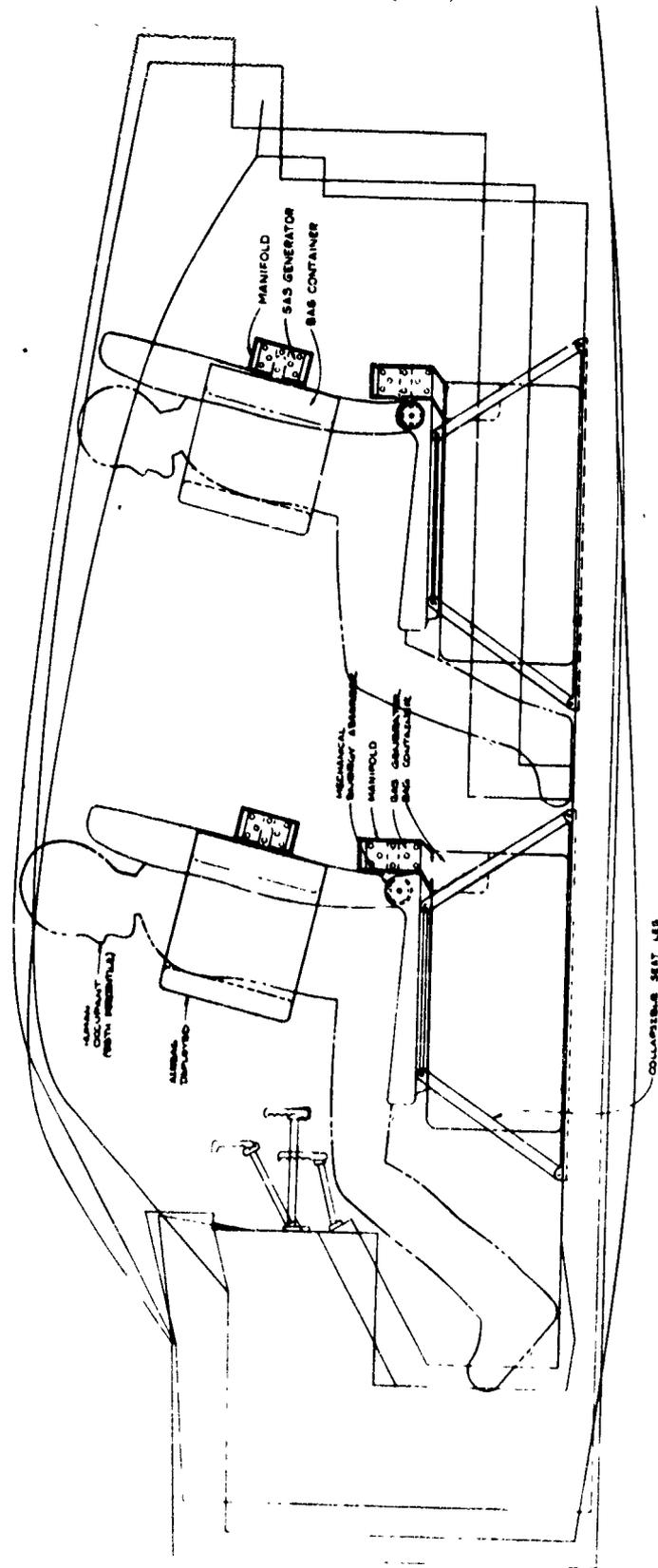


Figure 27a. Seat Back Inflatable Restraint System - Side View

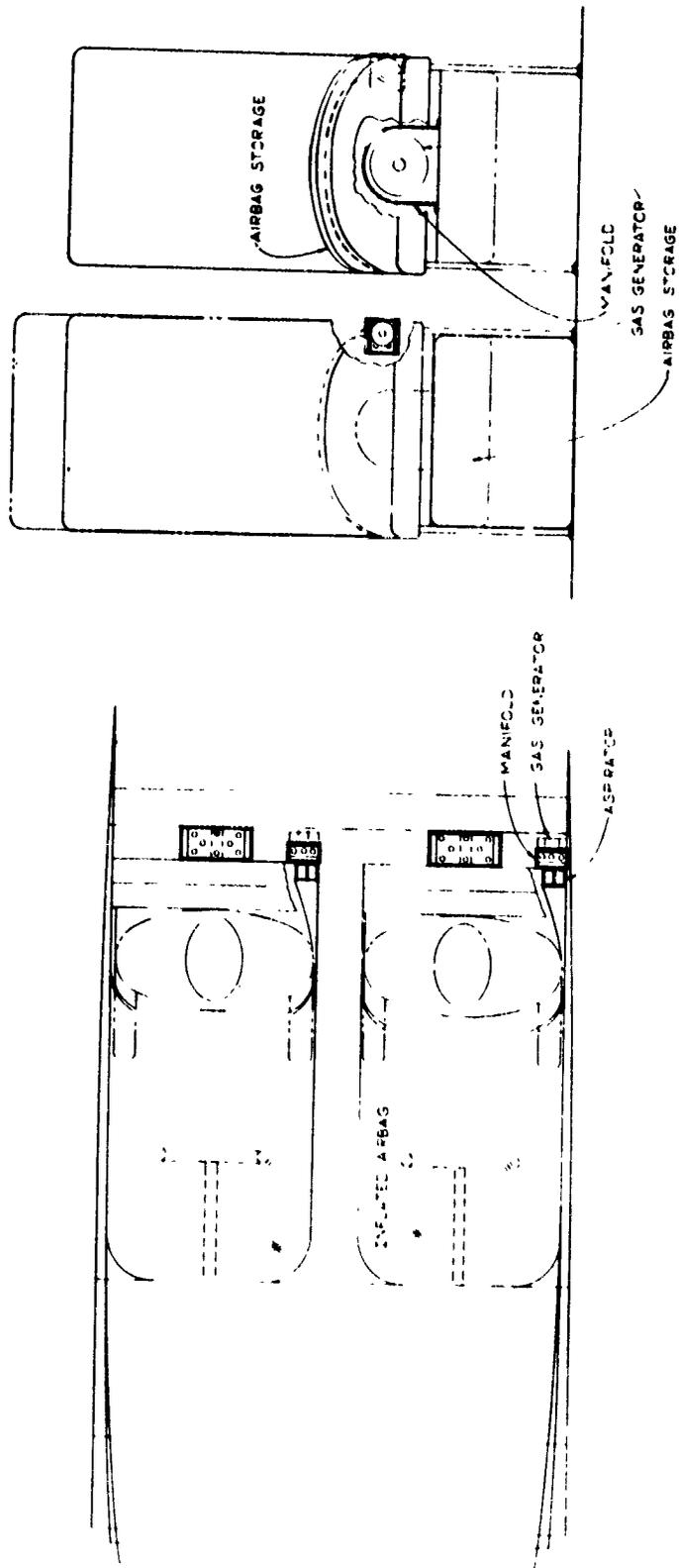


Figure 27b. Seat Back Inflatable Restraint System - Front and Top View

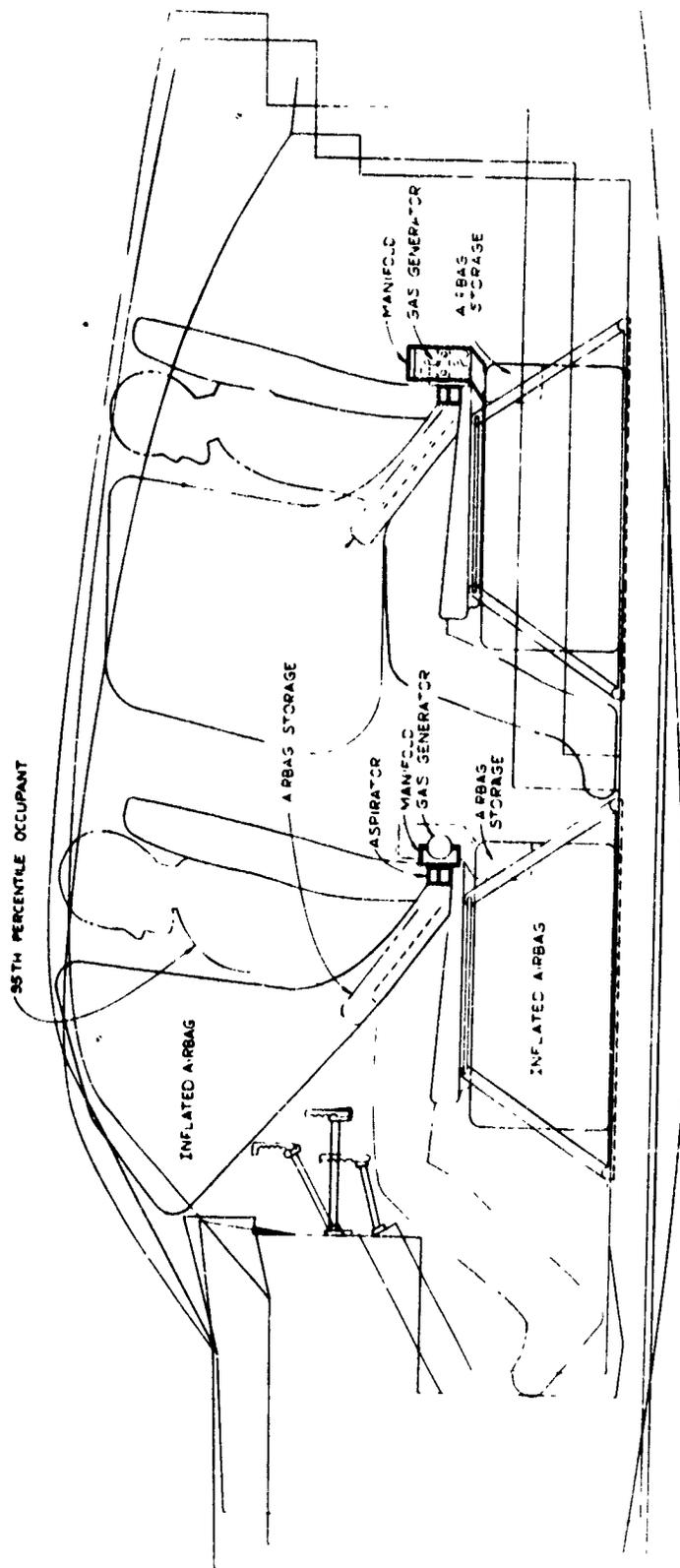


Figure 28a. Inflatable Belt Restraint System - Side View

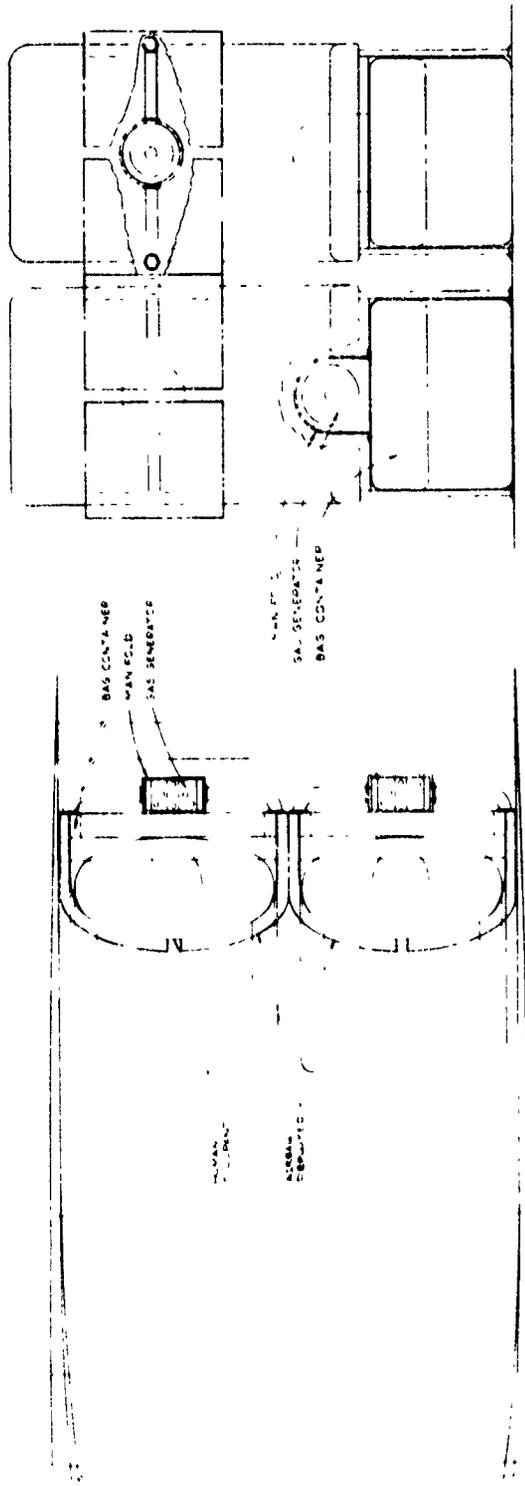


Figure 28b. Inflatable Belt Restraint System - Front and Top View

- ... provide restraint for all aircraft occupants
- ... protection from accidental operation
- ... no hazardous flight conditions
- ... minimum maintenance requirements
- ... retrofit capabilities
- ... no operational difficulties

This criteria was dictated by the objectives of the programs and is mostly self explanatory with the exception of operational difficulties. Operational difficulties were defined as problems that might arise when two or more inflatable systems in close proximity to each other are activated. Will the deployment of one restraint interfere with the deployment of an adjacent one?

An illustration of the comparison between concepts is given in Table VI. Each concept was compared with the evaluation criteria and given a value of one if it satisfied the criterion and a value of zero if it did not. A performance factor was determined for each concept by summing these criterion values. The concept with the highest performance factor was selected as the best inflatable restraint system for use in general aviation aircraft as seen from Table 6; this concept was the inflatable belt system.

Evaluation Criteria	INFLATABLE RESTRAINT CONCEPTS				
	Dual Cushion	Unit Cushion	Seat Back	Inflatable Belt	
Normal Operation	1	1	1	1	1
Interference	0	1	1	1	1
Visibility	0	1	1	1	1
Restraint - all occupants	0	0	1	1	1
Accidental Operation	1	1	1	1	1
Hazardous Conditions	1	1	1	1	1
Maintenance	1	1	1	1	1
Retrofit	0	1	0	1	1
Operational Difficulties	1	0	0	1	1
Performance Factor	5	7	7	9	9

Table VI. Comparison of Inflatable Restraint Concepts

CONCLUSIONS

The results of this program indicate that an inflatable restraint system can be used in a general aviation aircraft to fully protect the occupant against severe crash loads. In the longitudinal direction, an airbag restraint system can fully protect a lap belted occupant from the severest survivable crash input. The severity index for an occupant restrained by an airbag that fully deflates as the occupant is displaced forward is well below the threshold of head injury. If the airbag does not fully deflate and applies a force to the occupant as he returns to his initial position, the severity index is only slightly lower than the head injury threshold. Therefore, it appears that an airbag that fully deflates as the occupant goes forward is the type inflatable restraint system to be used in general aviation aircraft.

Another finding of the program was that an optimum airbag force existed for each occupant weight investigated. These optimum forces are in direct proportion to the occupant's weight. The heavier man has a higher optimum force than the lighter man. If the force applied to the occupant by the airbag depends primarily on the bag pressure and the contact surface between the occupant and airbag, lower weight occupants would have smaller contact surfaces than heavier occupants, and would naturally adjust a constant pressure airbag to a lower force. This means that it may be possible to have an inflatable restraint system designed for one pressure that would provide the optimum restraining force for every occupant weight.

This possibly should be further investigated since the interaction dynamics of the occupant and cushion are not well defined at this time. It is not certain exactly how the airbag forces are generated during occupant impact. Membrane effects, bag elasticity and pressure variations during impact could alter the possibility of using one airbag pressure for all occupant weights.

For protection from vertical crash loads, the program showed that an inflatable system can be used to reduce the crash loads to tolerable levels for the occupant in general aviation aircraft. However, to provide this protection and

dissipate the energy, the seat support structure will have to be modified to allow the seat to collapse. For the optimum protection of the seated occupant, the force at the seat pan and its displacement must be controlled. This optimum force-displacement characteristic can be provided by an airbag system together with a mechanism that allows the seat to collapse onto the airbag. Another modification to the seat support structure is also required to dissipate the energy in the vertical direction. The distance between the seat pan and the floor should be increased to twelve inches. This distance is necessary to provide the optimum energy absorption characteristics for attenuation of the vertical crash load.

The preliminary specifications for vertical and longitudinal inflatable restraint systems were determined on this program and used to develop airbag restraint concepts for general aviation aircraft. The values calculated for the inflatable system parameters are within the current capabilities of airbag systems manufacturers and the estimated additional weight of both systems is approximately eight pounds per occupant.

APPENDIX A
RESPONSES TO SYMMETRICAL PULSES

Responses to Symmetrical Pulses

The motion of a single degree of freedom, undamped linear system can be described by the second order differential equation given below:

$$x_r + \omega_n^2 x_r = -A(t)$$

$$x_r = \text{output}$$

$$A(t) = \text{input}$$

The solutions of this equation for four symmetrical pulse inputs and analytical descriptions of the inputs are:

Rectangular pulse:

$$A(t) = Ap \text{ (constant)} \quad 0 \leq t \leq \tau$$

$$x_r(t) = \frac{Ap}{\omega_n} (1 - \cos \omega_n t)$$

$$A(t) = 0 \quad \tau \leq t$$

$$x_r(t) = \frac{Ap}{\omega_n} \left[2 \sin \frac{\omega_n \tau}{2} \right] \sin \omega_n \left(t - \frac{\tau}{2} \right)$$

Half sine pulse:

$$A(t) = Ap \sin \frac{\pi t}{\tau} \quad 0 \leq t \leq \tau$$

$$x_r(t) = \frac{Ap \omega_n^2 \tau^2}{\omega_n^2 \tau^2 - \pi^2} \left[\sin \frac{\pi t}{\tau} - \frac{\pi}{\omega_n \tau} \sin \omega_n t \right]$$

$$A(t) = 0 \quad \tau \leq t$$

$$x_r(t) = \frac{Ap}{\omega_n} \left[\frac{2 \pi \omega_n \tau \cos(\omega_n \tau / 2)}{\pi^2 - \omega_n^2 \tau^2} \right] \sin \omega_n \left(t - \frac{\tau}{2} \right)$$

Versed sine pulse:

$$A(t) = \frac{Ap}{2\omega_h^2} (1 - \cos 2\pi t) \quad 0 \leq t \leq \tau$$

$$x_r(t) = \frac{Ap\pi^2}{\omega_h^2(4\pi^2 - \omega_h^2\tau^2)} \left[1 - \frac{\omega_h^2\tau^2}{4\pi^2} + \frac{\omega_h^2\tau^2}{4\pi^2} \cos \frac{2\pi t}{\tau} - \cos \omega_h t \right]$$

$$A(t) = 0 \quad \tau \leq t$$

$$x_r(t) = \frac{Ap}{\omega_h^2} \left[\frac{4\pi^2 \sin \omega_h \tau / 2}{4\pi^2 - \omega_h^2\tau^2} \right] \sin \omega_h \left(t - \frac{\tau}{2} \right)$$

Triangular pulse:

$$A(t) = 2Ap \frac{t}{\tau} \quad 0 \leq t \leq \tau/2$$

$$x_r(t) = \frac{2Ap}{\omega_h^2} \left[\frac{t}{\tau} - \frac{\sin \omega_h t}{\omega_h \tau} \right]$$

$$A(t) = 2Ap (1 - t/\tau) \quad \tau/2 \leq t \leq \tau$$

$$x_r(t) = \frac{2Ap}{\omega_h^2} \left[1 - \frac{t}{\tau} - \frac{\sin \omega_h t}{\omega_h \tau} + \frac{2\sin \omega_h (t - \tau/2)}{\omega_h \tau} \right]$$

$$A(t) = 0 \quad \tau \leq t$$

$$x_r(t) = \frac{8Ap}{\omega_h^2} \left[\frac{\sin^2(\omega_h \tau/4)}{\omega_h \tau} \right] \sin \omega_h (t - \tau/2)$$

APPENDIX B
AIRBAG PROGRAM

MIMIC SOURCE-LANGUAGE PROGRAM

```

CON(PB0,VB0,TB0)
CON(AT,AD,PDC)
CON(PA,TAO,VOP,EL,TH1,RO)
CON(W,HC,HF,L,LO,VC0)
PAR(WB0)
AIRBAG RESTRAINT SYSTEM PROGRAM
HIGH PRESSURE EXHAUST EQUATIONS
GS      (0.501*AT*PB)/SQR(TB)
GSS     AT*SQR(322.*PB*GAB*(EXP(1.6,PR)-EXP(1.9,PR)))
PR      PC/PB
GAB     (0.018*PB/TB)/12.
G       FSW(PR-0.533,CS,GS,GSC)
ING     INT(0,0.0)
WB      ABS(WB0-ING)
GO      (0.501*AT*PB0)/SQR(TB0)
GP      (1.0+0.125*GO/WB0*T)
PR      PB0*1./(EXP(10.,GP))
TB      (0.018*PB*VB0/WB)/12.
LOWDOUT PATCH EQUATIONS
GSP     (0.523*AD*PC)/SQR(TC)
GSSP    AD*SQR(226.*PC*GAC*(EXP(1.43,PR1)-EXP(1.71,PR1)))
PR1     PA/PC
GAC     (0.018*PC/TC)/12.
G1      FSW(PR1-0.528,GSP,GSP,GSSP)
LOWDOUT CONTROL
WAEB    INT(G1*G2,0.0,C,D)
G2      LSW(D,1.0,0.0)
PC1     FSW(PDC-PC,TRUE,TRUE,FALSE)
PC2     INT(PC,C.0,PC1,TRUE)
C       FSW(PC2,FALSE,FALSE,TRUE)
VC1     FSW(VC0-VC,TRUE,TRUE,FALSE)
VC2     INT(VC,C.0,VC1,TRUE)
D       FSW(VC2,FALSE,FALSE,TRUE)
ENERGY ENTERING SYSTEM
TT      (0.888*TB)
VT      (47.1*SQR(TT))
TTS     EXP(0.2,TB)
VTS     SQR(1780.*TB*(1.0-(TTS/TB)))
H1      189.-(.0033*PB)
V1      FSW(PR-0.533,VT,VT,VTS)
T1      FSW(PR-0.533,TT,TT,TTS)
E1      INT((H1+V1*V1/50200.)*G,0.0)
ENERGY LEAVING SYSTEM
TD      (0.833*TC)
VD      (49.9*SQR(TD))
TDS     EXP(0.286,TC)

```

```

VDS      SQR(125C.*TC*(1.0-TDS/TC))
H2       176.+(.3*(TC-460.))
V2       FSW(PRI-0.595,V0,V0,VDS)
T2       FSW(PRI-0.595,T0,T0,TDS)
E2       INT((H2+V2*V2/50200.)*G1*G2,0.0)
          WORK TERMS
          INERTIAL WORK OF BAG
HA       (HF-H0)/L
W1E      INT(((H.*XB+H0)*W*R)*2DXB)*1DXB,0.0)/386.
W1S      INT(((H.*XB+2.*H0)*XB*R0*2DXCG)*1DXCG,0.0)/386.
XCG      ((XB*XB)/(6.*L))+XB/2.
1DXCG    ((XB*1DXB)/(3.*L))+1DXB/2.
2DXCG    ((XB*2DXB)/(3.*L))+((1DXB*1DXB)/(3.*L))+2DXB/2.
E        SQR(1.+FA*HA)
W1I      INT((W*XB*B*RJ+2DXB*1DXB)/2.,0.0)/386.
          WORK AGAINST ATMOSPHERE
W2       INT((PC-PA)*1DVC,0.0)
1DVC     DER(T,V0,0.0)
          WORK OF BAG STRETCH
W3       INT(FE*1DXB,0.0)
          WORK OF DRAG
W4A      INT((.00238*(HA*XB+H0)*W*1DXB*1DXB)*1DXP,0.0)
W4       W4A/1728.
          TOTAL WORK
WT       (W1E+W1S+W1I+W2+W3+W4)/9330.
          BAG DYNAMICS
2DXB     (386./(-E*R0))*(-FD-FE-(999.*(XB-XS))-(1DXB-1DXS))
1DXB     INT(2DXB,0.0)
XB       INT(1DXB,0.0)
2DXS     (386./(-E*R0))*((PC-PA)*E+999.*(XB-XS)+(1DXB-1DXS))
1DXS     INT(2DXS,0.0)
XS       INT(1DXS,0.0)
AE       (HA*XB+FC)*W
FD       (0.00238*((HA*XB)+H0)*W*1DXB*1DXB)/1728.
FE       (EL+814S.*EPS)*EPS*(2.*W+2.*HA*XB)*ZHI
EPS      FSW(V0-V00,0.,0.,EPSA)
EPSA     (V0-V0B)/(W*HF*L+W*L+HF*L)
          CALCULATE BAG ENTHALPY
EI       E1-E2-WT
HC       (EI/MC)+176.+0.3*(TA0-460.)
MC       INT(G,0.0)-WAE8+((PA+VOP)/(55.15*12.*TA0))
TC       460.+(10./3.)*(HC-176.)
          CALCULATE BAG VOLUME
VCB      (((2.0*W*H0*XB)+(HA*XB*XB*W))/2.)+VOP
BQ       VCB*(.03325*PA-1.0875)
CQ       VCB*(.03325*MC+55.15*12.*TC)
VC       (-BQ+SQR(BQ*BQ+4.*CQ))/2.
PC       (MC*TC+55.15/V0)*12.+PA

```

```
DT --- --.001--  
FIN(T, .1)  
OUT(T, GS, GSS, G, GO, GP)  
OUT(, WB, PB, TB, TT, VT)  
OUT(, PR, TC, VC, ING)  
END
```

APPENDIX C
LONGITUDINAL RESPONSE PROGRAM

MIMIC SOURCE-LANGUAGE PROGRAM

* THIS PROGRAM CALCULATES THE DYNAMIC RESPONSE OF A SEATED
 * MAN, RESTRAINED BY A LAP BELT, TO AN IMPULSIVE ACCELERATION
 * READ IN SYSTEM CONSTANTS AND PARAMETERS
 * SYSTEM CONSTANTS

CUN(ALL,ALS,VDL,VDS)
 CUN(IX1,IXI,IX3,IXO,IOTHM,ITHM)
 CUN(RA)
 LAC CFN(3.0)

* SYSTEM PARAMETERS
 PAR(WB,ABTH,AIRAG)

* SYSTEM GEOMETRY CONSTANTS
 * ALL - LAP BELT ANGLE
 * ALS - SHOULDER BELT ANGLE
 * VDL - LAP BELT VERTICAL DISTANCE
 * VDS - SHOULDER BELT VERTICAL DISTANCE
 * LDL - LAP BELT LONGITUDINAL DISTANCE
 LDL VDL*COS(ALL)/SIN(ALL)
 * LDS - SHOULDER BELT LONGITUDINAL DISTANCE
 LDS VDS*COS(ALS)/SIN(ALS)

* ANTHROPOMETRIC CALCULATIONS

* HW - HIP WIDTH
 HW .0409*WB+7.75
 * HT - HIP THICKNESS
 HT .0365*WB+3.075
 A .5*HW
 B .5*HT
 P 1.57*SQR(A*A+B*B)
 LBL 2.*LBL+2.*LBD+P
 ELNG LBD/LBL

* RS - SHOULDER BELT RADIUS
 RS .0546*WB+14.24
 * RH - HEAD RADIUS
 RH .0625*WB+21.2
 * RT - TORSO CG RADIUS
 RT .0545*WB+9.24

* RESTRAINT SYSTEM FORCES

* LBL - LAP BELT LENGTH
 * LBD - LAP BELT DEFLECTION
 LBL SQR(LDL*LDL+VDL*VDL)
 LBD SQR((LDL+XR)*(LDL+XR)+VDL*VDL)-LBL
 * SBL - SHOULDER BELT LENGTH
 * SBD - SHOULDER BELT DEFLECTION
 SBL SQR(LDS*LDS+VDS*VDS)
 S LDS+XR+RS*SIN(THM)
 SBD SQR(S*S+VDS*VDS)-SBL

* ABTH AIRBAG IMPACT ANGLE
 * AIRAG AIRBAG ACCELERATION LEVEL

```

* AIRF AIRBAG FORCE
  FAB      MTU*AIRAC*G*ABSW
  ABSW     FSW(LDTHM,0.,0.,2.)
  AIRF     FSW(THM-ABTH,0.,FAB,FA3)
* FLB - LAP BELT FORCE
  BLB      0.0
  ELK      55000.
  FLB      ELK*ELNG+3LB*LDX
  THL      ATN((LBD+L3L)/VDL)
  THS      ATN((SBD+SBL)/VDS)
* FSB - SHOULDER BELT FORCE
  FSB      0.
* DIFFERENTIAL EQUATIONS OF MOTION

  TJ      .225
  TL      .275
  STH     .200.
  SLK     0.
  KTH     5000.
* MTU - UPPER TORSO MASS
  TU      TU*WB/G
* MTL - THIGH AND LEG MASS
  TL      TL*WB/G
  MT      MTU+MTL
* II - TORSO MOMENT OF INERTIA
  IT      ITU*RI*RT
  J       0.0
  ZDX0    RA*FJN(LAG,T)
  JX0     RA*IDX0
  JX0     INT(DX0,IX0)
  XJ      INT(DX0,IX0)
  TJ      0.
  VSW     FSW(IDX0,-1.,0.,2.)
* FSBX - SEAT FRICTION FORCE
  FSBX    MU*(WB*2.*FLB*SI I(THL))*VSW
  FLBX    COS(THL)*FLB*2.
  CFX     MT/MRXXA+MRXXA/IT
  XAIRF   AIRF*COS(TH4)
  CFX1    (MRG*LDTH4*LDTH4-FSBX-FLBX-XAIRF)/MRXXA
  CFX2    (MRG*2.-FSBX)/IT
  IX01    FSW(TH4-ITHM,0.,-1.,0.)
  DX1     (CFX1+CFX2)/CFX
  JX1     RA*IDX1
  DX1     INT(DX1,IX1)
  X1      INT(DX1,IX1)
  DX2     DX1-DX0
  X1      X1-X0
  FSBK    K2*(SB*0.5)(TH3-TH4)
  MKA     MTU*RI*RT+IT
  MKXA    MTU*RT*COS(TH4)
  ISG     ITU*RT*SI I(TH4)

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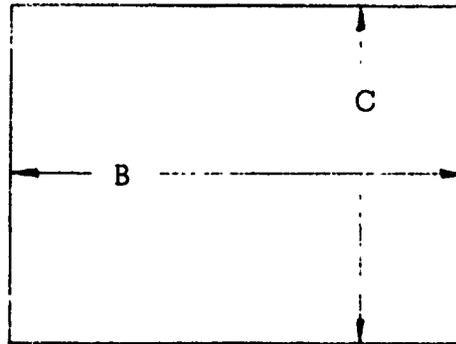
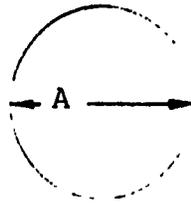
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      K<<      FSW(THM-ITHM,0.,0.,KTH)
      FTH     KR*THM
      2DTHM   ((MRG+MRG1)*G-MRXA*2DX1-KR*THM-BTH*1DTHM-AIRF*RS)/II
      1DTHM   INT(2DTHM,1DTHM)
      THM     INT(1DTHM,ITHM)
      HMX     XK+RH*SIN(THM)
      HMY     RH*(1.-COS(THM))
      *..... HDAC HEAD ACCELERATION
      HD      RH*2DTHM
      HDAC    FSW(THM-ABTH,0.,HD,HJ)
      HDS     FSW(HDAC,HJ,0.05,0.05)
      AHDS    ABS(HDS)/G
      IAHDS   EXP(2.,AHDS)
      SI      INT(IAHDS,0.)
      *      PRINT INTERVAL AND INTEGRATION STEP INTERVAL
      DT      .01
      DTMIN   .001
      *      LOGIC TO DETERMINE END OF RUN
      FIN(ITHM-THM,.05)
      *      SYSTEM VARIABLE TO BE PRINTED AND/OR PLOTTED
      OUT(T,2DX0,)DX0,X0,HMX,HMY)
      OUT(,2DX1,1DX1,X1,XR,FLU)
      OUT(,2DTHM,1DTHM,THM,ELNG,LBTL)
      OUT(,AIRF,XAIRF,HD,AHDS,SI)
      END

```

APPENDIX D
UPPER TORSO CONTACT SURFACE

Upper Torso Contact Surface



Weight (lbs)	A (in.)	B (in.)	C (in.)	Area (Sq in.)
214	6.5	20.	14.	313
164	6.2	18.	13.	264
124	5.8	16.	12.	218

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