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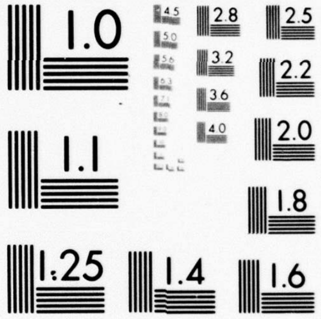

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Volume I

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INVESTIGATION OF A DEPLOYABLE POLYURETHANE FOAM GROUND IMPACT ATTENUATION SYSTEM FOR AEROSPACE VEHICLES

VOLUME I. FIAS Tests Numbers 1 Through 48

Stephen R. Mehaffie
Recovery and Crew Station Branch
Flight Vehicle Equipment Division

January 1979

TECHNICAL REPORT AFFDL-TR-78-145, VOLUME I

Final Report for Period June 1975 - November 1977

Approved for public release; distribution unlimited

AIR FORCE FLIGHT DYNAMICS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
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This technical report has been reviewed and is approved for publication.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An investigation was conducted to determine the feasibility of an advanced deployable impact attenuation system for use with aerospace vehicles. The operational parameters of the AQM-34V RPV were used as a basis for the determination of attenuator feasibility. A series of 91 tests were conducted to demonstrate the attenuation performance. The conclusion was that a deployable polyurethane foam impact attenuation system was eminently feasible for use

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in a premeditated recovery system such as used with the AQM-34V vehicle. Volume I of this report documents Tests #1 through #48, and Volume II documents Tests #49 through #91.

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FOREWORD

This report was prepared by the Aerospace Vehicle Recovery Group of the Recovery and Crew Station Branch of the Air Force Flight Dynamics Laboratory (AFFDL/FER), Wright-Patterson AFB, Ohio, under Project 1964, "Recovery System Technology Application to Remotely Piloted Vehicles." This investigation was performed in accordance with a Memorandum of Agreement (MOA) between the Remotely Piloted Vehicle System Program Office (RPV SPO), Aeronautical Systems Division (ASD), and the AFFDL dated 7 November 1974. This report documents the investigation results between June 1975 and November 1977 and was submitted for publication in August 1978. Volume I documents Tests #1 through #48, and Volume II covers Tests #49 through #91.

The in-house investigation described in this report was made possible through the collective efforts of a number of organizations and people. Special thanks are due to the Air Force Logistics Command/Air Force Packaging Evaluation Agency (AFLC/AFPEA) for their long term support in this investigation and especially to Mr. Paul Robbins of AFPEA whose personal expertise in foam-in-place technology greatly aided the advancement of this investigation.

The author wishes to thank Mr. R. Speelman (AFFDL) and Major R. Johnson (RPV SPO) for their excellent management combination of research and operational considerations into a single investigation. Mr. Michael W. Higgins, Mr. George Pitts, and Mr. Virgil H. King (AFFDL/FER) were instrumental in the accomplishment of the somewhat lengthy test program in a timely and professional manner.

The support and interest of the Aerial Delivery and Parachute Branch of the Directorate of Equipment Engineering (ASD/ENE) during this investigation is appreciated.

The accomplishment of a test program of the magnitude required in this investigation required the support and assistance of over a dozen different organizations located at Wright-Patterson AFB. This willingness of the Wright-Patterson technical community to support an in-house program of this magnitude in this time frame is deeply appreciated by the author.

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SECTION I

OVERVIEW AND BACKGROUND

1. OVERVIEW

This report (Volumes I and II) documents the first five steps, beginning in the research laboratory, in the solution of an Air Force operational problem. Because of the nature of the problem, the approach with the highest probability of success must include exploratory development combined with operational constraints. The ultimate operational user must be considered early in the research stage of the solution because his constraints will affect decisions in the laboratory. The approach used in the solution may be broken down into the following five steps:

Volume I	A. Problem Definition B. Concept Formulation C. Concept Testing (Vertical)
Volume II	D. Concept Testing (Vertical and Horizontal) E. Specific Vehicle Integration

This report documents steps A, B, and C in Volume I and steps D and E in Volume II.

2. LABORATORY BACKGROUND

During the time period from November 1974 to April 1975, a theoretical analysis (Reference 1) of the minimum weight of an aerospace vehicle recovery system was performed by the Aerospace Vehicle Recovery Group of the Recovery and Crew Station Branch of the Air Force Flight Dynamics Laboratory (AFFDL/FER). This theoretical analysis sought to determine the total recovery system weight based on present and future technologies. The analysis considered a recovery system to be defined as:

> "An Aerospace Vehicle Recovery System consists of those pieces of hardware which are essential to reduce the kinetic and potential energy of an airborne vehicle to zero relative to the earth's surface but which are not essential to the performance of the vehicle's combat mission."

Within this definition the analysis examined a schematic recovery system as depicted in Figure 1 and evaluated the minimum weight of that system against various technology advancements.

In Figure 2 a graphical summary of technology advancements and their effect on the total recovery system weight is presented. The total recovery system weight was considered to be the sum of the weights of the parachute subsystem, the impact attenuator subsystem and some independent components. The four cases illustrated are:

Case #1 a recovery system based on a nylon parachute with an airbag attenuation subsystem·

Case #2 a recovery system based on a KEVLAR parachute with an airbag attenuation system

Case #3 a recovery system based on a nylon parachute but with a purely theoretical advanced attenuation system

Case #4 a recovery system based on a KEVLAR parachute with the theoretical advanced attenuation system

The analysis conjectured the existence of an advanced attenuation system and sought to determine the relative payoff.

The conclusion that Figure 2 illustrates is that the development of an advanced attenuation system would have the same payoff in total system weight as the then current development of Kevlar parachute materials.

In June 1975 the Air Force Flight Dynamics Laboratory initiated an in-house exploratory development program aimed at developing an advanced impact attenuation system for aerospace vehicles.

3. OPERATIONAL BACKGROUND

The Tactical Air Command (TAC) flies and recovers Remotely Piloted Vehicles (RPV) on an operational basis. The recovery technique employed in the past has been the Midair Retrieval System (MARS). This system has performed adequately under the low sortie rates of past operations. However, the MARS technique is expensive to operate in that

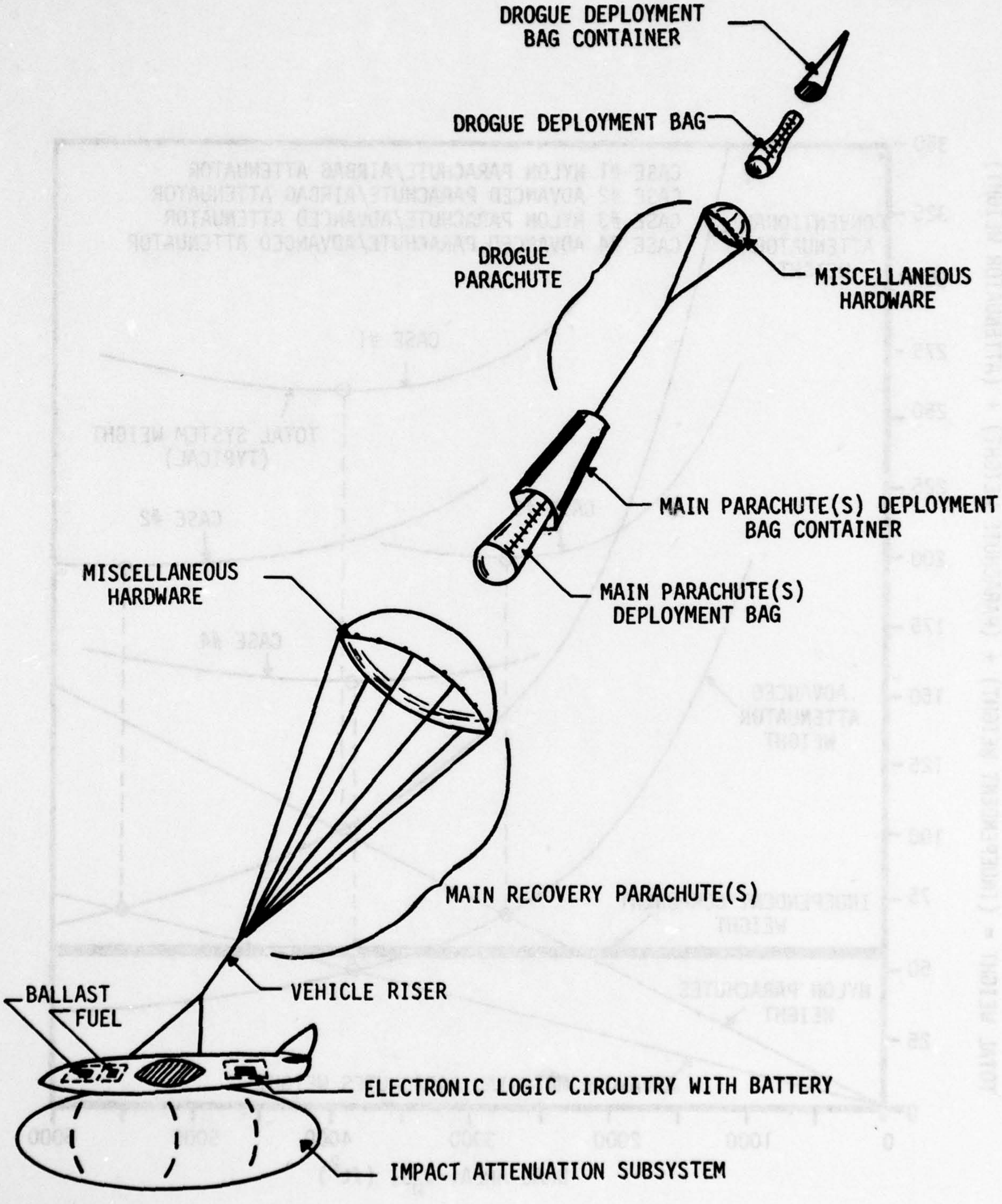


Figure 1. Schematic Recovery System

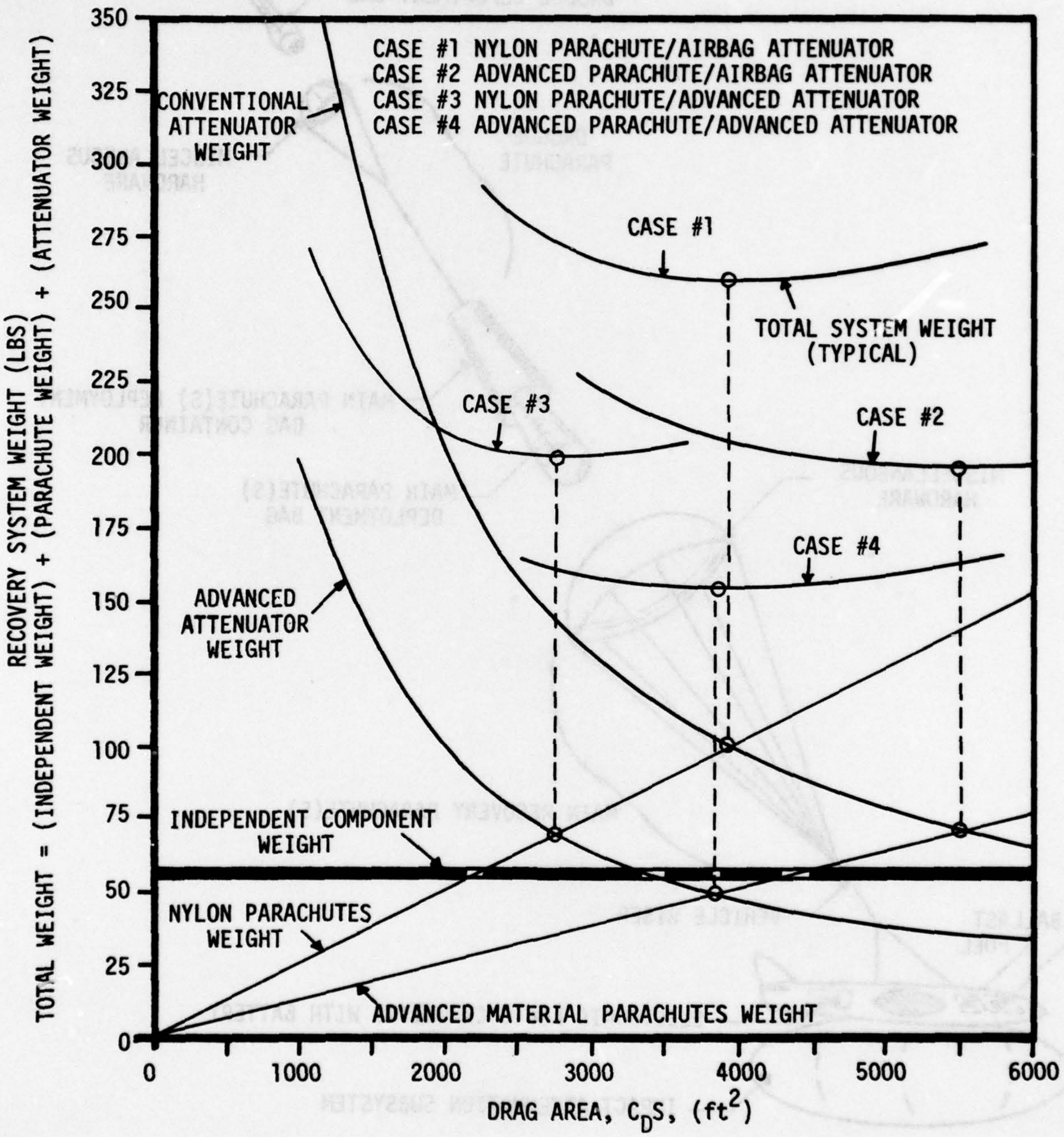


Figure 2. Comparison of Technology Advancements Against a Single Application

it requires a dedicated helicopter and crew. Future scenarios indicate that the MARS technique is not practical with increased sortie rates and/or multiple recovery situations. Attempts to ground recover the RPV's have resulted in expensive repairs due to ground impact damage and unacceptable turnaround times. In 1974 the Tactical Air Command issued a requirement for the operational capability to ground recover its RPV's. The purpose of this requirement was to reduce the cost associated with the MARS helicopters as well as increase the operational flexibility of recovering multiple RPV's. TAC's experience with ground landing the RPV using the MARS parachute system alone was that the average cost to repair a typical RPV (such as the AQM-34H) was on the order of $17,000 per ground landing (Reference 2).

The Air Force Systems Command Remotely Piloted Vehicle System Program Office (RPV/SPO) was tasked with developing a ground impact recovery capability for RPV's.

4. COMMONALITY OF PURPOSE

In November 1975 the Air Force Flight Dynamics Laboratory and the Remotely Piloted Vehicle System Program Office agreed to support the development of an advanced ground impact attenuation system designed for the requirements of the AQM-34V RPV. This agreement allows for both the expansion of the technology base of impact attenuation and the resolution of an Air Force operational problem. In hindsight, this has proven to be a very fortuitous agreement due to the interrelationship between the laboratory research decisions and the operational considerations.

SECTION II

PROBLEM DEFINITION

The RPV SPO was specifically interested in the ground recovery of the AQM-34V RPV with minimum impact damage. The AQM-34V RPV is representative of a premeditated (as opposed to an emergency) recovery situation involving a 3000 pound vehicle. At the time that this investigation was initiated, the AQM-34V was in production but had not yet flown. Previous work with this class of airframes indicated that difficulties with ground recovery were to be expected (Reference 2).

1. AIRFRAME

The AQM-34V RPV is shown in Figures 3, 4, and 5. The airframe is a direct descendent of the FIREBEE target drone originally designed in the late 1940's. The major changes to the airframe consist of a 60" lengthening of the fuselage, an increase in wing span from 12 feet to 14 feet, a reduction in internal structure not required for the MARS concept, and a recovery weight increase from approximately 1800 pounds to 3300 pounds maximum weight. The airframe can be recovered in three configurations known as (1) clean wing, (2) empty pods, and (3) full pods.

2. RECOVERY CONDITIONS

The AQM-34V is to be ground recovered by a 100-foot main recovery parachute. As the vehicle descends under its recovery parachute through 3000 feet AGL it is assumed to be committed to a ground recovery. The 3000' above ground level (AGL) altitude represents the minimum altitude for a safe MARS recovery. Table 1 lists the recovery conditions for the three vehicle configurations.

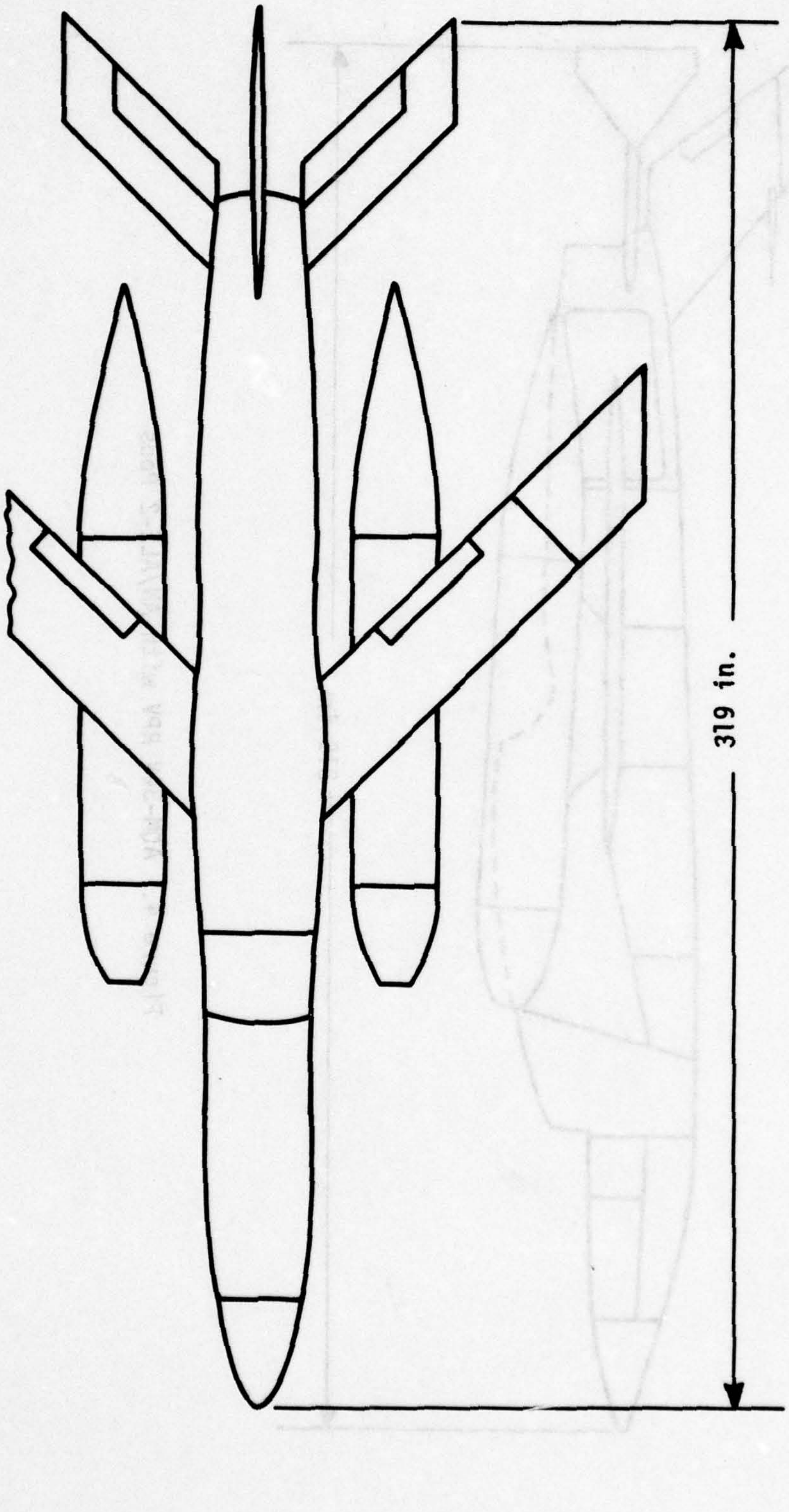


Figure 3. AQM-34V RPV with AN/ALE-2 Pods

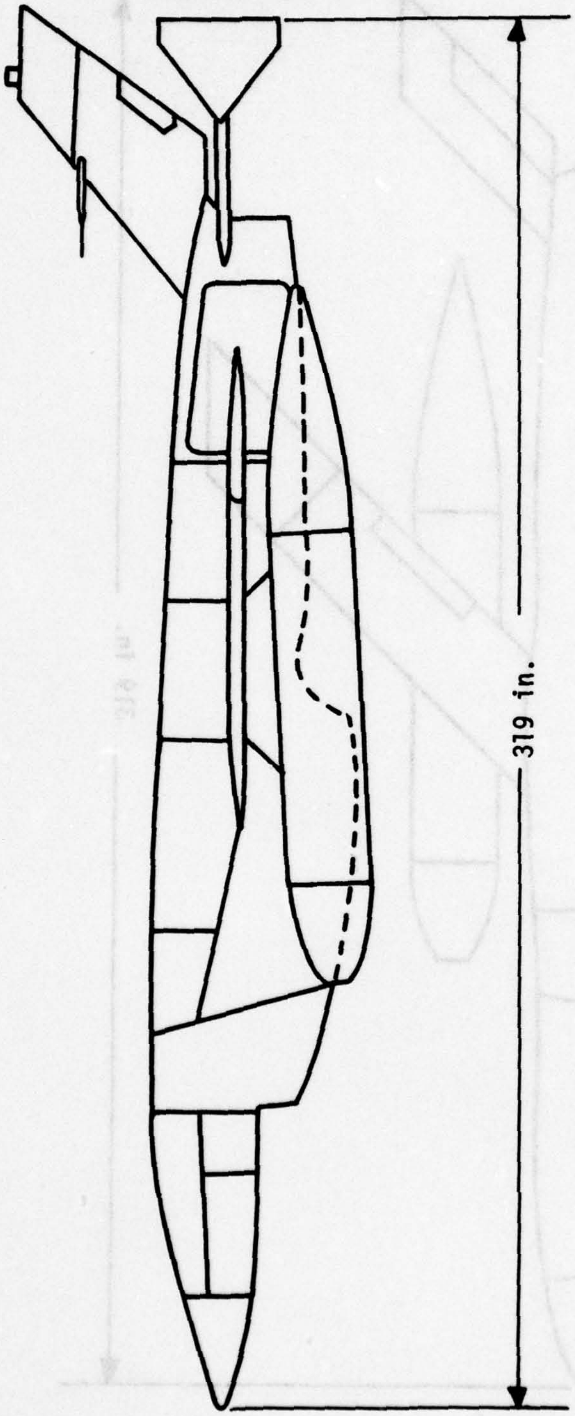


Figure 4. AQM-34V RPV with AN/ALE-2 Pods

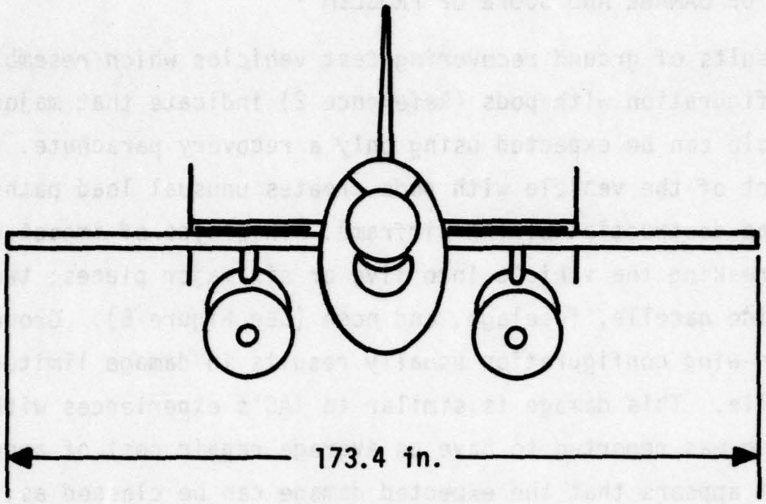


Figure 5. AQM-34V RPV with AN/ALE-2 Pods

TABLE 1

RECOVERY CONDITIONS

Recovery Parameter	Clean Wing	Empty Pods	Full Pods
nominal weight* (Refs. 3,4)	2000 lbs	2740 lbs	2945 lbs
Equilibrium Vert Velocity (S.L.)	16.3 fps	18.1 fps	19.6 fps
time from 3000' AGL to impact	184 sec	165 sec	153 sec
nominal wind conditions	10 kts	10 kts	10 kts
maximum wind conditions	15 kts	15 kts	15 kts
nominal suspension attitude	+5° pitch	+5° pitch (Pods Level)	+5° pitch (Pods Level)
off-design attitudes	0-10° pitch	0-10° pitch	0-10° pitch
normal impact terrain	Sandy	Sandy	Sandy
normal pods	N/A	ALE-2	ALE-2
alternate pods	N/A	ALE-38	ALE-38

*nominal weight does not include the weight of any attenuation system

3. EXTENT OF DAMAGE AND SCOPE OF PROBLEM

The results of ground recovering test vehicles which resembled the AQM-34V configuration with pods (Reference 2) indicate that major damage to the vehicle can be expected using only a recovery parachute. The ground impact of the vehicle with pods creates unusual load paths which result in the destruction of the airframe. This type of impact seems to result in breaking the vehicle into five or six major pieces; two pods, engine, engine nacelle, fuselage, and nose (See Figure 6). Ground impact of the clean-wing configuration usually results in damage limited to the engine nacelle. This damage is similar to TAC's experiences with the AQM-34H which was reported to have an average repair cost of approximately $17,000. It appears that the expected damage can be classed as; with pods - major damage-non-repairable; and without pods - major damage-repairable.

Thus, the scope of the problem is the prevention of the large scale destruction of the airframe. The immediate concern is to maintain the structural integrity of the airframe. Whatever accelerations the on-board equipment is experiencing is of secondary concern compared with keeping the engine nacelle attached to the fuselage.

4. SOLUTION DEFINITION

An impact attenuation subsystem is a piece of hardware incorporated into the vehicle recovery system in order to reduce the vehicle damage occurring at ground impact. As such, the attenuation system must reduce the operating costs per landing in order to be a solution. (For example: Assume that the average repair cost is $20,000 per landing without an impact attenuator. Now assume an impact attenuation system which costs $15,000 per landing to operate, the average repair costs using the attenuation system must then be less than $5,000 for the attenuation system to be a solution.) Note that in comparing costs with and without an impact attenuator, the entire life cycle costs of the attenuation system must be included. Since, within this definition of a solution, a cost savings of one dollar constitutes a solution, then the degree of success can be directly measured by the dollar amount of cost savings.

Figure 6. RPV Ground Recovery Damage

SECTION III

LITERATURE SEARCH

1. PURPOSE

A literature search was conducted which spans approximately 30 years of work in impact attenuation. This search identified approximately 200 reports and papers pertaining to the general area of impact attenuation (Appendix).

The purpose of this literature search was to determine the results of previous investigations and to determine the state of the art of impact attenuation as applicable to the RPV requirements.

2. STATE OF THE ART

In order to determine and understand the current state of the art of impact attenuation, it is necessary to examine the history, philosophy, and background of the technology area known as impact attenuation. Impact attenuation is not a discreet, well defined, technology; instead it encompasses a wide range of technical disciplines working on a broad spectrum of applications. As opposed to a continuously developing technical area, impact attenuation efforts are more accurately categorized as sporadic, repetitive, poorly documented, and seemingly devoid of any continuity. This situation appears to have arisen primarily due to the everchanging states of the art of the wide range of the disciplines and applications involved. From an analytical viewpoint, the physics and mechanics of the phenomena of impact and impact attenuation are poorly understood. The phenomena do not lend themselves to a simple analysis and even a complex analysis only produces approximations which must be verified by testing. This entire situation was succinctly stated in a monograph on impact attenuation published by NASA in 1970 (see Appendix, bibliography list, April 1970, Jones et al).

State of the Art (1970)

> "...attenuation-system designs frequently evolve from the experience of individual designers. Design concepts often reflect personal preferences and include features which affect landing performance in, at best, only a partially understood manner."
>
> NASA, 1970

The conclusion is that it is more correct to consider impact attenuation as an "art" than as a technical discipline.

The literature search uncovered four former "trade studies" having general applicability to the RPV requirements and which define the state of the art at different points in history. These four documents (listed in Appendix) are:

1.	July 1955	Cushioning for Airdrop, Pt 1
2.	January 1962	Study of Design Criteria for Landing Shock Absorption Devices for Recoverable Flight Vehicles
3.	May 1963	Investigation of Crew Escape System Surface Impact Technique for Advanced Aerospace Vehicles
4.	October 1975	A review of Energy Absorption Devices for application to Helicopter Crashworthiness

There are many other documents listed which purport to offer concept comparisons, trade studies, etc. In general, the other reports are either references to or referenced from the four reports indicated above.

The January 1962 and May 1963 reports are the two most useful documents listed in regards to a trade study for RPV applications. The July 1955 and October 1975 reports offer two views of the State-of-the-Art of impact attenuation concepts separated by some 20 years.

The results of the previous trade studies and the approaches used are similar in many aspects. In general, there are over a hundred different concepts which have been investigated to attenuate the kinetic energy of impacting objects. A major criteria in selecting a concept is the requirement of deployability. Once it is determined that an application requires a deployable attenuator (as is the case for a RPV) then the number of possible concepts is reduced to three: Retrorockets, Airbags, and Deployable Crushables. When these three concepts were evaluated against additional criteria, such as state of development and demonstrated performance, the airbag concept consistently emerged as superior to the alternate concepts. The airbags had faster and more demonstrated deployment than the deployable crushables and did not require the sophisticated control of a retrorocket system. It was within these general guidelines that airbags were selected for application to the X-7A, GAM-72, XQ-4A and Q-2C aerospace vehicles as well as the F-111 and B-1 emergency crew escape capsules. Additionally, airbags have been selected/investigated for application to the aerial delivery of cargo, the protection of automobile passengers, and a wide variety of conceptual studies.

A quantitative evaluation of airbags with respect to the two alternate deployable attenuators is difficult due to the lack of development of the alternate concepts. Based on past performance and studies, a qualitative statement of the airbag concept as applied against the RPV requirements is possible. An airbag is capable of attenuating a limited range of kinetic energies due to the functioning of the "blow-out" ports. When an airbag is impacted at a higher than design kinetic energy level then the vehicle will impact with excess (unattenuated) energy. When an airbag is impacted at a lower than design kinetic energy level then rebounding may occur. In multiple airbag systems under certain impact conditions, both of these phenomena may occur simultaneously due to vehicle attitude and/or horizontal velocity components (reference: Study of Design Criteria for Landing Shock Absorption Devices for Recoverable Flight Vehicles, June 1959). An example of an airbag system tolerance of off-design kinetic energy levels is that the F-111 capsule is undergoing recertification of its recovery system due to a weight increase from a capsule design weight of 2,900 pounds to a new upgraded capsule design weight of 3,350 pounds. The RPV requirements (as stated) show that a wide variation in vertical kinetic energy levels is to be expected. The literature search did not reveal any airbag systems capable of attenuating this broad range of vertical kinetic energy levels. As the vertical kinetic energy at impact (vehicle weight) differs more and more from the nominal (design) condition, the more damage to the vehicle is to be expected.

In the horizontal mode, the airbag concept has repeatedly shown marginal performance in oblique impacts (ibid.). The limited ability of airbags to resist shear forces caused by horizontal sliding of the vehicle relative to the ground results in a tendency for the airbags to "roll-under" the vehicle. The position of the vehicle C.G. in combination with this "roll-under" effect results in decreased vehicle stability during slideout and may result in vehicle-ground contact and/or tumbling. The RPV requirements show that a nominal surface wind of 10 knots is to be expected and that surface impact in winds of up to 15 knots is possible. The magnitude of the horizontal energy components of the RPV requirements indicate that stability during slide out is of prime consideration. The ability of an airbag system to provide this required stability is considered, (based on test data, ibid.) to be marginal. As the surface wind velocity increases, so will the probability of vehicle damage.

In summary, although the airbag concept is the only proven deployable impact attenuator for RPV's based on the prior state of the art, there still remain severe shortcomings inherent in the concept in its ability to attenuate off-design vehicle weights and oblique impacts.

3. STATE OF THE ART OF RELATED TECHNOLOGIES

The literature search discovered that both retrorockets and deployable crushables had been considered as alternates to the airbag concept. Previously these concepts had been rejected due to voids in their own respective states-of-the-art. An investigation was conducted to determine what the respective problems were and if they had been solved in the current state-of-the-art (1976).

a. Retrorockets

Retrorockets form an attractive concept in terms of the attenuating ability versus the retrorocket system weight. The major problem areas previously encountered were an inability to handle off-design vertical energies, difficulty in control of the time of rocket firing, and inability to attenuate horizontal energies.

The rockets can be designed to attenuate a limited range of vertical kinetic energies. If the vehicle impacts at precisely this energy level then the retrorocket system is viable. However, if the vehicle is on the heavy side of the design weight (off-design, heavy) then the retrorockets will attenuate only the design energy and the vehicle will impact with excess (unattenuated) energy. If the vehicle is at the off-design, light, condition the retrorocket will bring the vehicle to a halt in mid air and then lift the vehicle some distance before retrorocket burn out and subsequent free fall of the vehicle back to the ground.

The timing of the retrorocket firing is similarly critical. If fired at the correct time (altitude) then the system is viable. If fired late, then the vehicle impacts the ground before the retrorockets have attenuated the total amount of energy. If fired early, the retrorocket will bring the vehicle to its impact kinetic energy condition (ideally zero) some distance above the actual terrain. Subsequent rocket burn out will then cause the vehicle to free fall onto the ground. The retrorocket concept has not been demonstrated capable of attenuating the horizontal energy components, subsequently the vehicle would still have a horizontal slide out on the ground.

A developmental test effort for a Crew Escape Retrorocket Concept (concluded in early 1976) was conducted by the A.F. Flight Dynamics Laboratory. One of the conclusions of this effort was that based on a design vehicle weight of 7,750 pounds the retrorocket could tolerate only a ± 250 pound weight variation. The report (Reference 5) also concludes that a variable ignition height and variable thrust arrangement would be required to accommodate a wider range of off-design vehicle weights. Such an arrangement would involve the onboard sensing of impending impact conditions and has not been demonstrated as of this writing. Examining the results of this retrorocket program with regard to the RPV requirements indicates that the weight variation of an RPV is beyond the current state of the art of a retrorocket application.

b. Deployable Crushables

The area of deployable crushables had been examined in two forms; radially expanded honeycomb and foam-in-place plastic foam.

The radially expanded honeycomb was considered only briefly in the literature (circa 1962) and no further efforts have been uncovered pertaining to its development.

The foam-in-place plastic foam proved to be the most interesting area in terms of a progressing technology. The concept of a deployable plastic foam attenuator has been examined by several investigators since the mid-1950's time period. The plastic foam was attractive due to its ability to resist shear forces during a horizontal vehicle slide out, as well as its stress-strain characteristics (see Figure 7). The problem previously encountered with the foam concept were that (1) the "curing time" of the plastic foam was excessively long (on the order of hours) and (2) means of mixing (dispensing) the plastic foam chemicals were complex and cumbersome.

A review of commercially available plastic foams and foaming equipment revealed three conditions now existed:

a. Plastic foams with "curing time" of less than 10 seconds are available.

b. Simplified foam mixing (dispensing) equipment is available.

c. Plastic foam technology is advancing extraordinarily rapidly due to a wide variety of applications within a large commercial market.

4. CONCLUSION

The conclusion which resulted from this examination of the state of the art of alternate deployable attenuator concepts was that the plastic foam appeared the most promising of the concepts examined and that further investigation was warranted.

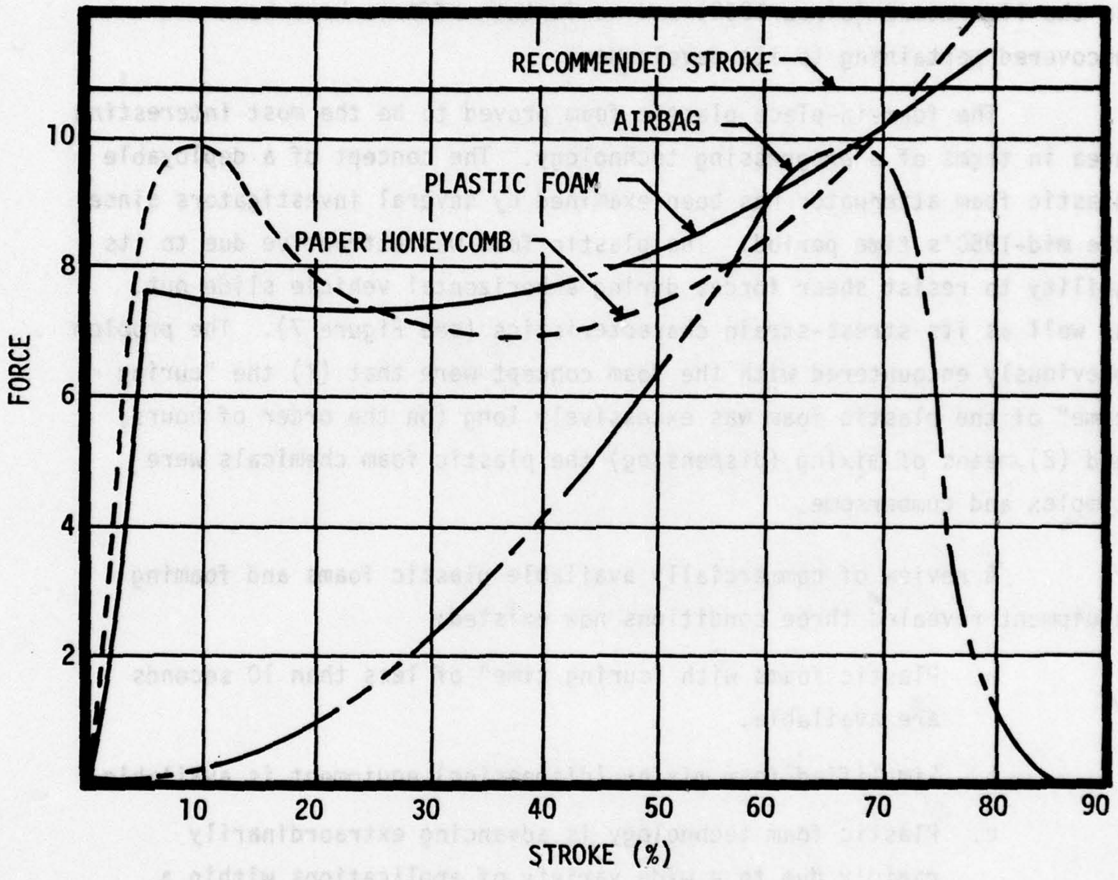


Figure 7. Parallel Paper Honeycomb, Plastic Foam and Airbag Force vs. Deflection Characteristics

SECTION IV

APPROACH

The impact attenuation problem had been defined in terms of the aerospace vehicle involved and the desired solution, but the method of obtaining the solution was not specified. The objective here is to outline the chosen approach which was based on the state-of-the-art, the physics of ground impact, and the available engineering tools which would yield the highest probability of a successful solution.

1. PHYSICS OF ATTENUATING GROUND IMPACT

This problem deals with the ground landing of a vehicle descending under a recovery parachute. The ground landing can be considered as an energy transfer process between two equilibrium energy states. Prior to landing the vehicle is descending at an equilibrium velocity implying a constant kinetic energy level relative to the ground. After landing the vehicle's kinetic energy is zero relative to the ground by definition. The landing is thus the transformation of the vehicle's kinetic energy into other forms of energy such as heat, noise, plastic deformations, etc. An impact attenuation system serves as a control mechanism in this energy transformation process. By introducing an impact attenuation system into the landing process a designer is seeking to control both the type of energy transformation (heat vs plastic deformation) and the rate at which the kinetic energy is transformed. The rate of energy transformation is important due to its relationship with accelerations and inertial loads on vehicle structure. The control considerations of an impact attenuation system include:

a. The attenuator should lengthen the time duration of the energy transformation. The longer the time duration the lower the average energy transformation rate.

b. The attenuator should limit the maximum energy transformation rate in addition to lowering the average rate.

c. The attenuator should control the total amount of energy involved.

d. The attenuator should control the type of energy transformations involved. (i.e., sacrificial plastic deformation of attenuator components in lieu of more valuable vehicle components).

Given that these four considerations are the criteria for an impact attenuation system then how is a candidate system's performance predicted, measured and analyzed?

2. APPLICABLE ENGINEERING TECHNIQUES

A well understood, workable analytical approach to this problem does not exist. Several analytical tools (NASTRAN, Finite Element Analysis, etc.) are usable to some extent but are ponderous in regard to the complex structure of an AQM-34V RPV. This deficiency in the analytical base mandated a logic approach of "hypothesis and test" (also known as "cut and try"). The purpose of this inductive approach is to develop a general theory of the attenuator's performance. By quantifying the knowns and the unknowns, then applying engineering judgment to the effects of the unknowns and testing for correctness of jodgment a general theory of performance could be induced. The major implication of this logic approach was that a large number of tests would be required.

The engineering tool of full scale testing with boilerplate models was selected for this problem. By testing in full scale the effects of unknown scaling parameters would be negated. The use of boilerplate models would reduce both testing costs and possible repair costs if unsuccessful tests were encountered. The number of variables was reduced in the early testing by employing only vertical drop tests so that a one degree of freedom situation was to be dealt with. Later testing was to be expanded into the full six degrees of freedom, representative of the real life problem. The measurement of the attenuators performance during these tests presented a difficulty in that energy is a concept and not a directly measurable entity. Accelerometers and rotational rate transducers were to be employed in the testing with their outputs mathematically interpreted as energy parameters provided that these sensors were operating in their design, linear, environment. Both linear and nonlinear environments may be present during this type of testing and so the limitations of transducers as engineering tools had to be recognized.

The analysis of the attenuation system performance was based on the technique of energy management. The objective of this technique, applied to this process, is to determine; where the energy went? how it got there? and what intermediate steps were involved? This powerful engineering analysis technique would yield valuable information so long as the input measured data was valid; when the energy transformation process went nonlinear this technique quickly degenerated.

3. SUMMARY OF APPROACH

The approach used in this investigation was to (1) hypothesize some feature of the attenuation system performance, (2) conduct full scale testing (3) measure and analyze (where possible) the correctness of the hypothesis, and (4) if found to be correct incorporate the hypothesis into a general theory of performance.

SECTION V

HYPOTHESIZED SYSTEM

In order to investigate an advanced foam impact attenuation system it was necessary to hypothesize a system and examine it for technical feasibility and shortcomings relative to the various technologies involved.

1. SYSTEM DESCRIPTION

The general components and arrangement are shown in Figure 8. Prior to initiation the valves to the manifold feedlines are closed. The tanks ("A" and "B") are pressurized to some level with inert gas. The fabric bag is in a collapsed, stowed condition in the vicinity of the nozzles.

At initiation (Figure 9) both the "A" and "B" manifold feedline valves are opened simultaneously. The gas pressure in the chemical tanks forces the chemicals to flow into the manifold feedlines and hence the manifold. Up to this point the chemicals "A" and "B" are not in physical contact with each other. The manifold serves to feed the two chemicals into the mixing nozzle(s) where physical contact and mixing (through turbulent fluid flow) occurs. The mixed chemical formulation is then dispensed (Figure 10) into the confines of the fabric bag where it "rises" (expands in volume) into plastic foam. The flow of chemicals down to and through the mixing nozzles continues until the chemicals in the tanks are exhausted and the pressurized gas in the tanks "blows dry" through the mixing nozzles effectively reducing the internal tank pressures to ambient conditions (Figure 11). The reacting chemicals (foam) in the bag expand and fill the bag in a shape determined by the bag geometry. Within a short period of time the plastic foam has developed the properties of a solid substance instead of its original liquid properties. At this time the fabric bag is usable as an impact attenuation system.

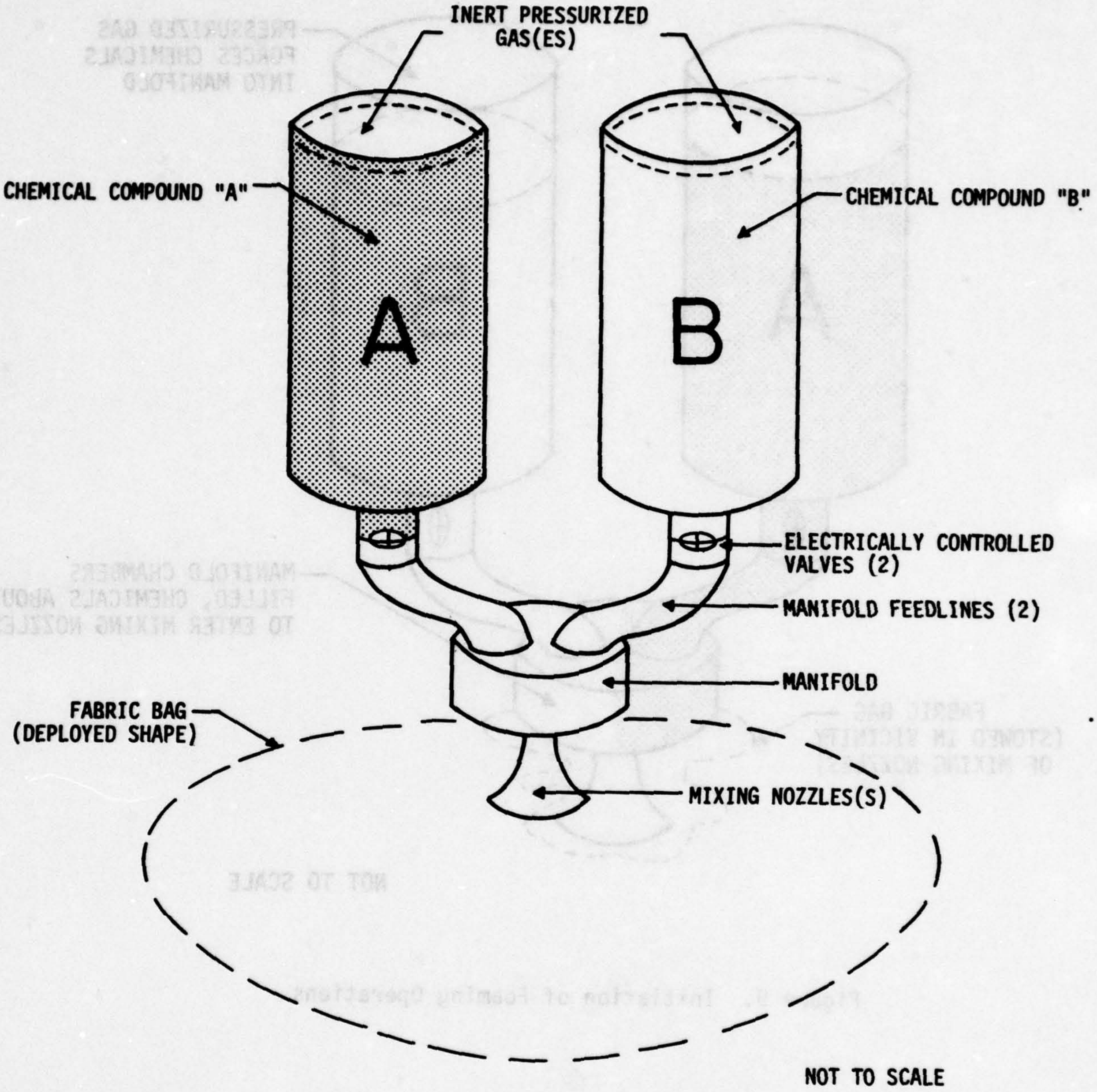
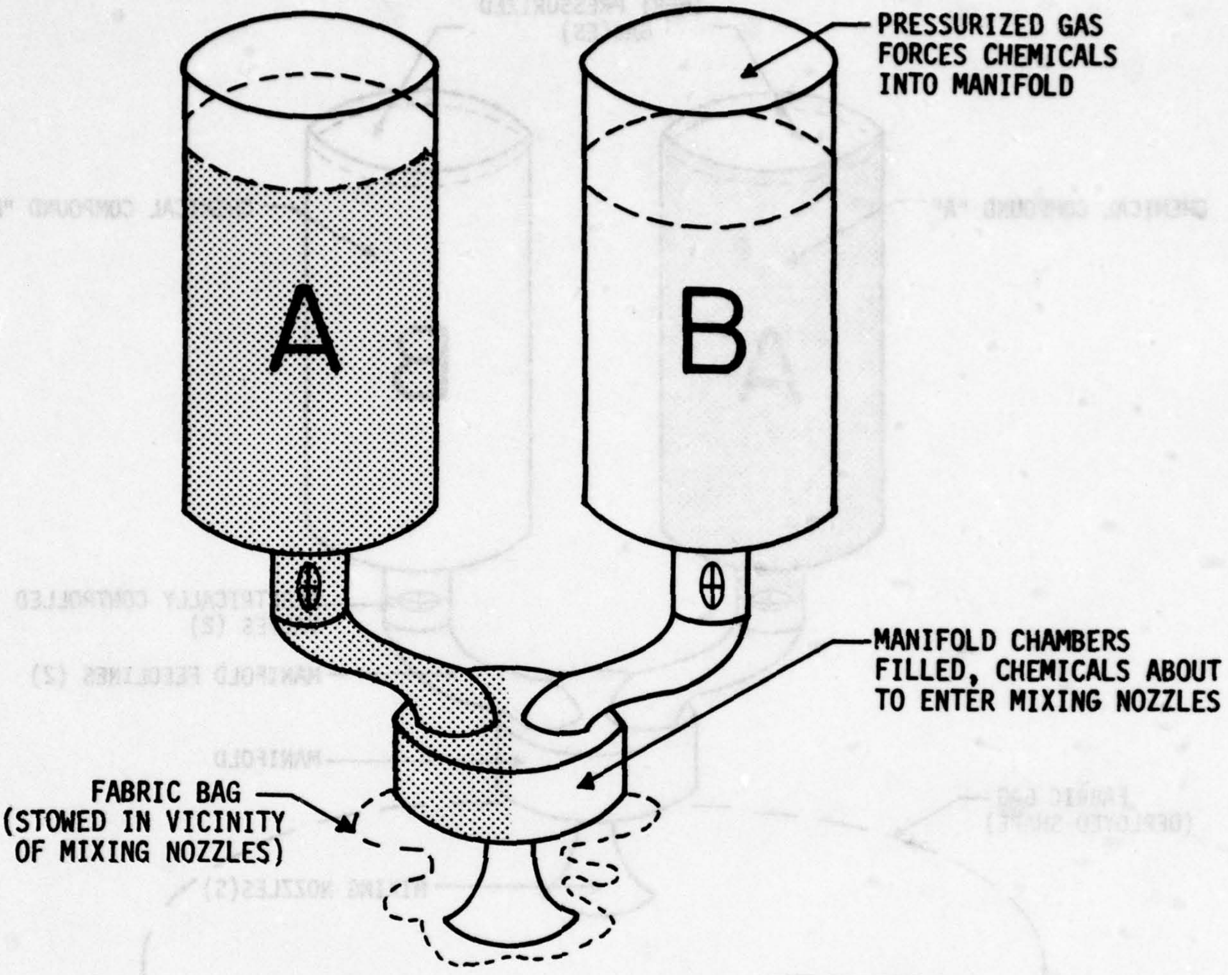


Figure 8. General Arrangement



NOT TO SCALE

Figure 9. Initiation of Foaming Operations

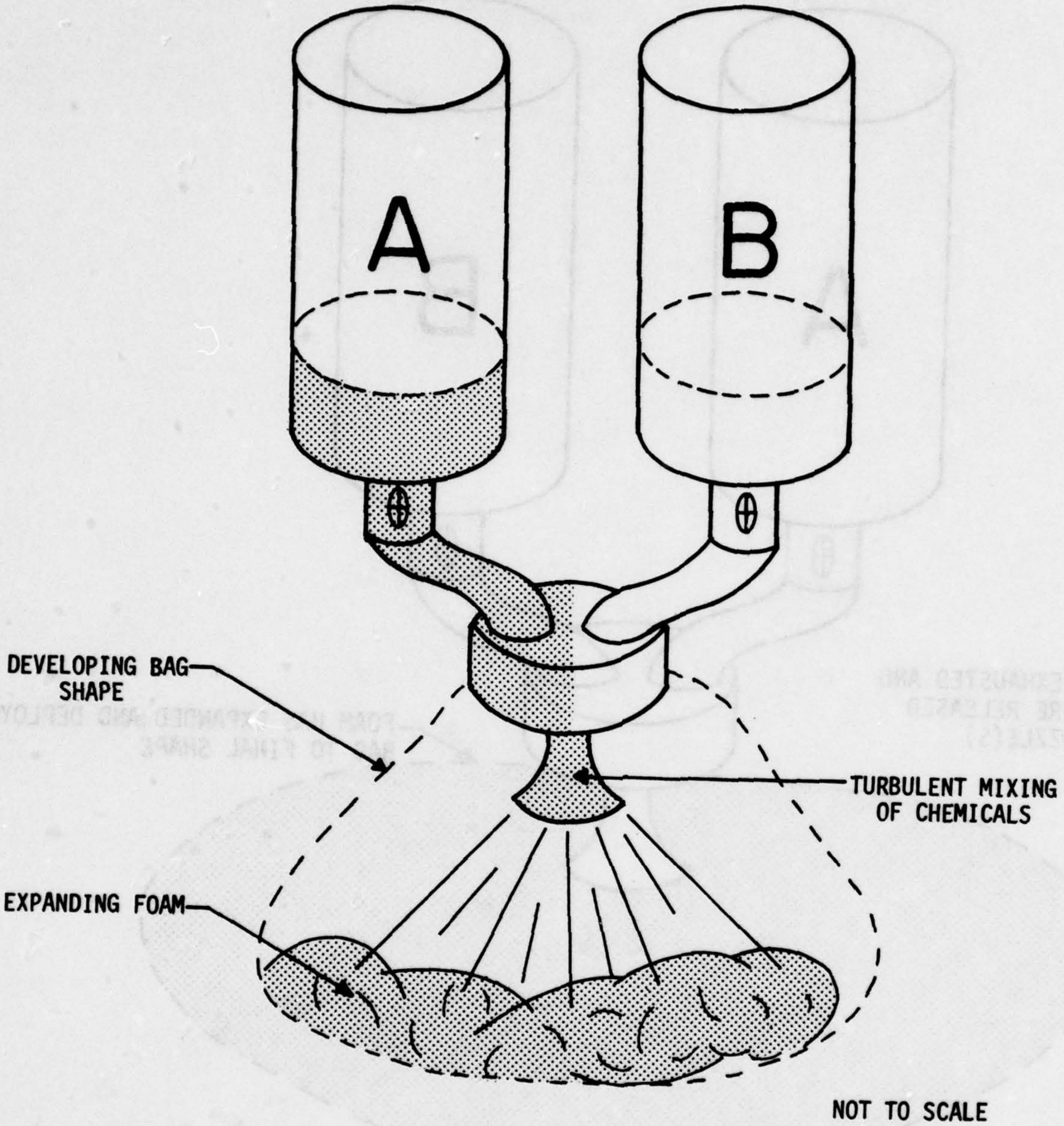


Figure 10. Foam Dispensing

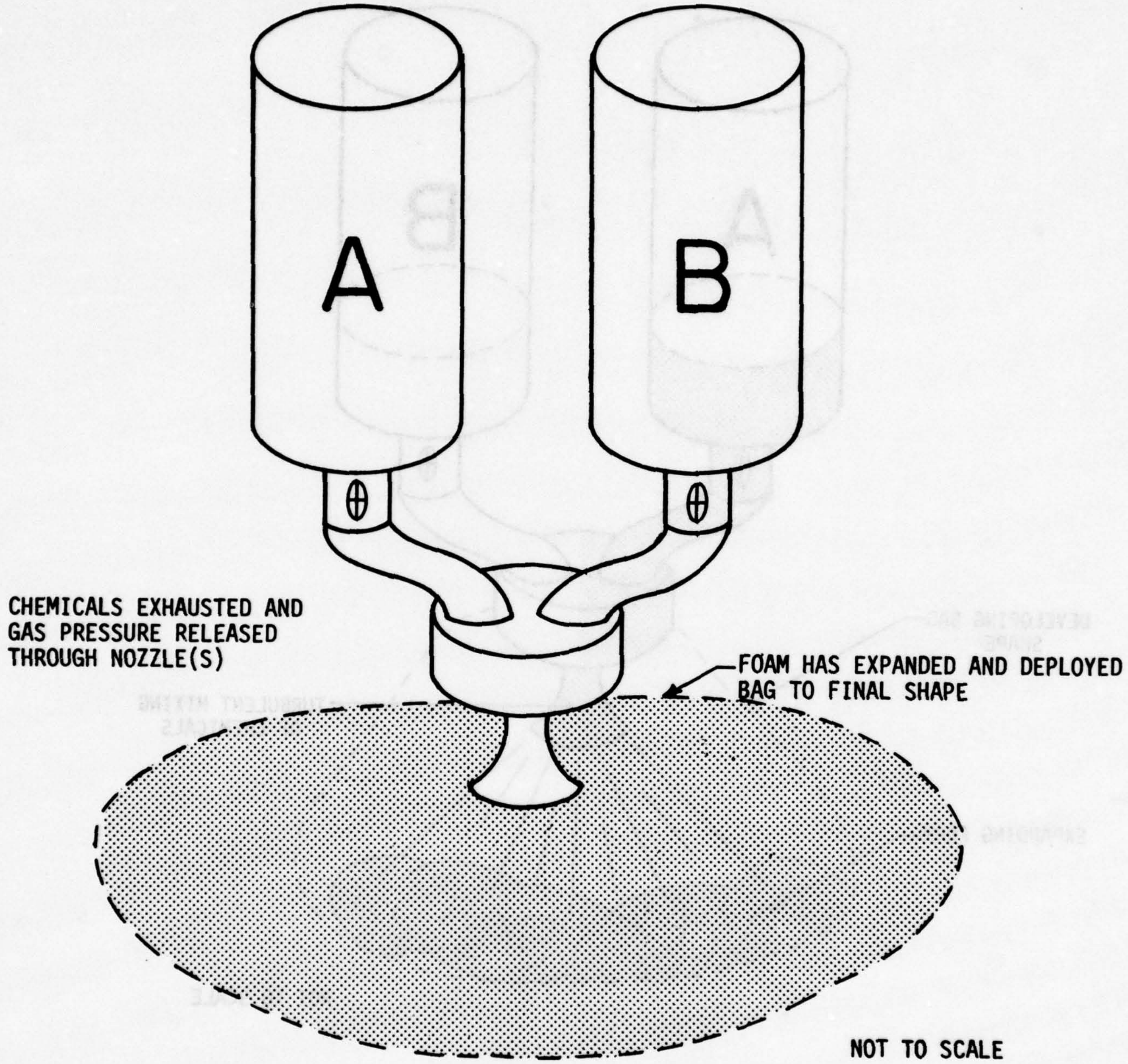


Figure 11. Termination of Foaming

2. SYSTEM COMPONENTS DESCRIPTION

a. Chemical Tanks

The chemical tanks are used to store the separate foam chemicals prior to initiation of the system. The tanks are pressurized with an inert gas such as nitrogen partially for the purpose of moving the chemicals to and through the mixing nozzle(s). This scheme eliminates the need for an external power source such as a mechanical pump. Although the tanks could be installed in any geometry (upside down, sideways, etc.) a geometry as depicted in Figure 8 is preferred for simplicity. This geometry lends itself to installation in a vehicle since the foam filled bag is on the bottom of the vehicle in its recovery attitude.

The gas pressures employed and hence the required tank structure strength required are relatively low. Tank pressures on the order of 200 and 250 psi have been used successfully (note that each tank may have a different pressure to account for viscosity differences). The resulting tank structural requirements are therefore on the order of commercial aerosol cans as opposed to 3000 psi pressure vessels. The major implication of these low pressures is that the tanks are not required to be round in cross section as is desirable with high pressure bottles. Instead the tanks could be rectangular, square, or almost any other geometrical shape in cross sections. This ability to make a usable tank in an irregular shape lends itself to the installation of this subsystem into existing vehicles where volume and shape limitations are a problem. Flexibility in tank geometry could be an important advantage of this impact attenuation system over conventional attenuation systems requiring high pressure bottles.

b. System Actuators (Electric Valves)

These valves serve as the tank closure mechanism prior to operation. The opening of these quick opening valves is the initiation of the system operation. Once opened there is no system requirement for these valves to function again. As such, instead of valves a frangible diaphragm either mechanically or pyrotechnically activated could be employed. Activation of these valves (or diaphragms) by an electrical system is required for remote operation.

c. Manifold Feedlines

The purpose of the manifold feedlines is to transport the liquid chemicals from the tanks (valve connection) to the manifold. As in the case of the valves, the inside diameter of these feedlines is determined by the desired filling rate. The length of these lines is dependent upon the locations of the tanks and manifold. The manifold feedlines should be constructed from materials which are nonreactive (inert) with respect to the foam chemicals. The low pressures of the fluids allow for a wide selection of suitable commercial tubing and hoses.

d. Schematic Manifold

The manifold serves as both the fluid reservoir feeding the mixing nozzle(s) and as the attachment fitting for the mixing nozzle(s). Additionally, depending upon individual vehicle installations, the manifold may serve as an attachment fitting for the fabric bag. The purpose of the manifold is to transition the fluid flow of the liquid chemicals from the large manifold feedlines to the much smaller intake lines of the mixing nozzle(s) in such a manner so that in operation the mixing nozzles are not "starved" of either chemical component. The manifold thus assures a uniform constant flow of chemicals into the mixing nozzle(s).

The manifold consists of two chambers side-by-side separated by a wall so that the two chemical components in the respective chambers cannot come into contact. Each chamber is fed by its respective manifold feedline and is emptied through one of the two mixing nozzle feedlines. This concept is shown in Figure 12. This concept allows the use of multiple nozzles all being fed from common chambers.

The manifold should be constructed of materials which are inert with respect to the chemicals to be used. The manifold can be constructed of metallic or nonmetallic materials and, therefore, could be made flexible in nature thus allowing more latitude in its installation.

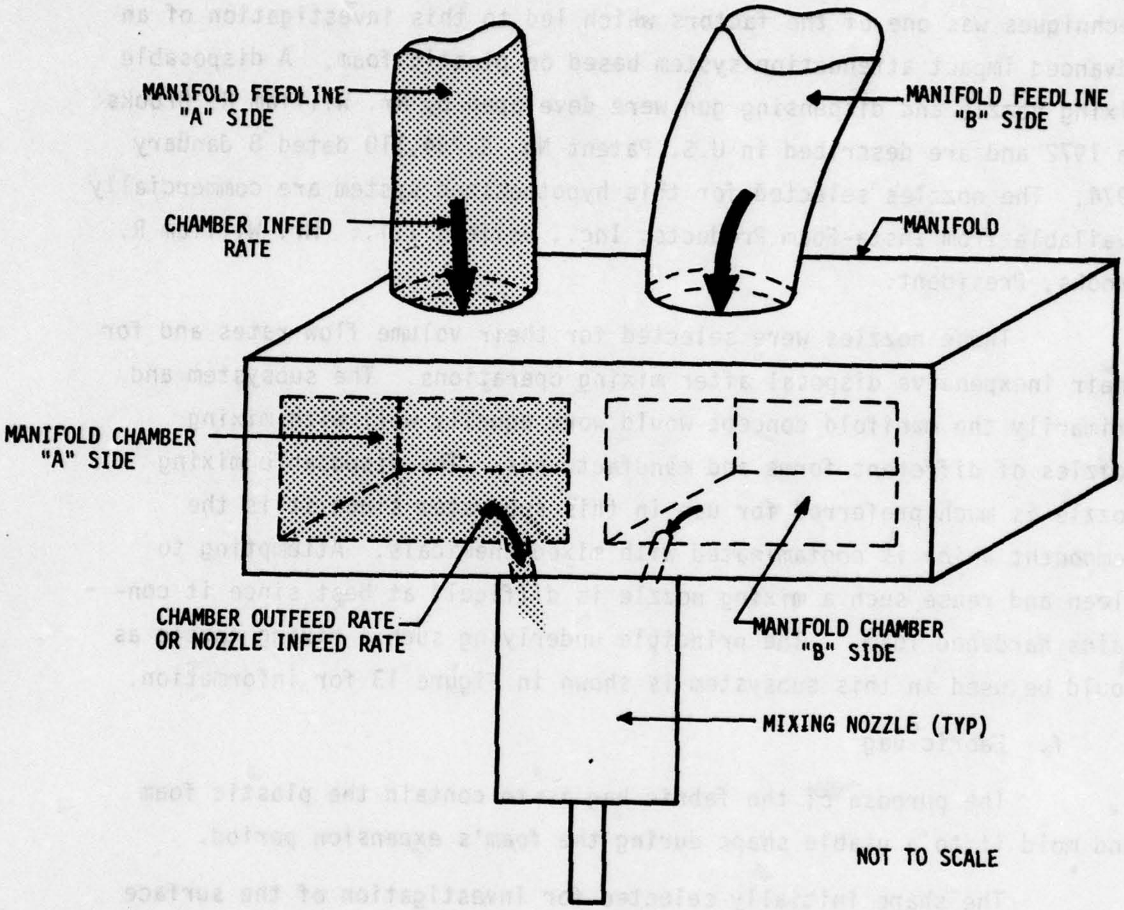


Figure 12. Manifold Concept

e. Mixing Nozzles

The commercial development of simplified foam mixing/dispensing techniques was one of the factors which led to this investigation of an advanced impact attenuation system based on plastic foam. A disposable mixing nozzle and dispensing gun were developed by Mr. William R. Brooks in 1972 and are described in U.S. Patent No. 3,784,110 dated 8 January 1974. The nozzles selected for this hypothesized system are commercially available from Insta-Foam Products, Inc., Joliet, Ill.: Mr. William R. Brooks, President.

These nozzles were selected for their volume flow rates and for their inexpensive disposal after mixing operations. The subsystem and primarily the manifold concept would work equally well with mixing nozzles of different forms and manufacturers. The disposable mixing nozzle is much preferred for use in this subsystem since it is the component which is contaminated with mixed chemicals. Attempting to clean and reuse such a mixing nozzle is difficult at best since it contains hardened foam. The principle underlying such a mixing nozzle as could be used in this subsystem is shown in Figure 13 for information.

f. Fabric Bag

The purpose of the fabric bag is to contain the plastic foam and mold it to a usable shape during the foam's expansion period.

The shape initially selected for investigation of the surface impact attenuation of RPVs is an oblate spheroid. The random nature of the horizontal velocity component made a round bag desirable. The ability to slide over the terrain rather than "dig in" led to a large radius curve at the outside edge in all directions (360°). The oblete spheroid with its elliptical cross section satisfies both of these requirements. Additionally, the bottom surface is relatively flat allowing for a broad initial footprint.

The bag is constructed using two circular pieces of cloth joined along their circumferences and tied together by tie strings in the interior. The length and locations of the tie strings are adjusted to obtain a good approximation of an oblate spheroid when inflated.

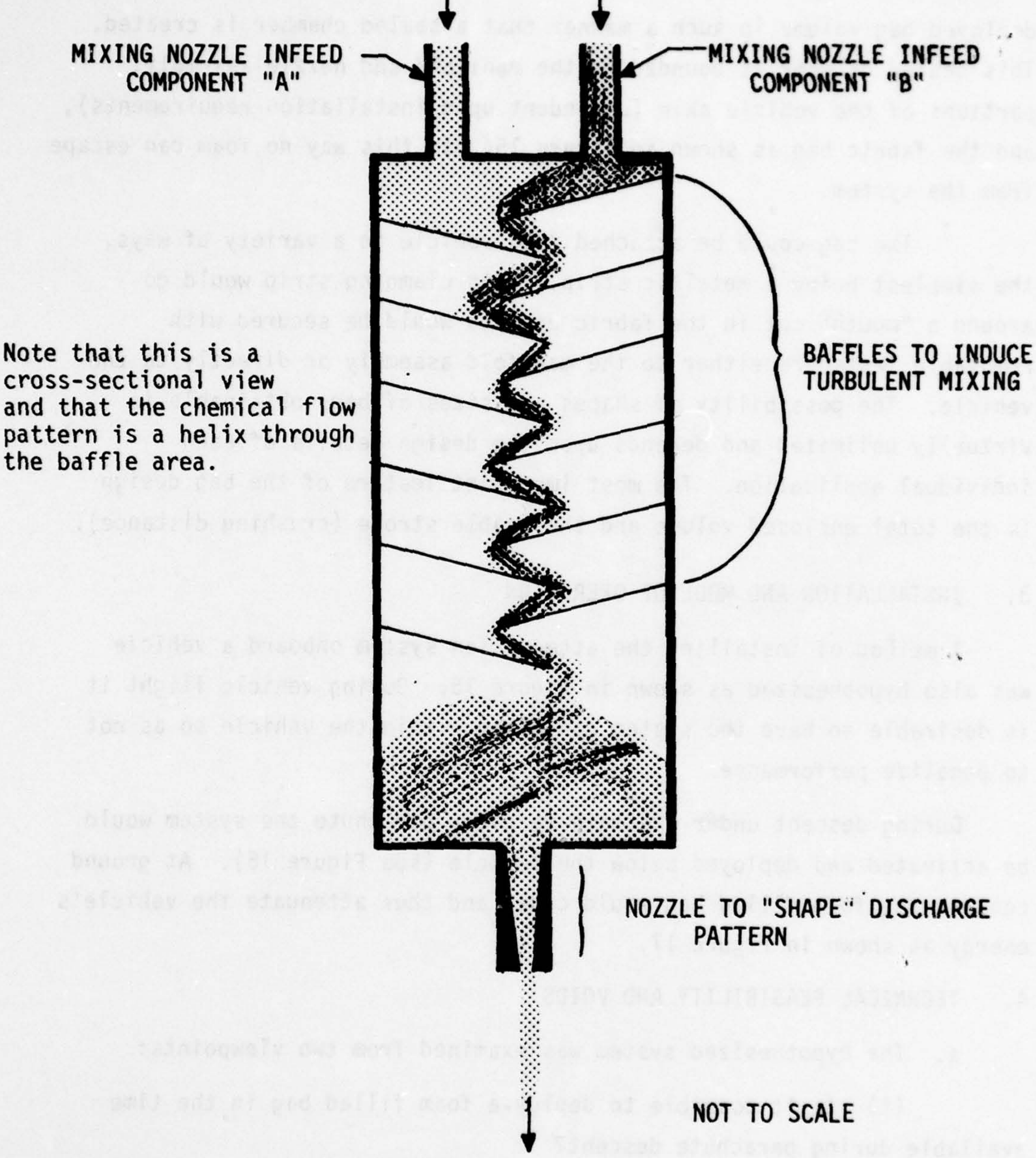


Figure 13. Nozzle Cross-Section

The deployed bag shape and construction details of a typical bag are shown in Figure 14. When installed, the manifold and nozzles protrude into the deployed bag volume in such a manner that a sealed chamber is created. This sealed chamber is bounded by the manifold and nozzle assembly, portions of the vehicle skin (dependent upon installation requirements), and the fabric bag as shown in Figure 15. In this way no foam can escape from the system.

The bag could be attached to a vehicle in a variety of ways, the simplest being a metallic strip. This clamping strip would go around a "mouth" cut in the fabric bag and would be secured with removable fasteners either to the manifold assembly or directly to the vehicle. The possibility of shapes and sizes of bags obtainable is virtually unlimited and depends upon the design details of each individual application. The most important feature of the bag design is the total enclosed volume and the usable stroke (crushing distance).

3. INSTALLATION AND MODE OF OPERATION

A method of installing the attenuation system onboard a vehicle was also hypothesized as shown in Figure 15. During vehicle flight it is desirable to have the system contained within the vehicle so as not to penalize performance.

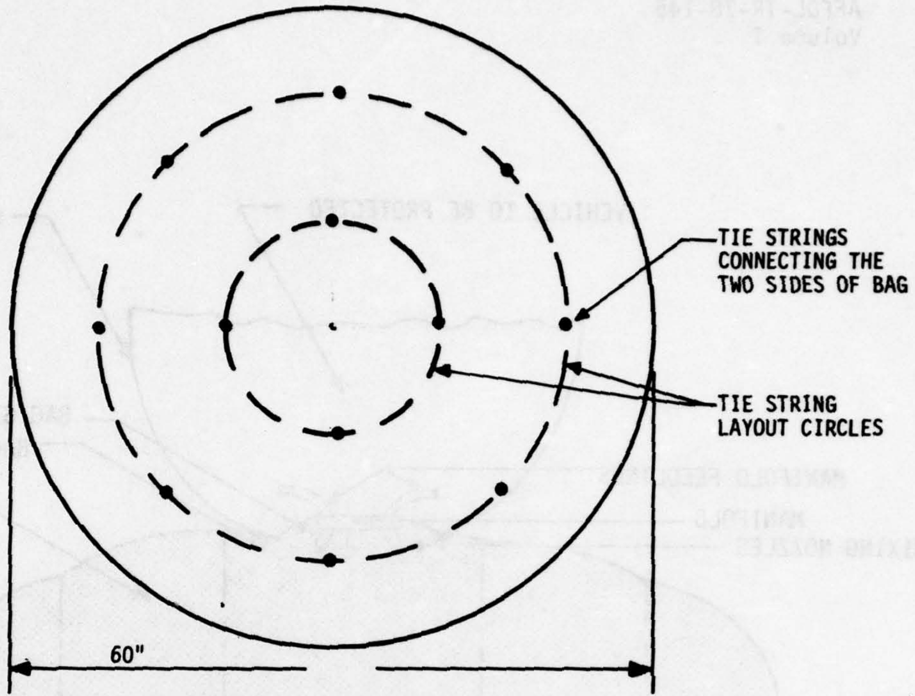
During descent under the main recovery parachute the system would be activated and deployed below the vehicle (see Figure 16). At ground contact the foam filled bag would crush and thus attenuate the vehicle's energy as shown in Figure 17.

4. TECHNICAL FEASIBILITY AND VOIDS

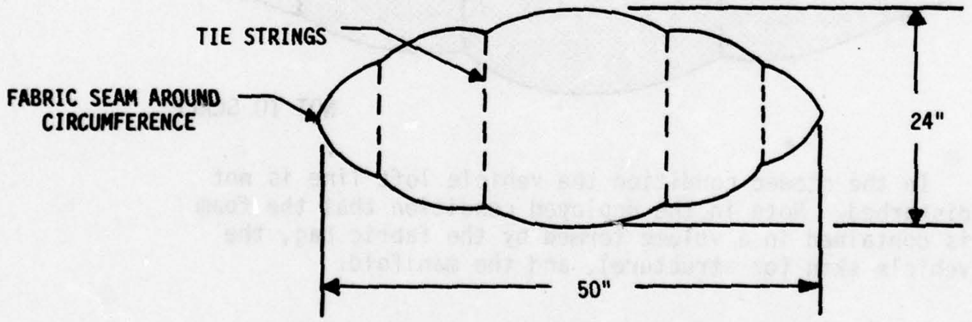
a. The hypothesized system was examined from two viewpoints:

(1) Is it possible to deploy a foam filled bag in the time available during parachute descent?

(2) Could a foam filled bag attenuate the impact energy of a vehicle?

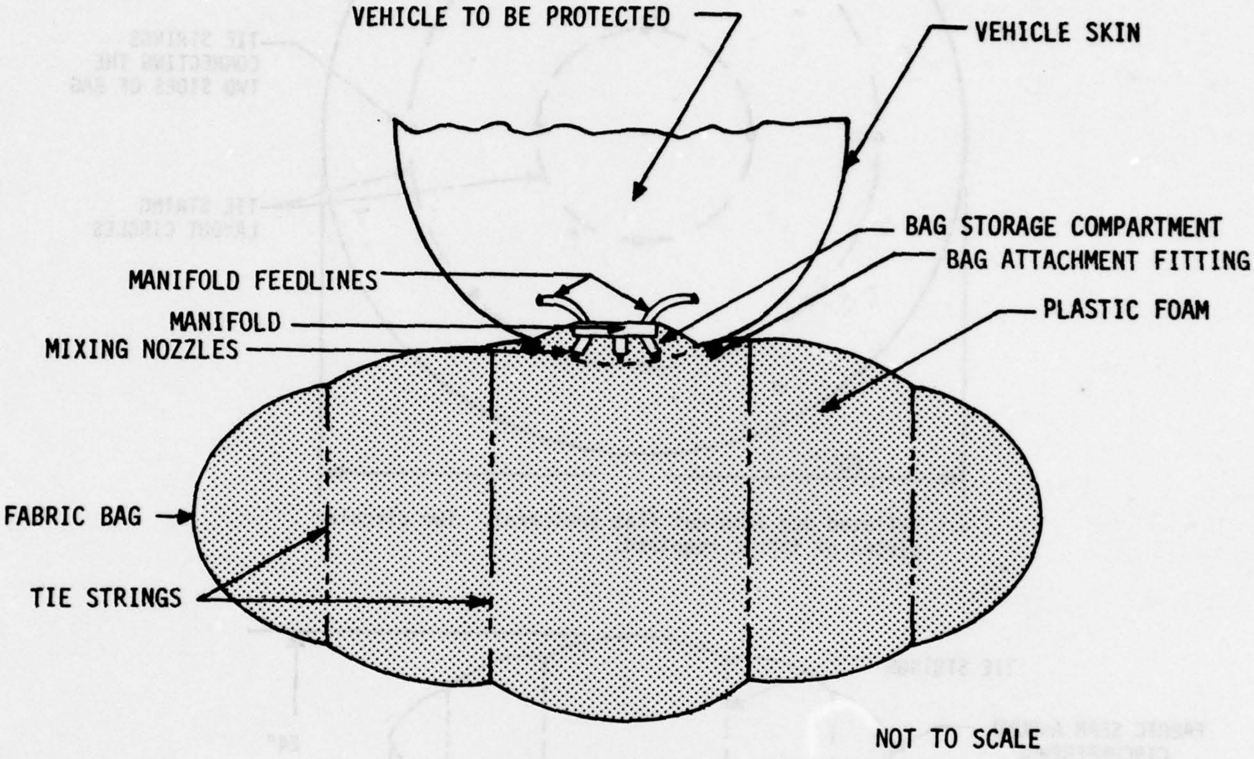


a. Deflated bag laid out flat (pattern). Two circular pieces of fabric required.



b. Inflated bag cross-section, note approximation of an elliptical cross-section.

Figure 14. Typical Bag Construction and Shape



In the stowed condition the vehicle loft line is not disturbed. Note in the deployed condition that the foam is contained in a volume formed by the fabric bag, the vehicle skin (or structure), and the manifold.

Figure 15. Typical Installation Geometry

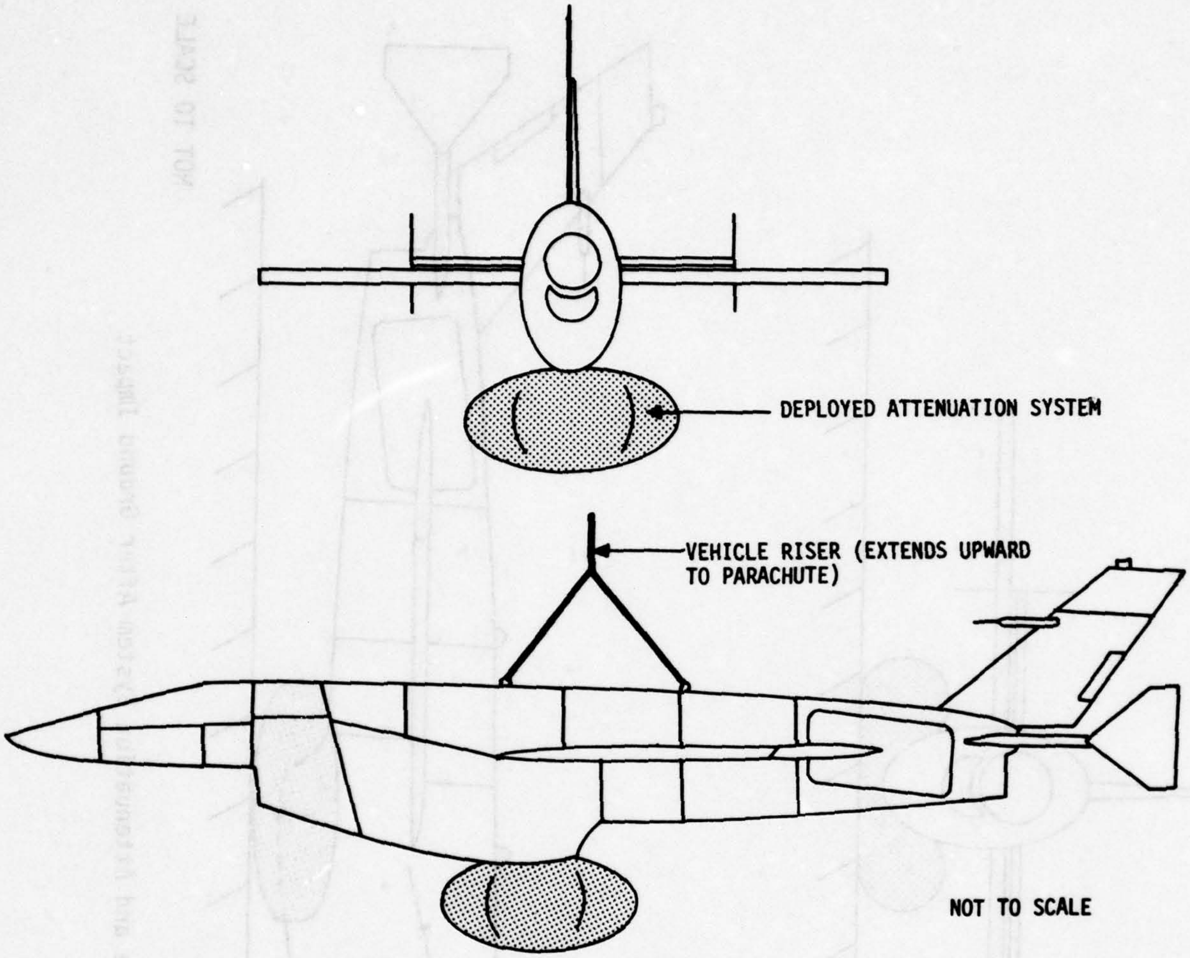


Figure 16. Vehicle Suspended from Parachute with Deployed Attenuation System Prior to Ground Impact

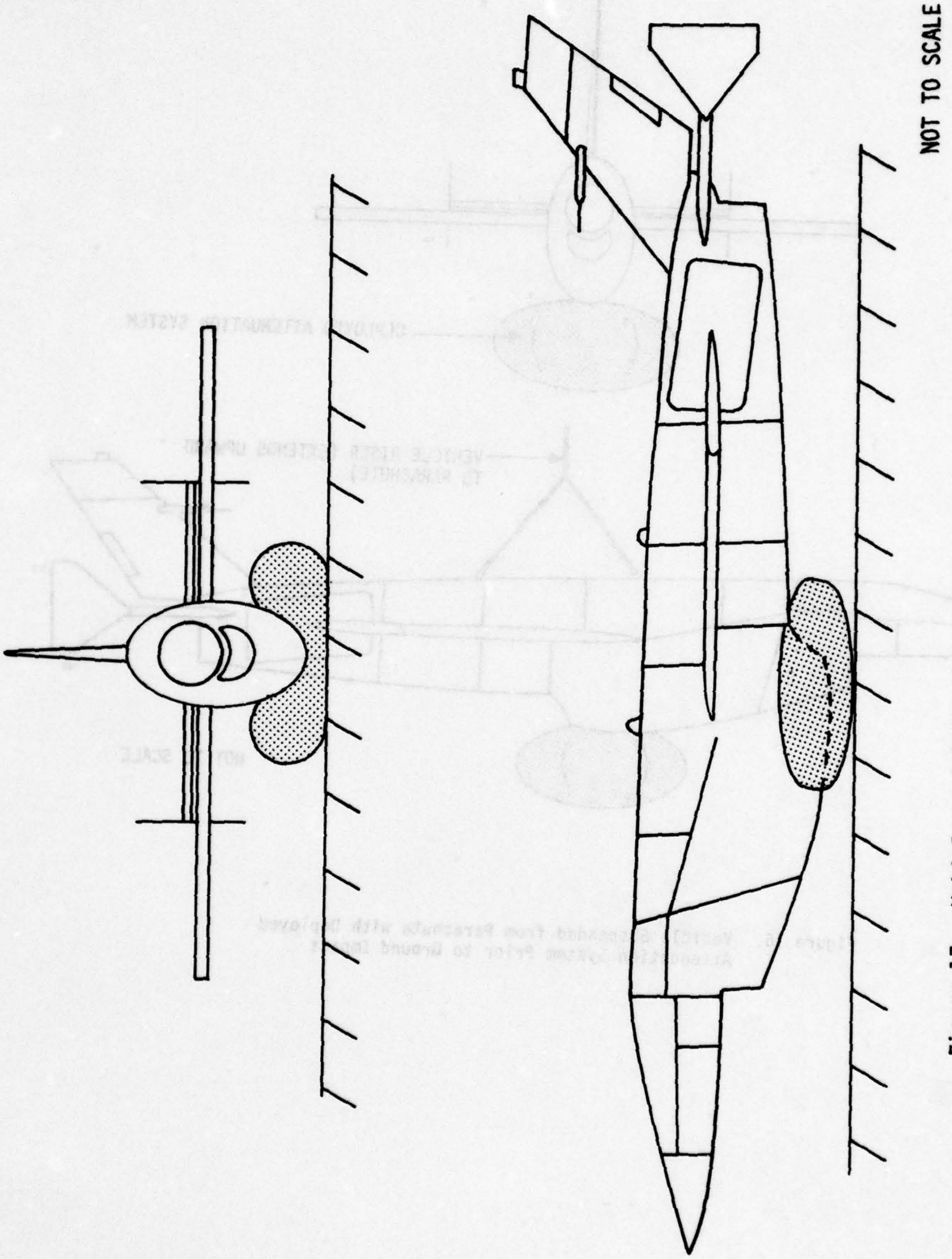


Figure 17. Vehicle and Attenuation System After Ground Impact

b. The results of this examination were that concern existed in the following areas (these may be considered as known unknowns):

(1) What types of plastic foams were available? What were the desired properties? What was the specific energy absorption of the available foams? What chemical family of foams was desirable (e.g. polyurethanes versus polystyrenes versus urea-formaldahydes, etc.)?

(2) The existing technical information on foams and their material properties was based on steady-state, long-time duration applications. No data was available on the material properties of foams in the very early time period after chemical reaction. It was known that the chemicals were undergoing a change from the liquid state to an expanded solid state, but the properties during the transition had not been previously investigated.

(3) The disposable mixing nozzle concept had a maximum demonstrated flow rate of 10-12 pounds per minute. Higher flow rates and/or multiple manifolded nozzles had not been demonstrated.

(4) The homogeneous filling of a fabric bag had not been demonstrated. The homogeneous filling of a rigid mold (injection molding) was well understood but a flexible cloth bag was beyond the current state-of-the-art.

(5) How would the foam filled bag react to the impulsive impact loading? Some knowledge of foams impact behavior existed but primarily for packaging type applications involving long time spans between reaction and impact.

(6) What was the minimum deployment time that a foam based attenuation system could be designed for?

(7) Could the foam attenuators behavior during impact be understood and analytically modeled? This qualification of the physics and mechanics involved would be the basis for analytical design of a foam based attenuator and would reduce the cut and try methods of the past twenty years.

In addition to these major areas of concern, it was suspected that additional areas of concern would appear as work progressed (i.e., unknown unknowns would appear). This was strongly suspected due to both the "black art" history of impact attenuation efforts over the preceeding 30 years and the knowledge that plastic foams also had "black art" aspects in their development history of the last 20 years.

SECTION VI

TEST EQUIPMENT

The full scale impact testing of the deployable polyurethane foam ground impact attenuation system was performed on an in-house basis at Wright-Patterson Air Force Base, Ohio. The physical size of the apparatus involved and the energy levels being investigated dictated that the safety of test be designed into the testing setup from the beginning. The test setup was designed to yield the maximum number of tests and amount of information for a minimum expenditure of money and manpower. By "designing in" test safety and economy a simple, flexible, and highly productive test series was accomplished in a relatively short time.

1. GENERAL ARRANGEMENT

The full scale testing of the attenuation system required four basic systems for operation.

a. Foam dispensing system
b. Test Vehicle and Impact site
c. Instrumentation and Recording Equipment
d. Test engineers and technicians

Three test cells located in Building 255, WPAFB, were used to house the test apparatus. Each of these cells were designed for explosives testing and hence are constructed with extra thick double reinforced concrete walls. If an undesired event occurred in any one of the test cells it would be contained within that cell and would not affect equipment (or people) in an adjacent cell. The general arrangement is shown in Figures 18 and 19. The foam dispensing system together with the solvents and working area were in Test Cell 103 with chemical transfer lines running to Test Cell 104. The test vehicle and impact testing was performed in Test Cell 104 with hard wire instrumentation leading to the expensive recording equipment located in Test Cell 105. During testing all spectators and test personnel watched from the hallway which served as a fourth isolation area.

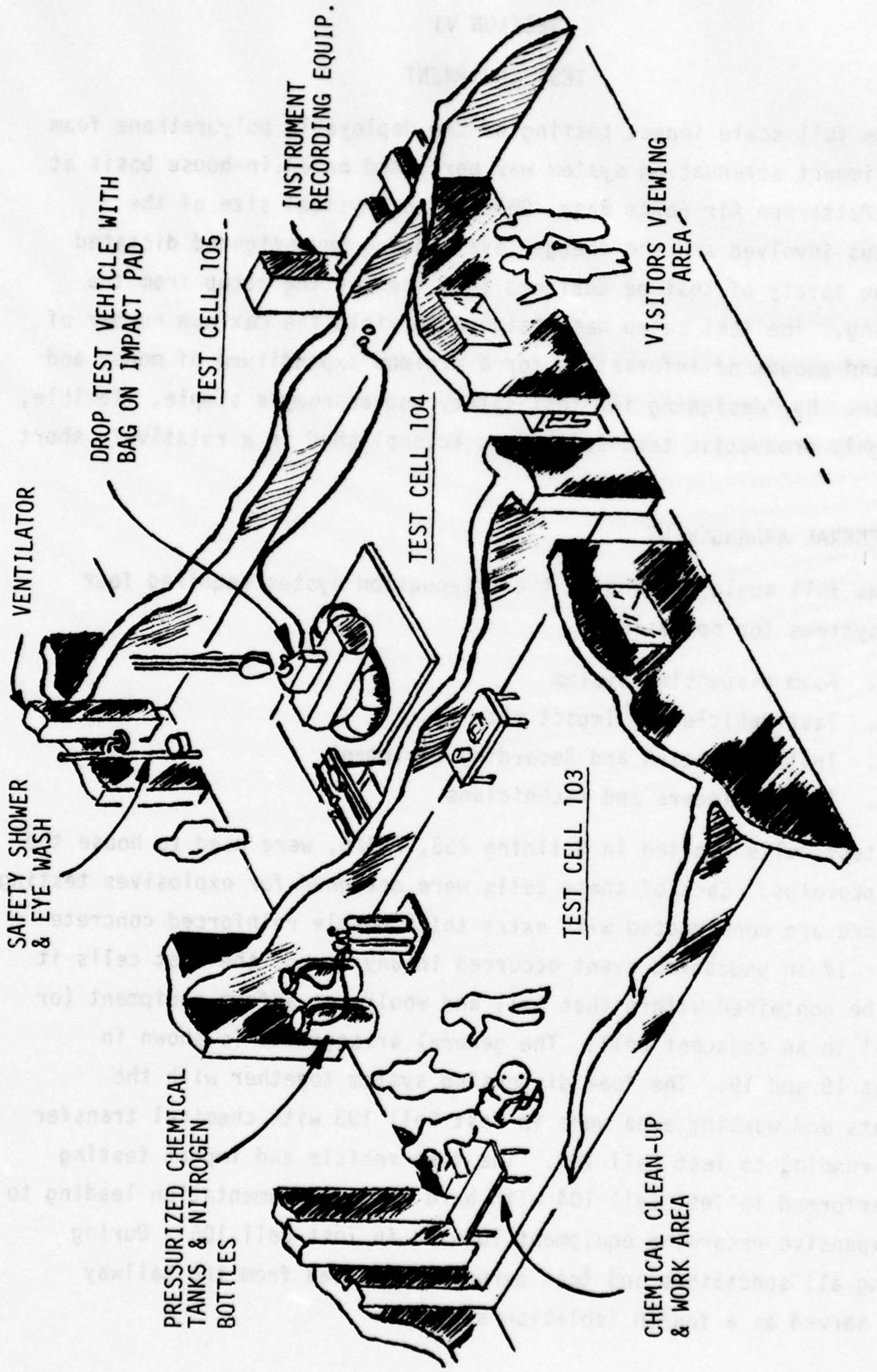


Figure 18. General View of Test Facility

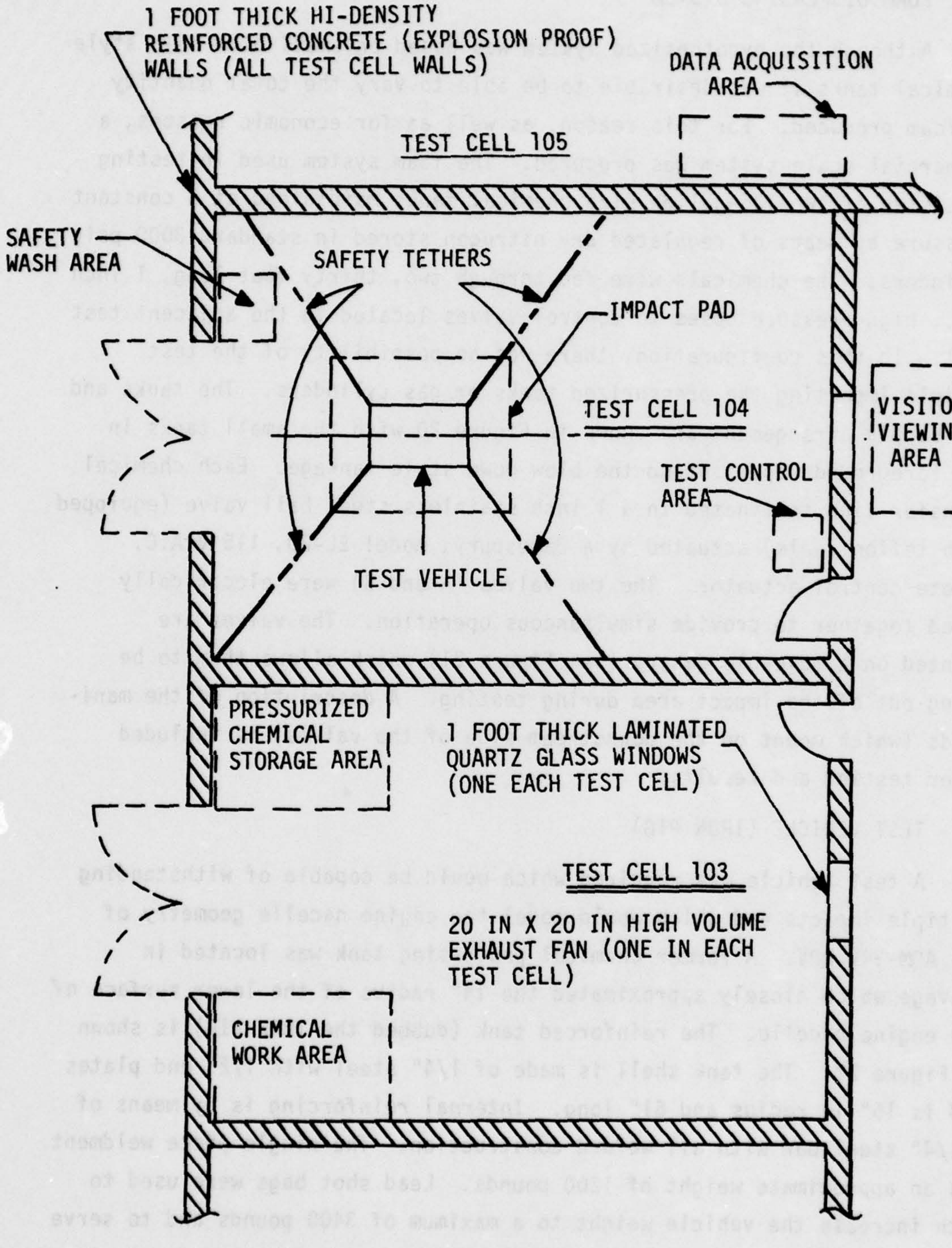


Figure 19. Safety Arrangements

2. FOAM DISPENSING SYSTEM

Although the hypothesized system was based on small blow down style chemical tanks it was desirable to be able to vary the total quantity of foam produced. For this reason, as well as for economic reasons, a commercial scale system was procured. The foam system used in testing consisted of two 125-gallon size chemical tanks maintained at a constant pressure by means of regulated dry nitrogen stored in standard 3000 psig cylinders. The chemicals were fed through two, thirty foot long, 1 inch I.D., high pressure hoses to control valves located in the adjacent test cell. In this configuration, there was no possibility of the test vehicle impacting the pressurized tanks or gas cylinders. The tanks and gas supply arrangement are shown in Figure 20 with the small tanks in the foreground representing the blow down style tankage. Each chemical transfer line terminated in a 1 inch stainless steel ball valve (equipped with teflon seals) actuated by a Jamesbury, model EL-20, 115 V.A.C. remote control actuator. The two valves (A and B) were electrically wired together to provide simultaneous operation. The valves are mounted on a moveable gantry (see Figure 21) which allows them to be swung out of the impact area during testing. A description of the manifolds (which mount on the downstream side of the valves) is included under testing and results.

3. TEST VEHICLE (IRON PIG)

A test vehicle was required which would be capable of withstanding multiple impacts and which would model the engine nacelle geometry of the AQM-34V RPV. A former chemical processing tank was located in slavage which closely approximated the 14" radius of the lower surface of the engine nacelle. The reinforced tank (dubbed the IRON PIG) is shown in Figure 22. The tank shell is made of 1/4" steel with 1/2" end plates and is 15" in radius and 61" long. Internal reinforcing is by means of 1-1/4" steel bar with all welded construction. The single piece weldment has an approximate weight of 1200 pounds. Lead shot bags were used to both increase the vehicle weight to a maximum of 3400 pounds and to serve as mechanical damping of the shell vibrations during impact.

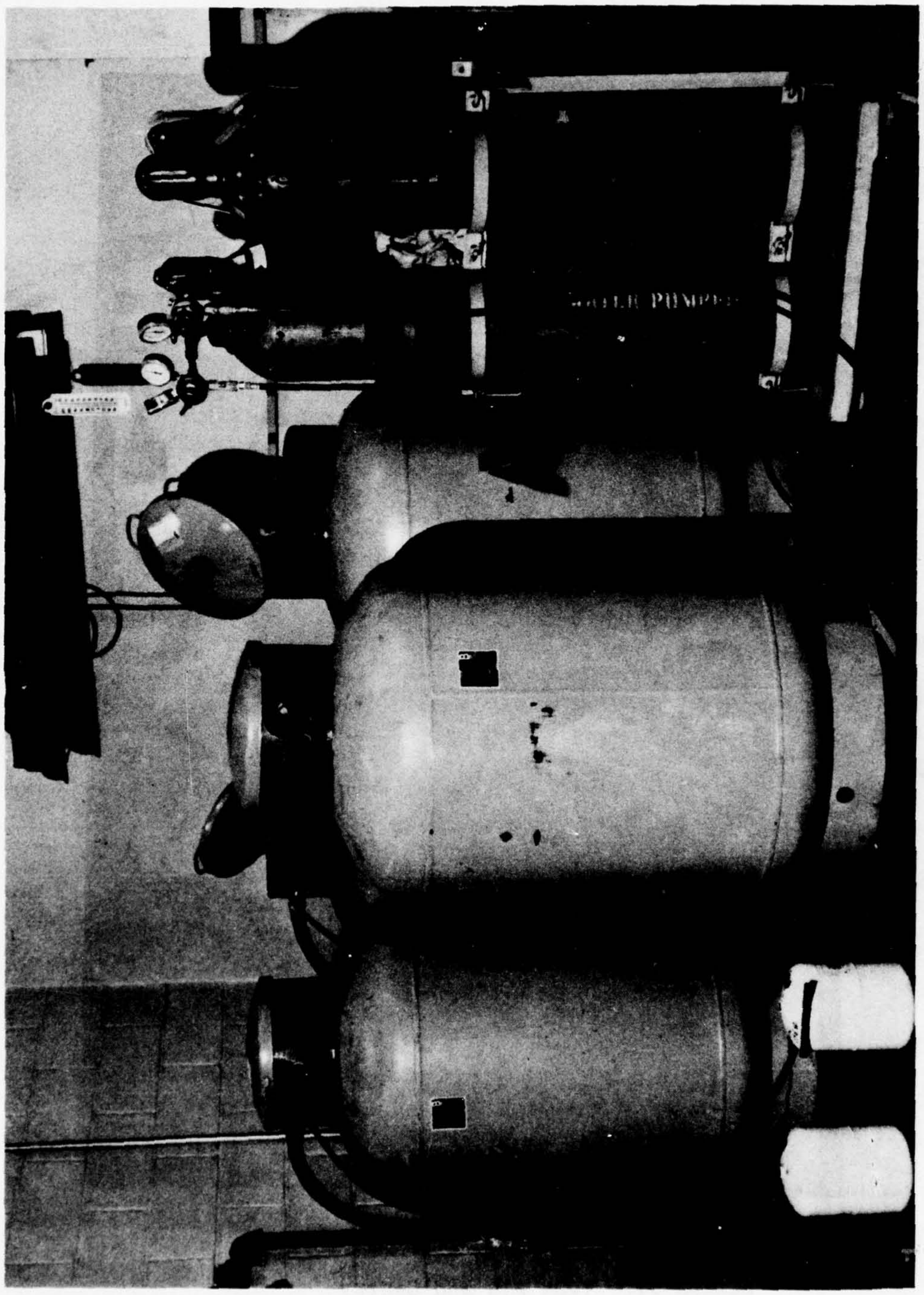


Figure 20. Chemical Tanks

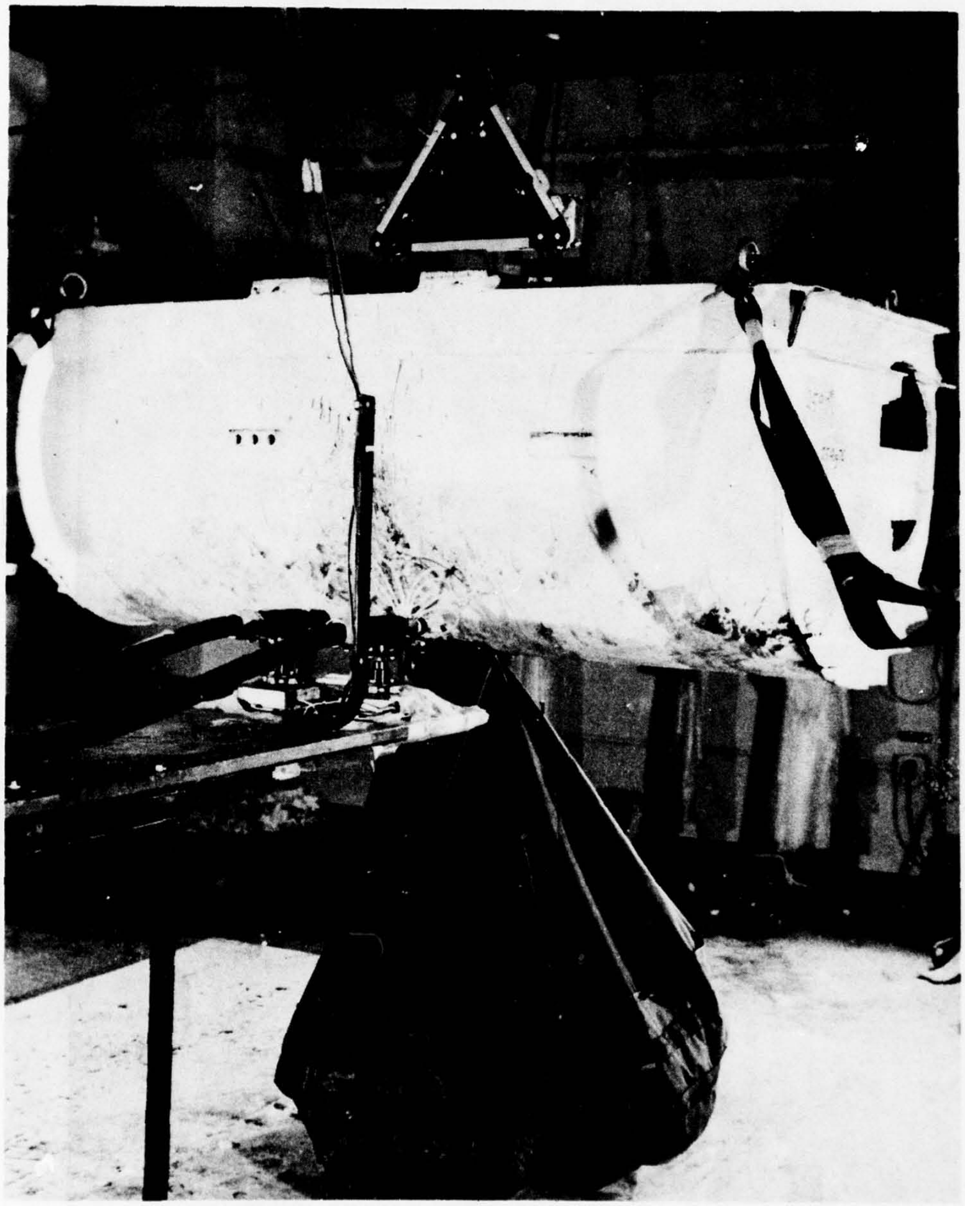


Figure 21. IRON PIG and Gantry

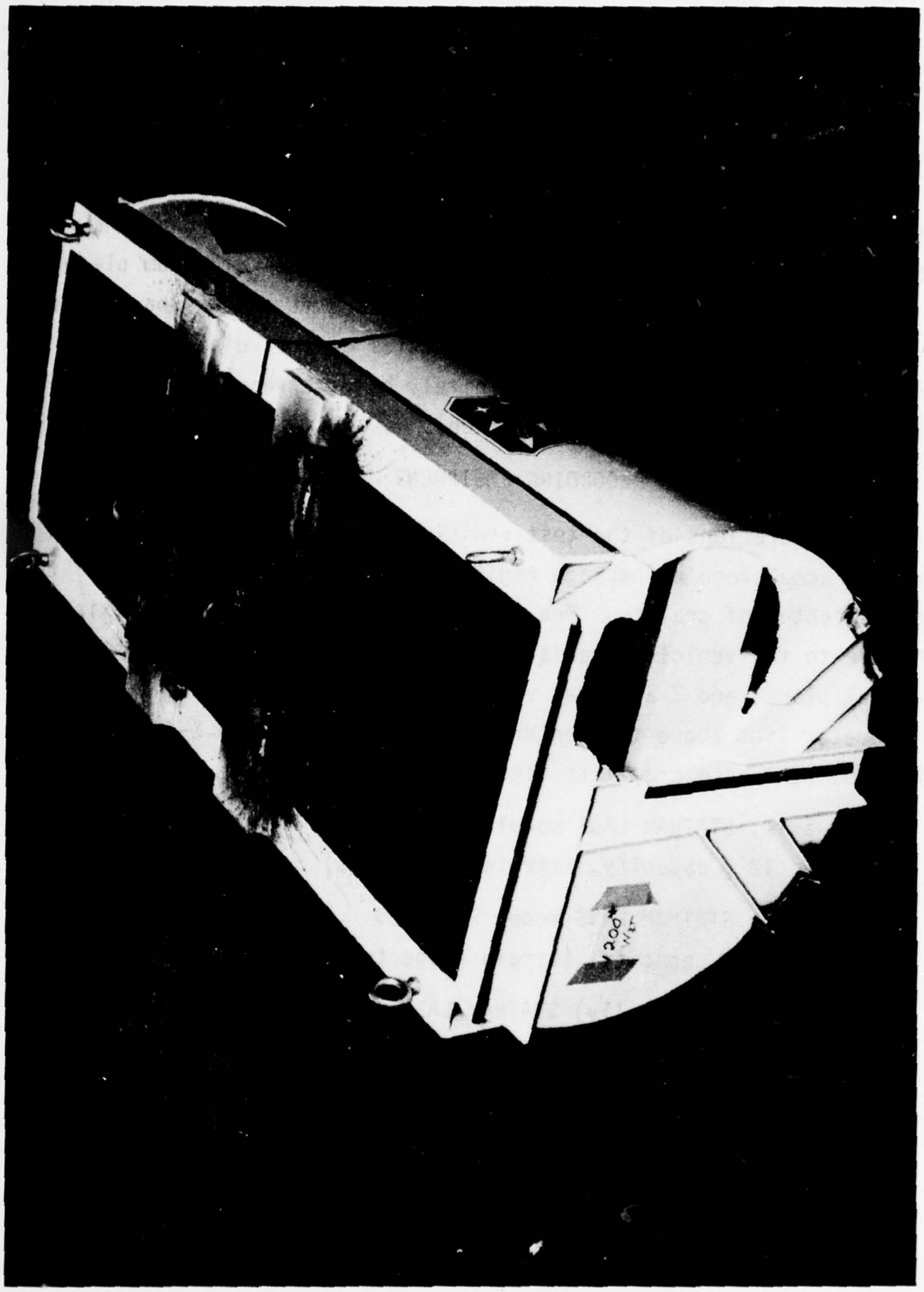


Figure 22. IRON PIG Test Vehicle

The IRON PIG was suspended and released by means of a 10,000 pound bomb rack assembly mounted on a 3 ton capacity overhead crane (see Figure 23). The release mechanism was actuated by a push-pull cable from a remote location. Tethers were located at each of the tour corners of the IRON PIG in such a manner that vertical movement was unimpeded but that horizontal movement was restricted to approximately two feet in any horizontal direction. The vehicle and attenuation system dropped onto an impact pad consisting of 2-1/2" aluminum plate. This impact pad covered a rectangular area 8 by 9 ft and was backed by 3/4" plywood to accommodate any irregularities of the reinforced concrete floor. In this manner, an infinitely hard terrain was simulated (believed to be the worst case condition).

4. INSTRUMENTATION AND RECORDING EQUIPMENT

The accelerations of the test vehicle were measured by means of a three axis accelerometer package rigidly mounted along the Z axis of the vehicle's center of gravity. The coordinate system used was; X axis, lengthwise to the vehicle; Y axis perpendicular to the X axis in the horizontal plane, and Z axis was vertical. In Figure 24 the Z axis accelerometer lies above the center of gravity but on the X-Y coordinates of the C.G. The accelerometers used were:

X-axis; STATHAM LABS model AR-12V-120
12 g capacity, (strain guage type)

Y-axis; STATHAM LABS model R-12-120
12 g capacity, (strain guage type)

Z-axis; (originally) STATHAM LABS model R-25-120
25 g capacity (strain guage type); later
replaced by a Bell and Howell model
4-202-0001, 50 g capacity (piezoresistive
type)

The accelerometer signals were fed by hardwire to a Honeywell Model 1508 visicorder during the early testing. Later testing used a Bell and Howell model VR-3700B magnetic tape recorder to record the accelerometer signals. Once recorded the signal could be fed into a

Figure 23. IRON PIG and Vertical Release

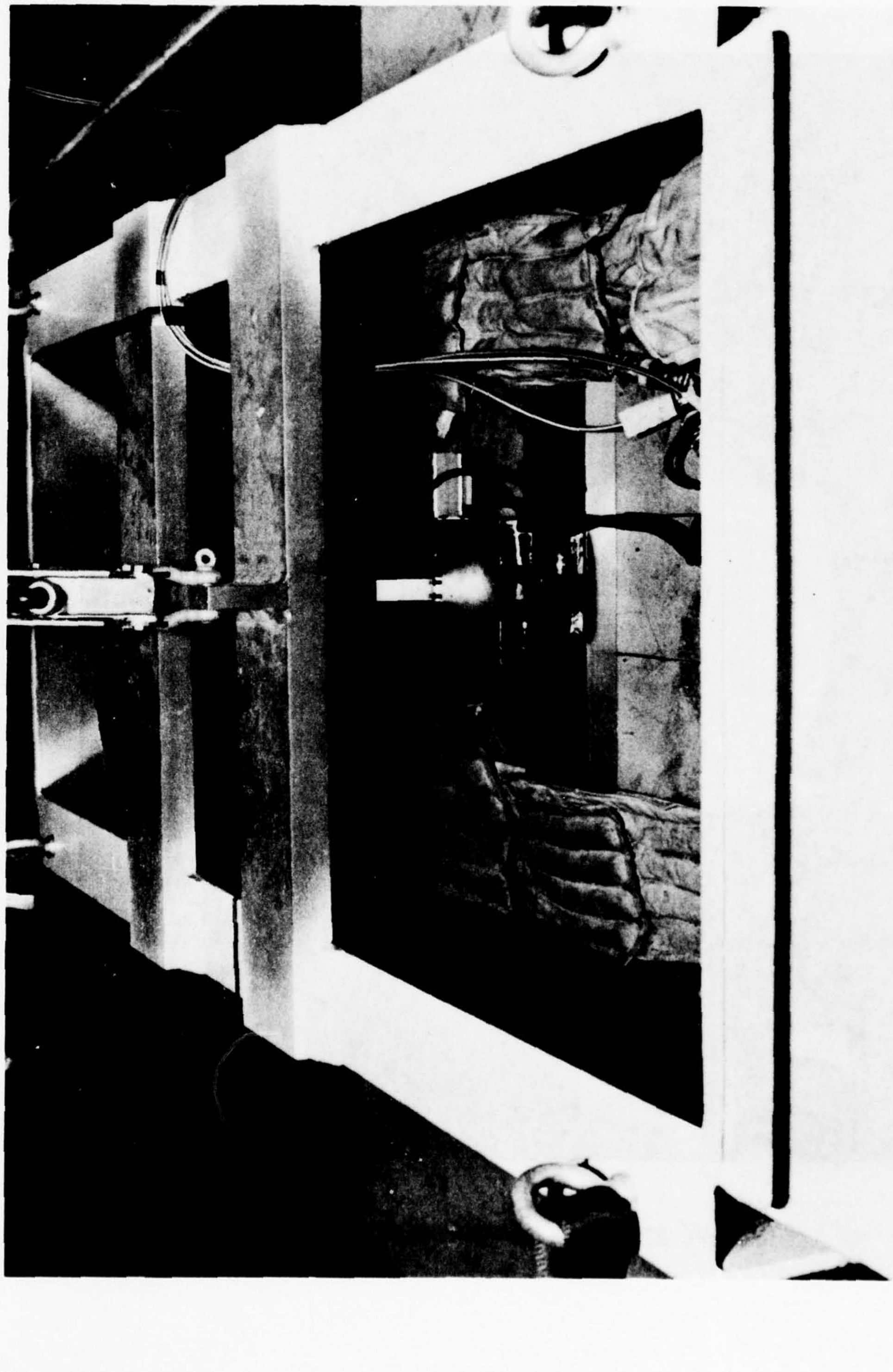


Figure 24. Instrumentation Arrangement

Nicolet Instrument Corp. digital oscilliscope (model 1090) which was interconnected to a Hewlett-Packard Model 9810A calculator which could record processed data via a peripheral X-Y plotter (Omnigraphics recorder, model 6550, Houston Ominigraphic Corp.).

The result of this recording/analysis set up was a quick data processing and interpretation of the results. This speed of analysis allowed a rapid rate of testing consistent with knowledgeable planning.

In addition to the electronic data gathering equipment, each test was photographically documented. A pair of Mitchell cameras operating at 64 frames/second were used to record each test from initiation of foaming operations through impact of the test vehicle. The cameras were arranged in adjacent corners of the test cell so as to record the impact from both sides of the test vehicle. The color coverage provided an excellent record of the foam/bag behavior during impact. The film processing/turnaround time provided by 4950th/ENP technical photographic service averaged one to two days post test and was consistent with the desired testing rate.

5. GENERAL COMMENTS

The test equipment and setup described constituted a simple, safe, flexible, research tool. The ability to test, analyze the results, and test again the following day with full knowledge of the previous results greatly speeded the investigation of a deployable polyurethane foam ground impact attenuation system.

SECTION VII

FOAM SELECTION AND INITIAL INVESTIGATION

The initial phase of investigation of an advanced impact attenuation system based on plastic foam was the selection of a specific plastic foam compound. In this phase the investigative technique was to consult with experts in related fields and then test the most reasonable approaches. This technique was mandated by a lack of precedence among prior foam applications.

1. FOAM SELECTION

A variety of plastic foams have been formulated during the last twenty years. Each different family of compounds has its own characteristics which may be advantageous or disadvantageous depending upon the intended application. During prolonged discussions with foam chemists and applications engineers it was decided that the polyurethane family of foam compounds offered the greatest potential for a successful application.

By limiting the initial foam selection to those polyurethane foam formulations which were commercially available one of two things would occur: 1. a formulation suitable for the impact attenuation application would be found, or 2. enough knowledge would be gained during this process that the specifications for a new "custom formulated" foam could be written. This approach was reasonable because the available polyurethane formulations ranged in density from 1/2 pound to 40 pound (i.e., foam is described as "X pound" which means X pounds per cubic foot, the "...per cubic foot" is understood). They could be formulated as rigid, semirigid, semiflexible or flexible (these terms describe the relative resiliency and are somewhat subjectively defined).

The polyurethanes also lent themselves to a variety of reaction times, by the addition of a suitable catalyst the rise time could be varied from a few seconds through several minutes. (Rise time is the time from initiation of the chemical reaction to 95% expansion). The foam mechanism which absorbs (attenuates) energy is the compressive stress over a given area ($Lbs/ft^2 \times ft^2 = Lbs$) crushing through some stroke (Ft-Lbs) therefore the compressive yield stress of the foam was an important consideration. The foam compressive yield stress of the available density foams ranged from approximately 0.5 psi for a 1/2 pound polyurethane to several thousand psi for a 40 pound polyurethane (such as might be used to mold "wood carvings" for furniture making). Faced with this wide range of polyurethane foams to choose from, each of which could attenuate energy, the question of foam selection still remained.

The question of foam selection was finally narrowed down by examining the operational parameters of the AQM-34V RPV. By examining the operating time available (descent from 3000' AGL to ground impact) a target goal of 120 seconds from initiation of foaming to impact was arbitrarily established. Further through discussions with the RPV structural engineers it was estimated that the vehicle skin could withstand a bearing pressure of approximately 10 psi without skin failure. This narrowed the field of available foams to the 1/2 - 2 pound density range. By estimating the maximum allowable vehicle accelerations together with the contact area and initial velocity conditions, a rough estimate of the bag shape, volume, chemical flow rates, reaction times (rise times), etc. could be made but there was still no method of choosing a "best" foam formulation.

2. FILLING A BAG

In order to further define a "best foam" it was decided to fill some bags with candidate formulations and subject them to low energy level impacts with the IRON PIG test vehicle.

The preliminary estimations resulted in a bag design of approximately twenty cubic feet in volume. The bag was an oblate spheroid 22" in minor diameter by 55" major diameter and was constructed of 7-1/4 oz nylon duck. The design used two solid flat circular pieces of cloth joined at the circumference with the elliptical cross-section maintained by 550# cord tiestrings. This bag design was used from test #1 through #32 (with minor variations as noted).

Attempts to fill this 20 ft^3 bag resulted in nonhomogenous foam fills characterized by lumps, voids, wrinkles, etc. The dispensing equipment being used was a commercial foaming machine (production line style) which had a limited flow rate. When a scaled down version of the bag was used (4 ft^3 volume) with the same foam formulation a good homogeneous foam was created. Analysis of this phenomena suggested that the nonhomogeneity of the large bag (20 ft^3) was due to the relatively low flow rate. It appeared that the voids, etc., were being caused by the first increment of foam being expanded and behaving as a solid while later increments were in a fluid type state. The solid portions blocked the fluid portions and thus prevented the homogeneous filling of the bag. In the small bag (4 ft^3) the first increments had not yet become a solid material before the filling process was completed. It was postulated (and later shown to be true) that the ratio of fill time divided by rise time should be less than one for a homogeneous foam mass to be created. An experiment was set up to evaluate this premise without regard to the impact attenuation problem. Because the bag contained 20 ft^3 of foam and the maximum flow rate obtainable from the foam machine was approximately 25 pounds per minute an available 2-1/2 pound polyurethane with a rise time of three minutes was selected. The actual filling time on the experiment was 2 min 45 sec or a ratio value of 0.91. The resulting foam filled bag had no wrinkles or voids and was homogeneous throughout. Thus the first analytical tool for the design of a foam impact attenuator was established (Equation 1).

$$\frac{\text{Fill Time}}{\text{Rise Time}} < 1 \qquad (1)$$

where Fill Time = the time to mix and dispense the total amount of foam required
Rise Time = time from initiation of reaction to 95% expansion of the foam

The existence of this fill time/rise time ratio requirement further narrowed the field of available foams to choose from. For example, assume a 1 pound foam were selected, using the 20 ft^3 bag, twenty pounds of foam were to be mixed in the "fill time." If this foam were to be catalyzed to a rise time of 5 seconds then the required flow rate through the mixing nozzles would be greater than 240 Lbs/min in order to maintain the ratio requirements. Because the state of the art of the disposable nozzles was 10-12 Lbs/min then the very short rise time formulations were not feasible. Conversely if the 10 Lb/min flow rate was maintained then the allowable foam rise time (for this example) became 120 seconds. The operating time for the system (from initiation to impact) is the sum of the fill times and rise times or (in this 10 Lb/min flow rate case) a total of 4 minutes. This four minute operating time violated the target goal of 2 minutes for the AQM-34V application.

Out of this dilemma came the decision to increase the mixing nozzle flow rates by manifolding multiple nozzles. Because the operating time of a deployable attenuation system is one of the most critical parameters (regardless of vehicle application) and because chemical formulations having shorter than useable rise times existed, then the increased mixing nozzle flow rates would be the most beneficial area of investigation. If a scheme could be devised to satisfy the 120 second goal of the AQM-34V application then the technology base would exist to tackle different applications requiring shorter operating times.

3. INITIAL IMPACT TESTING

A series of eleven impact test (test no's. 1-11) were performed during the period of 18 Dec 75 to 29 Jan 76. These tests were conducted using the bags which were filled previously and hence were nonhomogeneous and old, cold foam. The purpose of these tests was to gain a foothold on what density (compressive stress) foam was required as well as to obtain an estimate of the foam bags reaction to impact. These bags were strapped to the bottom of the IRON PIG and the energy levels were based on initial contact with the impact pad. The individual tests will be discussed briefly with conclusions following.

Test #1 (18 Dec 75)	A 20 ft^3 bag filled with nonhomogeneous 1 pound foam was impacted with 7500 Ft-Lbs initial kinetic energy. The 2500# test vehicle experienced a peak deceleration of 8.5 g's. A secondary (bounce) peak of 1.9 g's was recorded.

Test #2 (28 Jan 76)	A 20 ft^3 bag filled with nonhomogeneous 1/2 pound foam was impacted with 5000 Ft-Lbs resulting in a 6 g maximum deceleration during a 220 µsec pulse.
Test #3-8 (29 Jan 76)	A set of six impacts on the same nonhomogeneous 1 pound foam bag, each impact was 2500 Ft-Lbs resulting in a total energy attenuation of 15,000 Ft-Lbs (6 x 2500). During the series, the bag became crushed more and more and "molded" itself to the test vehicle. This was reflected in higher onset rates and shorter pulse times as the series progressed. The maximum accelerations were: (in sequence) 4.5, 6.0, 8.0, 8.2, 8.9, and 9.2 g's.
Test #9 (29 Jan 76)	A nonhomogeneous 1/2 pound bag was impacted with 2500 Ft-Lbs. The bag ruptured at 4 g's causing the 2500 Lb test vehicle to bottom out. An extrusion type rupture was noted as well as a constant deceleration of 4 g's lasting $\approx$ 45 µsec. This test suggested that extrusion as well as crushing may be possible.
Test #10 (29 Jan 76)	Test conditions identical to test #9, result was a max deceleration of 5 g's with a pulse duration of 210 µsec but without bag rupture.
Test #1 (29 Jan 76)	This 2500 Ft-Lb test was conducted on 1/2 pound foam but without the bag. The structural integrity of the bag was destroyed by cutting prior to test. It was an attempt to determine what (if any) contribution the bag made to the attenuation. Result was a rapid bottoming of the test vehicle with very little attenuation evident. The low density foam appeared to move out of the way, rather than crush.

The conclusions of these tests were that a 1 pound polyurethane with a 20 ft^3 bag appeared as a reasonable basis for investigation. The possibility of extrusion as an energy attenuating mechanism was noted. The 1/2 pound foam concept appeared to be marginal at this low energy level (2500 Ft-Lbs) and higher energy levels were doubtful. It appeared that the fabric bag played a significant role in the attenuation process and that further investigation of that role was warranted. It should be noted that in these tests the 1/2 pcund foam was rated with a compressive yield stress of 0.5 to 1.0 psi while the 1 pound foam was rated at 5 - 8 psi.

In terms of the old, cold long term material properties the 1 pound polyurethane appeared as a viable candidate foam. The next phase was to determine its impact behavior within the 120 second desired operating time.

SECTION VIII

120 SECOND FOAM

The selection and initial investigation of a 1 pound polyurethane foam had shown the potential of old, cold foam but had not addressed the problem of the impact behavior of the foam in its early time period after reaction.

On 6 February 1976, Test #12, this question was addressed for the first time.

Test #12 (6 Feb 76)	The first real time deployment and impact of a polyurethane foam impact attenuator was performed on 6 Feb 76. The elapsed time from initiation of foaming to impact of the IRON PIG was 120 seconds, which corresponded to an initiation altitude of 2400 AGL for the AQM-34V RPV. The 2500# IRON PIG experienced a peak deceleration of 8 g's during the 7500 Ft-Lb impact. A breadboard style nozzle assembly was commercially procured and delivered 15 pounds of one pound foam in 17 sec. for a flow rate of 53 Lb/min.

This test showed that the foam had developed sufficient material properties within a time span considered feasible for an impact attenuation application. The feasibility of an advanced impact attenuation system based on plastic foam had been verified but the practicability remained unanswered.

SECTION IX

MIXING NOZZLE MANIFOLDING

The time period from 23 July 76 through 7 Aug 76 was devoted to developing a working manifold mixing nizzle arrangement. The tests conducted during this portion were tests #13 through #24. The five month interval between tests #12 and #13 was devoted to a multiple source procurement of foam and supplies. The nozzle manifolding used during Test #12 was extraordinarily cumbersome and was not even practical for laboratory testing. A redesigned manifolding system was delivered on 28 June 76 and prepared for test #13 on 23 July 76. A brief description of the testing is given below.

Test #13, #14, #15, #16 (23 Jul 76)	These tests with commercial manifolding were designed to check the quality of foam produced and to calculate the foaming systems flow rate. The results of these four tests were that no foam was produced. Instead a sputtering mess of raw chemicals was produced. Assumed cause was foreign material in lines causing blockage.
Test #17 (29 Jul 76)	With lines thoroughly purged, attempted to check foam quality and flow rate. Achieved a flow rate of 60 Lb/min for 30 seconds with good quality foam being produced.
Test #18 (30 Jul 76)	Attempted to fill 20 ft^3 bag, result was partially foam, partially raw chemical, erratic mixing, low flow rate.

After Test #18 the erratic behavior of the manufacturer's equipment was clearly unacceptable, although it was understandable since it was an advancement in the state of the art. An analysis of the fluid flow in the manifolding yielded a theoretical cause of the erratic behavior and suggested a relatively simple solution. The chemicals in this system contain dissolved fluorocarbon gases and in effect do not exist as a fluid at pressures below approximately 50 psig. At lower pressure the chemicals tend to froth and resemble shaving cream in consistency. The manifolding as supplied by the manufacturer contained the equivalent of three sharp edge expansion orifices as well as having an initial evacuated chamber volume of 72 in^3 before opening of the control valves. It was theorized that the chemicals were frothing in the manifold chamber and that this froth was obstructing the nozzle inlets and not some unknown foreign material in the lines. The solution which was suggested was to redesign the manifold with a much smaller evacuated volume and eliminate the expansion flow areas. A manifold was designed with a chamber volume of 1.3 in^3 and no expansion orifices, this manifolding is shown in Figure 25, and was used for the duration of the testing. The manifold consists of a 3/4" I.D. X 3" extra heavy wall black iron pipe nipple sealed at one end with a standard pipe cap. The manifold threads directly into the remote control valves as shown. The aluminum nozzle tubing adapters (to which the 1/8" nylon tubing connects) are epoxied into drilled holes along the manifold. This simple and cheap arrangement allowed manifolds to be made up for four or more nozzles with a minimum of effort.

Test #19 (5 Aug 76)	Ran new manifolds for first time, achieved 81 Lbs/min of good quality foam, manifold worked.
Test #20 (5 Aug 76)	Attempted to fill bag using new manifolds. One of the nozzle feedlines became unfastened during test, test stopped.
Test #21 (6 Aug 76)	Attempted to fill bag using 55" long nozzle feedlines. Achieved only 47 Lbs/min. Was low flow rate caused by long nozzle feedlines or by interference inside the bag?
Test #22 (7 Aug 76)	Filled bag with a flaired nozzle pattern to prevent interference inside bag, ran with 55" long nozzle feedlines, still got short fill.

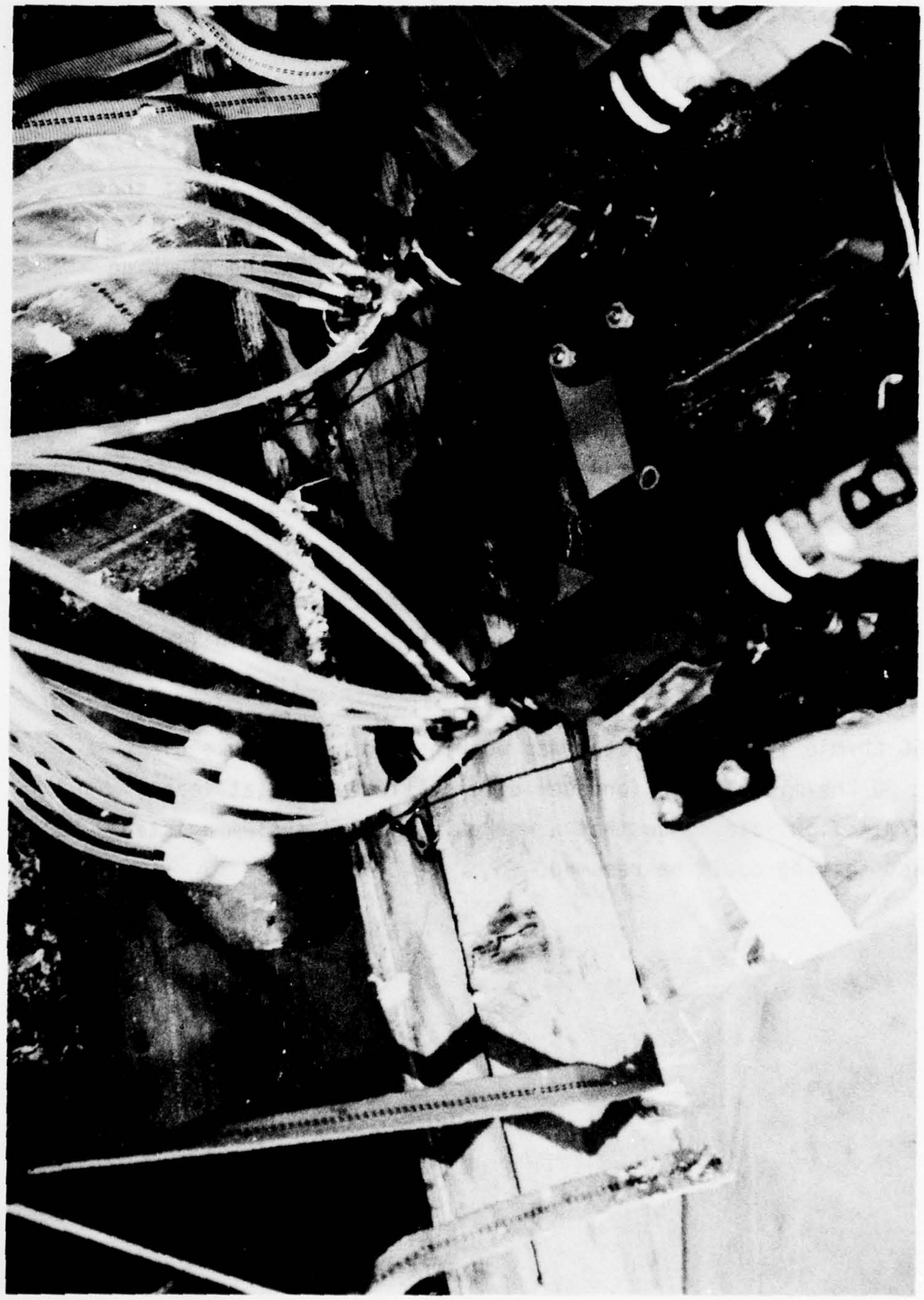


Figure 25. Manifolding

Test #23 (7 Aug 76)	Ran calibration shot (no bag) with 55" long lines, achieved 41 Lbs/min flow rate.
Test #24 (7 Aug 76)	Ran calibration shot (no bag) with 24" long nozzle feedlines, achieved 60 Lbs/min flow rate.

The conclusions reached from this series of tests were that the manifolding of multiple nozzles was a practical concept and readily achievable provided certain conditions of fluid flow in the plumbing were maintained:

1. Sharp pressure drops are to be avoided.
2. Total manifold chamber volume downstream of the valves should be as small as possible. 72 in^3 - too big, erratic; 1.2 in^3 - allowable, good flow.
3. The flow rate was very sensitive to the length of the 1/8" nozzle feedlines. A difference in length of one inch would cause a measurable change in flow rate.

A 60 Lb/min flow rate system was working and was capable of reachine 80 Lbs/min with no foreseen difficulties up to (at least) a 100 Lb/min flow rate. Now that a workable foaming system existed the impact testing could be resumed.

SECTION X

IMPACT TESTS NUMBERS 25 THROUGH 32

In this series of tests conducted between 9 August 1976 and 18 August 1976, the objective was to gain an understanding of the foam's behavior during impact so that an analyses could be performed. If an analytical model could be generated then the design of a workable system would be simplified.

Test #25 (9 Aug 76)	Attempted a 13,000 Ft-Lb impact, inadvertent bag overfill, 40# of foam in a 20 ft^3 bag, test stopped
Test #26 (10 Aug 76)	Attempted a 13,300 Ft-Lb impact, chemical temperatures were 66°F, no reaction, no foam, test stopped
Test #27 (10 Aug 76)	Checked foam reaction and quality at 77°F, good results
Test #28 (10 Aug 76)	Attempted 13,300 Ft-Lb impact, bag ruptured, prior to rupture had 7.6 g's max, rupture occurred at 120 μsec into pulse, 23 g spike after rupture
Test #29 (16 Aug 76)	Calibration of flow rate, prior test thought to be overfill
Test #30 (16 Aug 76)	7770 Ft-Lb impact, again bag ruptured but no bottoming spikes, saw 8.2 g's maximum
Test #31 (17 Aug 76)	10,360 Ft-Lb impact, bag modified with 2 lateral reinforcing bands. Result; severe bounding, 1st impact - 10 g's max 2nd impact - 4.5 g's max 3rd impact - 2 g's max
Test #32 (18 Aug 76)	13,300 Ft-Lb impact again used reinforcing bands, bag ruptured, 14 g maximum, but no rebound, did appear to be at edge of bottoming

The photographic coverage of these tests showed that the bag failures originated along the major diameter of the bag perpendicular to the IRON PIG longitudinal axis. By observing the bag ruptures and by selected orientation of the bag seams during testing an estimation of the bag stress pattern was evolved although stress levels were not determinable. The data obtained during these tests yielded an empirical relation between the apparent bag pressure against the test vehicle and the depth of penetration of the test vehicle into the bag. The results of test #32 indicated that 13,300 Ft-Lbs was very near the bottoming energy level of this bag/foam combination and that higher energy level testing should not be run on this design. Tests #26 and #27 indicated that the chemicals had a minimum initial temperature requirement which would have to become a design parameter for a prototype unit.

SECTION XI

FOAM DESCRIPTION AND THEORETICAL ANALYSIS

An analysis was performed which sought to explain the phenomena of the foam/bag behavior during the impact attenuation. Portions of this analysis had been accumulated since the beginning of the program and are presented here in a consolidated form.

1. FOAM DESCRIPTION, AGED PROPERTIES

The foam which was selected for investigations was a one pound (per cubic foot, nominal density), semirigid polyurethane formulation. The material properties of the aged foam are:

85% closed cells
1.0 pound nominal density
5 psi compressive yield stress at 5% strain
15 psi tensile yield stress

2. FOAM DESCRIPTION, CHEMICAL PROPERTIES

The precise chemical formulation of the foam is proprietary to the manufacturer. The chemicals do share the common properties of all polyurethane foams with one notable exception. The polyurethane family is of course an organic compound and the general types of agents employed in the formulations are as shown:

Part "A"	Part "B"
1. isocynates	1. polyols
2. blowing agents	2. catalysts
3. cell control agents	3. cell control agents
4. flame retarders	4. blowing agents
	5. flame retarders

It is important to note (from a toxicological viewpoint) that formulations containing toluene diisocyanate (TDI) have been expressly forbidden during this investigation.

Historically a severe problem existed in the thorough mixing of the two parts. The "A" component was (generally) a highly viscous fluid while the "B" component (generally) had a low viscosity. This mismatch in viscosities created complex mixing heads requiring large expensive mixing machines and high maintenance costs. The formulation selected is such that the viscosities of the two components are relatively equal. This viscosity matching allows the use of the simple, disposable nozzles. This advancement in foam technology was one of the factors uncovered during the state-of-the-art portion of this investigation. A simplified system of this general description is offered on the commercial market by at least two manufacturers (hence the multiple-source procurement of the foam and foaming system). In the scheme used by one manufacturer the two components each contain dissolved fluorocarbons in their formulation. A pressure of approximately 50 psig is necessary to maintain this solution. By increasing the pressure to approximately 200 psig over the chemicals a power source for the movement and mixing of the chemicals is created. This concept results in a self contained "blow down" foaming system requiring no external power source for the dispensing of foam.

3. FOAM'S IMPACT BEHAVIOR, PRIOR RESEARCH

The bulk of research work on foams impact behavior during the last five years has been directed towards a packaging application in which small, repeated, impacts were considered. The most applicable investigations dealing with simple, large scale crushing impacts were performed by the University of Texas Structural Mechanics Research Laboratory during the time period of 1957 through 1960. This organization under a contractural arrangement with the U.S. Army has performed an excellent, long term study of impact and impact attenuation phenomena. The reports documenting their investigation are listed in the Appendix. One report in particular is of special interest to this current investigation. The report entitled High-Velocity Impact Cushioning, Part VI, 108C and 100C Foamed Plastics prepared by R. Shield and C. Covington in 1960 investigated the effects of varying densities, impact energies, masses, and velocities at constant energy levels, and resiliencies at the total energy levels currently under investigation. Several of their test findings in the form of stress-strain impact curves are included here as supportive of an analytical model generated by this investigation (Figures 26 through 29). The conclusions of the referenced report which are pertinent to the present analysis are:

1. "Energy absorption and crushing stress increase with material density..."
2. "Energy absorption and crushing stress are independent of impact velocity..."
3. "Energy absorption and crushing stress are independent of the impacting mass..."

4. THEORETICAL MODEL

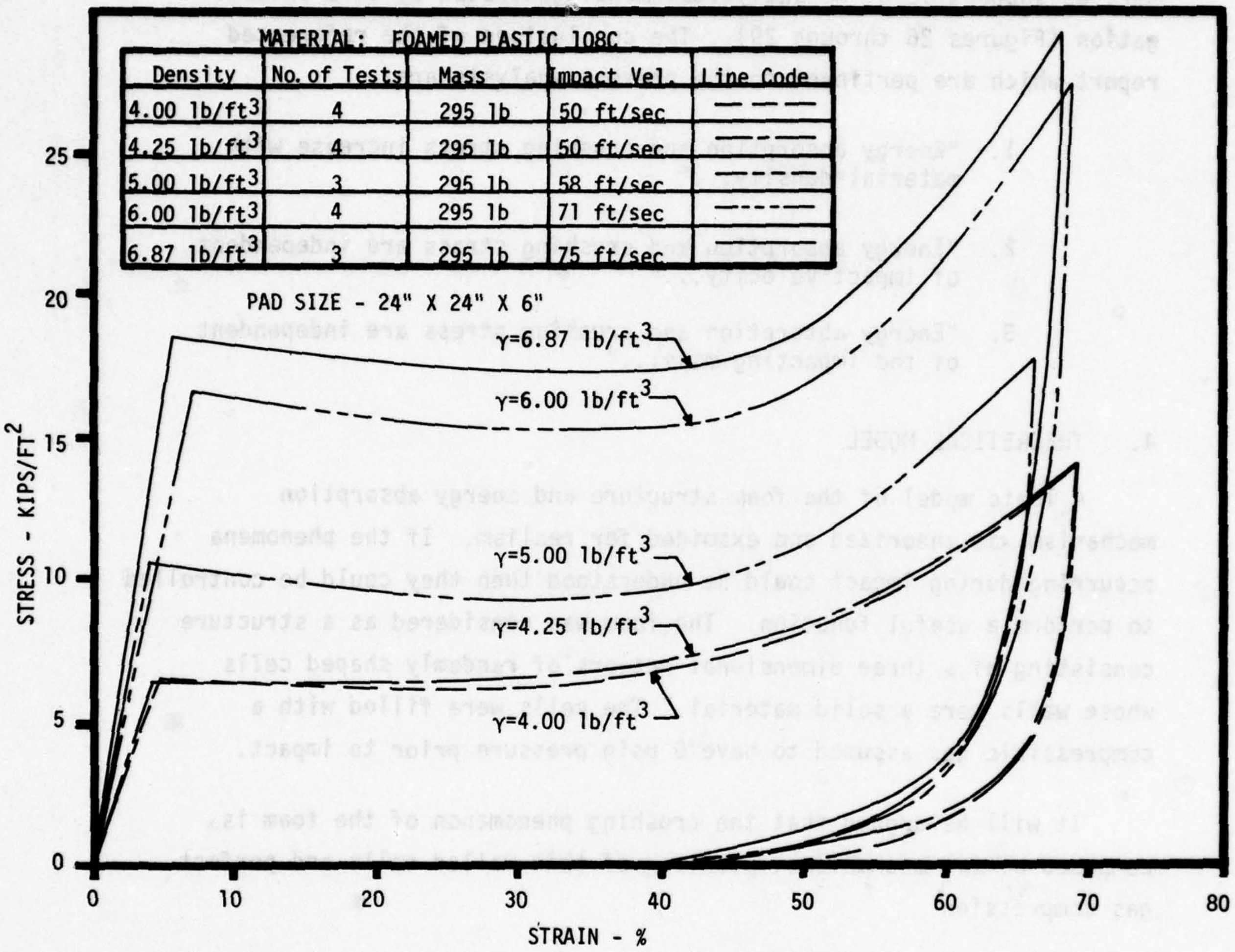
A logic model of the foam structure and energy absorption mechanism was theorized and examined for realism. If the phenomena occurring during impact could be understood then they could be controlled to perform a useful function. The foam was considered as a structure consisting of a three dimensional network of randomly shaped cells whose walls were a solid material. The cells were filled with a compressible gas assumed to have 0 psig pressure prior to impact.

It will be argued that the crushing phenomenon of the foam is composed of two mechanisms, buckling of thin walled cells and perfect gas compression.

5. ANALYSIS OF THE STRESS-STRAIN CURVES

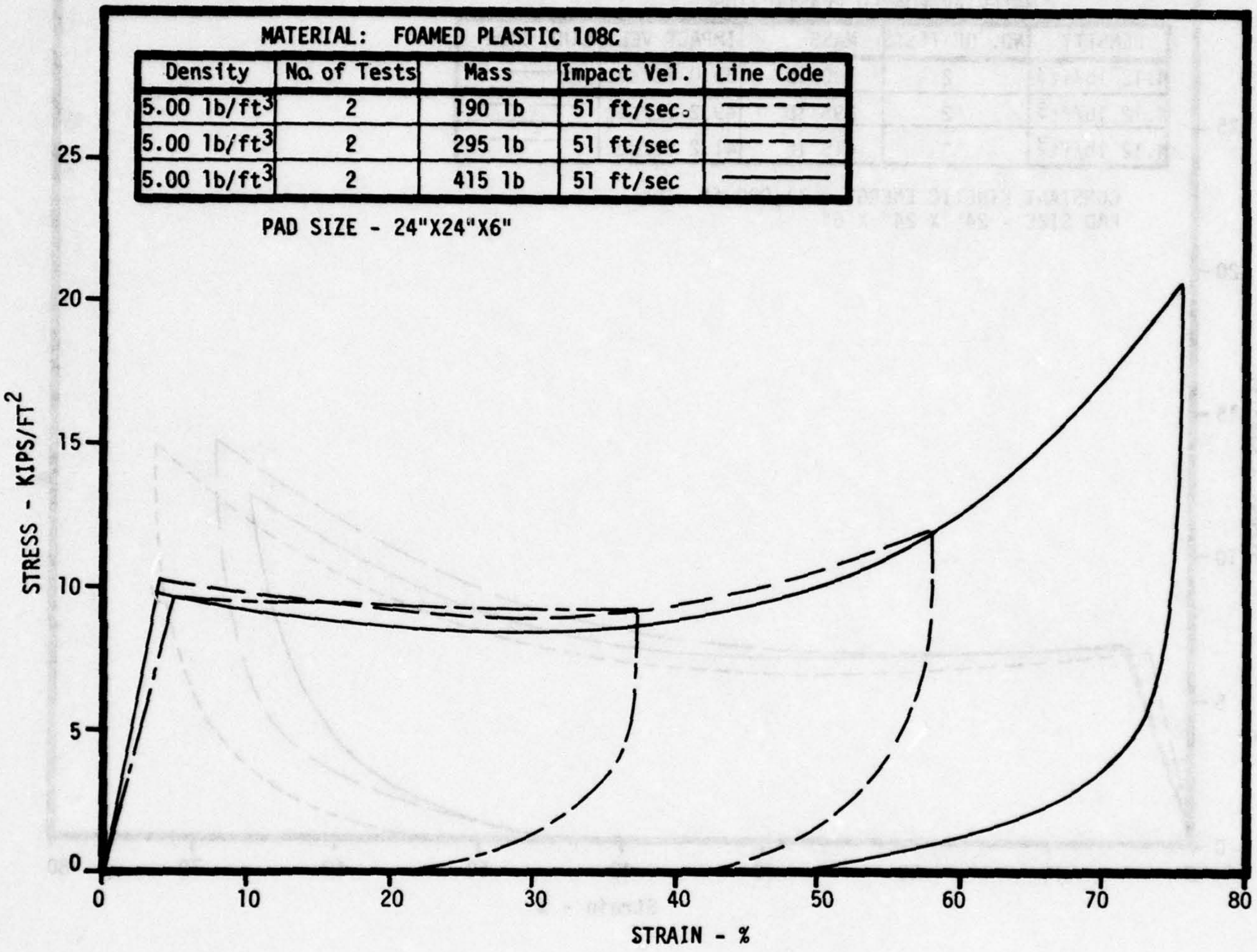
The stress-strain curves experimentally determined by Shield and Covington can be considered as being composed of three parts.

A. Elastic behavior
B. Compressive fluid behavior
C. Residual gas expansion



Density	No. of Tests	Mass	Impact Vel.	Line Code
4.00 lb/ft³	4	295 lb	50 ft/sec	— — —
4.25 lb/ft³	4	295 lb	50 ft/sec	—— - ——
5.00 lb/ft³	3	295 lb	58 ft/sec	—— - - ——
6.00 lb/ft³	4	295 lb	71 ft/sec	—- - - ——
6.87 lb/ft³	3	295 lb	75 ft/sec	——————

Figure 26. Effect of Density on the Stress-Strain Curve for Foamed Plastic 108C



Density	No. of Tests	Mass	Impact Vel.	Line Code
5.00 lb/ft^3	2	190 lb	51 ft/sec.	— — —
5.00 lb/ft^3	2	295 lb	51 ft/sec	—— ——
5.00 lb/ft^3	2	415 lb	51 ft/sec	———

Figure 27. Effect of Impact Mass on Stress-Strain Curve for Foamed Plastic 108C

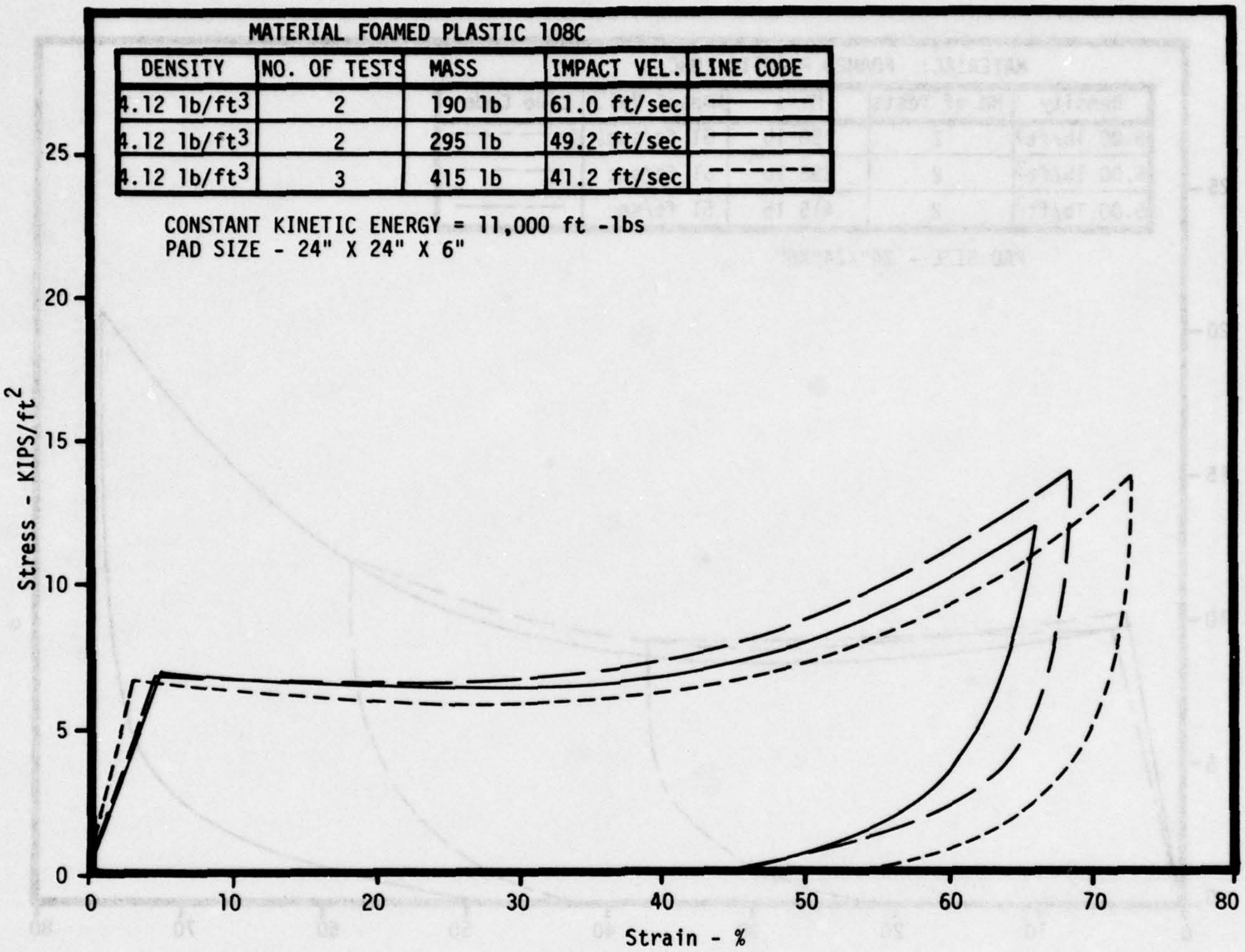


Figure 28. Effect of Simultaneous Change in Mass and Impact Velocity with Constant Kinetic Energy on Foamed Plastic 108C

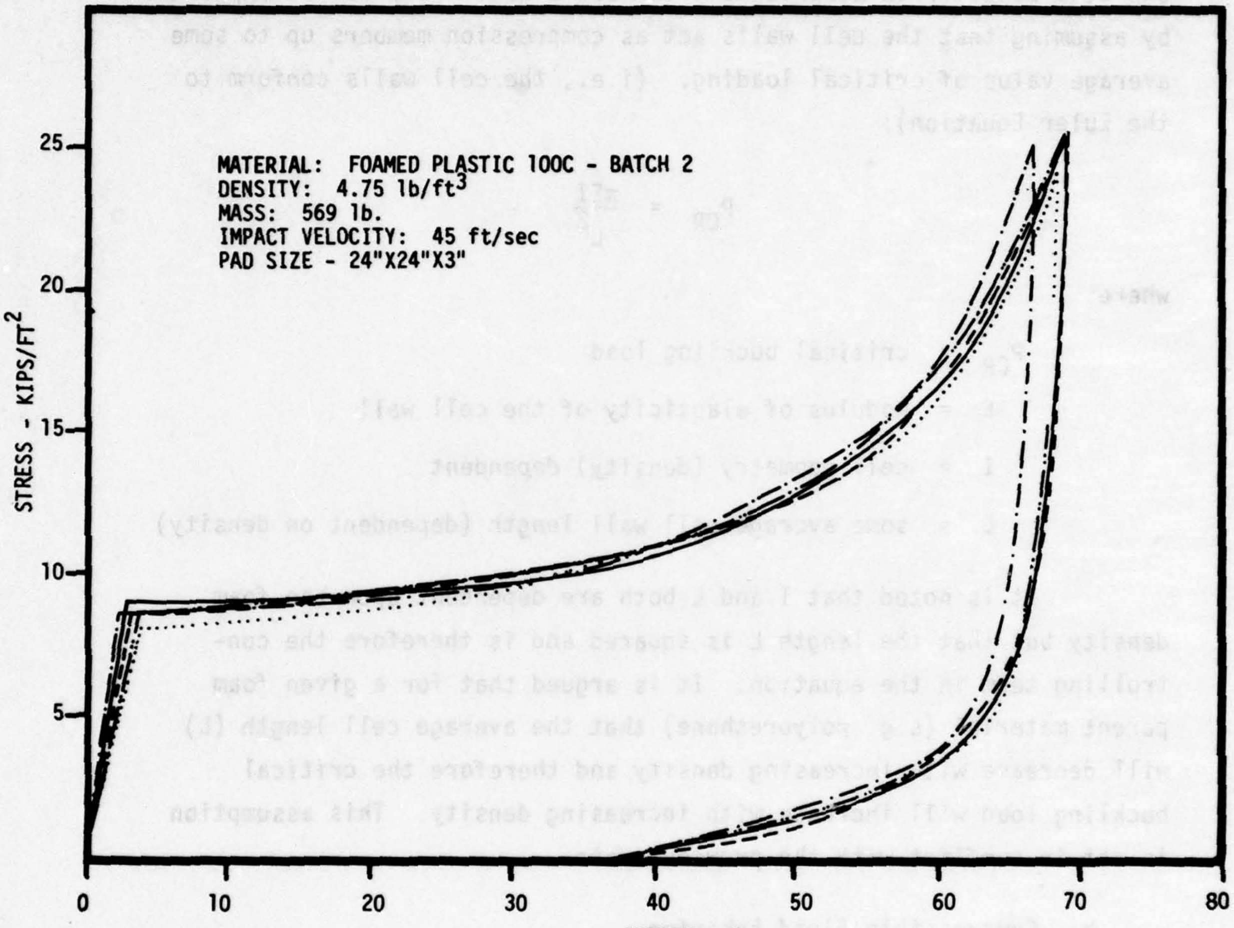


Figure 29. Family of Curves from Five Identical Tests

a. Elastic Behavior

In the initial portion of the stress-strain curve the foam exhibits behavior in accordance with Hook's Law. This can be explained by assuming that the cell walls act as compression members up to some average value of critical loading. (i.e., the cell walls conform to the Euler Equation):

$$P_{CR} = \frac{\pi EI}{L^2}$$

where

P_{CR} = critical buckling load

E = modulus of elasticity of the cell wall

I = cell geometry (density) dependent

L = some average cell wall length (dependent on density)

It is noted that I and L both are dependent upon the foam density but that the length L is squared and is therefore the controlling term in the equation. It is argued that for a given foam parent material (e.g. polyurethane) that the average cell length (L) will decrease with increasing density and therefore the critical buckling load will increase with increasing density. This assumption is not in conflict with the previous data.

b. Compressible Fluid Behavior

Beginning at the yield point of the elastic behavior portion the total foam structure appears to act as if it were a compressible fluid initially pressurized to the critical buckling load psi level. Considering the gases trapped within the cells this appears reasonable. The relation between the amount of gas which remains trapped in the cells and hence pressurized, versus the amount of gas which can escape through connecting cells (open cell foam) and surfaces is not known but appears to be related to the quantity of open cells in the foam. The pressurization process can be modeled based on the changing volume of the foam mass as the impacting object penetrates it in accordance with the perfect gas law.

c. Residual Gas Expansion

The final portion of the stress-strain curve appears to be caused by the residual gases which remain trapped expanding to some equilibrium pressure consistent with the collapsed wall structure.

6. ENERGY ATTENUATION MECHANISM

a. Macroscopic

The energy of an impacting object is transferred into pushing an inelastic force through a distance. The force is a combination of structural compression and fluid compression. The distance through which this force is pushed is the crushing distance.

b. Microscopic

The impacting energy is both partially absorbed within the plastic foam and partially transferred out of the plastic foam. Some of the energy is absorbed by the buckling of the cell walls as strain energy. Some of the energy is transferred into pressurization of the trapped gas which then escapes into the ambient atmosphere, and some of the energy is ultimately transferred to the ground.

c. Strain Rate Sensitivity

The stress-strain curve of impacting foam would appear to be sensitive to the strain rate due to the mechanism of the escaping gas. The gas escape rate would appear to be determined by the amount of open cells and the surface geometry. For this present investigation this effort will be recognized but ignored, since the minimum test velocity is on the order of 10 ft/sec.

7. FOAM APPLICATION PECULIARITIES

The foaming of a homogeneous mass of foam with a minimum dimension of 2-3 feet constituted a special class of foaming known as "thick-section" foaming. This area arises due to the foam reaction being exothermic and the resulting foam being an excellent insulation material. In thick-section foaming, these two properties combine to yield a mass of foam with a "hot core." The reaction is releasing heat in the center of the foam mass but the foam itself is preventing the heat from escaping. The result is a significant temperature rise in the center of the foam with a significant temperature gradient throughout the foam. The temperature difference believed to exist in the attenuator foaming process is thought to be on the order of 100° - 200°F between the surface and the center of the foam pile. The result is that the foam will solidify at different densities (i.e., compressive yield stress levels) depending upon the local temperature of the blowing agents. Additionally the cell walls in the center of the pile may be completely formed and finished (so far as the reaction is concerned) but their strength will be degraded by the ambient temperature of the hot-core. In some foaming applications (especially with the higher density foams) the heat generated by the reaction and contained by the thick-section phenomena may be sufficient to raise the temperature of the center of the pile to the autoignition temperature.

The problem from an analysis standpoint is that in this application what appears to be a homogeneous mass of foam actually contains gradients in temperature, density, and compressive stress yield points. This then is the difference between the attenuation application and old-cold foam applications.

8. STATEMENT OF THEORY

The foam filled bag under investigation produces a deceleration force as if it were filled with a compressible fluid whose initial pressure was equal to the compressive yield stress of the foam at the initial volume of the bag and which obeys the perfect gas law as the bag volume decreases.

9. FABRIC BAG

While the compressible fluid theory seemed to explain the reactions of the test vehicle it did not explain why the fabric bag was rupturing. Analyzing the bag as containing a pressurized gas with the properties as stated above predicted a maximum fabric tension of 70 Lbs/inch. Yet the bag fabric had a 300 Lbs/inch breaking strength. Even allowing for sewing efficiencies this disparity seemed too large.

Examining the motion picture coverage and the ruptured bags indicated that while the foam was acting as a compressible fluid in the active crushing zone it was acting as an elastic solid elsewhere. In addition the foam tended to bond to the nylon fabric (albeit somewhat poorly). The results indicated that as the test vehicle penetrated into the bag the cross-sectioned bag circumference increased even though the bag volume decreased. The sides and bottom of the bag did not radically change in geometry during the impact and the adhesion of the foam to the cloth prevented the bag from sliding relative to the foam. The result was that the top portion of the bag had to stretch to accommodate the increased circumference caused by the test vehicle. The change in circumference is greatest at the bag cross-section at the center of the bag (see Figure 30).

This stretching of the top portion of the bag was capable of rupturing the 300 Lb/in material and seemed to explain the observed rupture patterns. It was also noted that a total of approximately 110 linear inches of fabric was being loaded in this manner.

At 300 Lb/in breaking strength and with a 30% elongation factor the nylon bag appeared to be capable of storing energy in an elastic manner which could be returned to the test vehicle in the form of rebound. That is, an elastic energy storage mechanism existed in the fabric bag.

10. NEW BAG DESIGN

The analysis and the theory generated above were used to design a new bag. The bag was designed based on a foam compressive stress of 5 psig, a maximum energy of 30,000 ft-lbs, a useable stroke of 30 inches and a total bag volume of 40 ft^3. The bag shape was the previous oblate spheroid split along the major diameter with a 13" thick 55" diameter cylinder inserted. Overall thickness was 35 inches (22" minor oblate spheroid diameter + 13" insert) and the diameter was unchanged at 55 inches.

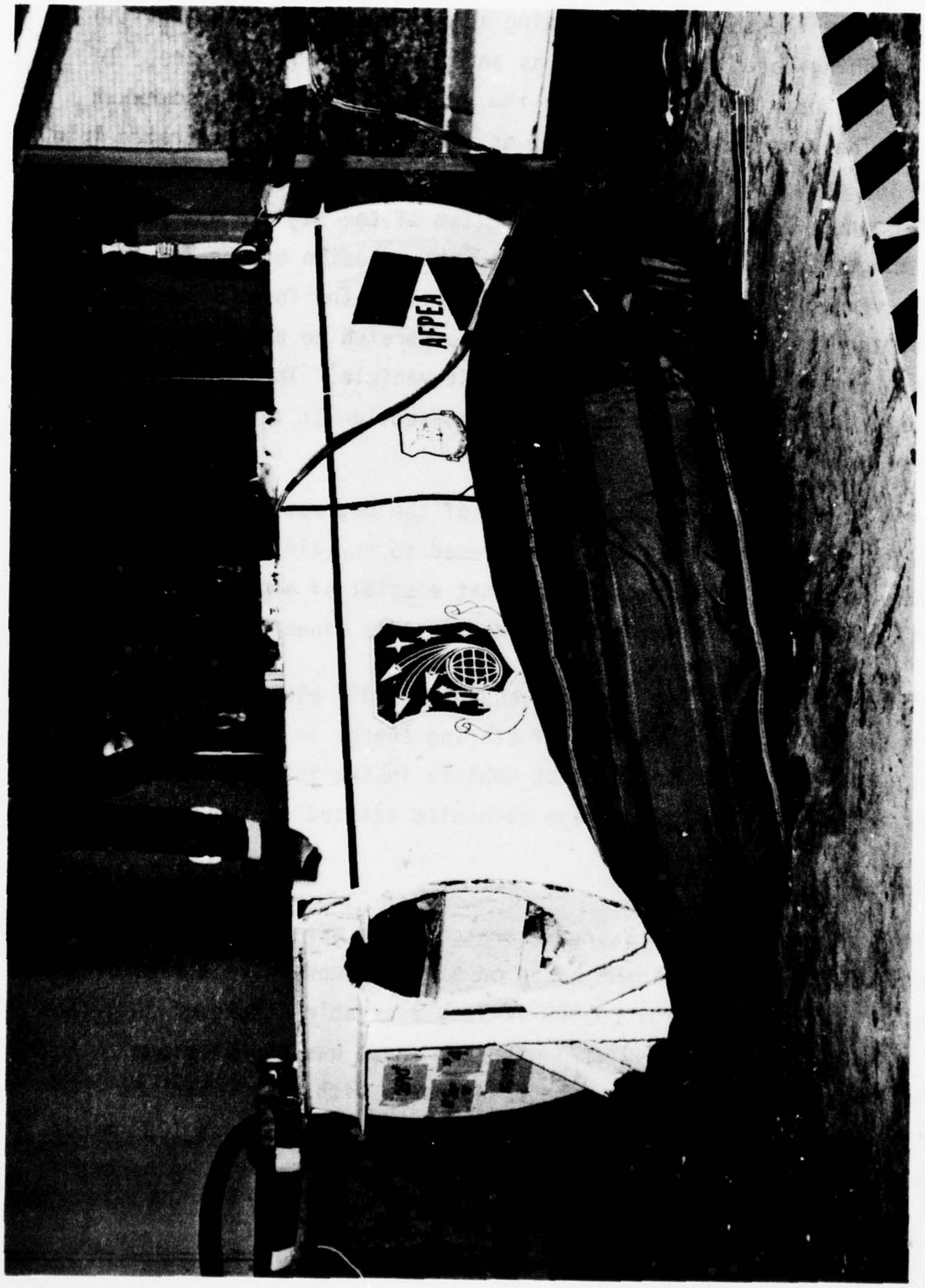


Figure 30. Bag Deformation

11. CONCLUSION OF THEORY

An attempt had been made to quantify and predict the foam bag impact performance. Due to the quantity and quality of the unknowns and assumptions made in the analysis, the final answer could only be determined in the test cell.

SECTION XII

THEORY DEMONSTRATION

A series of tests were conducted between 25 Aug 76 and 16 Sep 76 in order that the new bag design could be evaluated against a 19,000 ft-lb impact condition. These tests used the 40 ft^3 bag described in Section XI and were considered representative of a design landing condition for the AQM-34V. The tests conducted during this series are #33 through #39 and Test #43. Test #40-42 were a separate investigation and are documented in Section XIII. A brief description of the tests is given below with conclusion following:

Test #33 (25 Aug 76)	The new bag required a higher flow rate and this test was a seven nozzle calibration, achieved a 70 lb/min flow rate.
Test #34 (25 Aug 76)	13,300 ft-lbs impact test, inadvertent overfill of bag, estimated at 25%. Bag ruptured violently, maximum acceleration was 6.5 g's with no bottoming or rebound.
Test #35 (26 Aug 76)	13,300 ft-lb impact test, achieved a 100% fill, max acceleration was 9.0 g's with prominent rebounding. Bag did <u>not</u> permanently crush!
Test #36 (30 Aug 76)	Attempted a 13,300 ft-lb impact, "A" chemical tank blew dry, test stopped.
Test #37 (1 Sep 76)	Calibration run using new chemical tanks.
Test #38 (1 Sep 76)	13,300 ft-lb impact, 75% bag, max accel, was 10-1/2 g's moderate rebound.
Test #39 (14 Sep 76)	Calibration test after two week layoff!
Test #43 (16 Sep 76)	13,300 Ft-Lb impact, 75% bag, max acceleration was 8-1/2 g's, moderate bounce.

This series of impact tests demonstrated a number of interesting characteristics. Test #34 resulted in an overfilled bag rupturing violently and yet the test vehicle saw only 6.5 g's without bottoming or rebounding. The energy storage mechanism responsible for the rebounding had not existed after bag rupture. The next day on Test #35 a "perfectly filled" bag exhibited even more surprising behavior. Even though the bag developed a reaction force of 23,000 lbs against the 2590# test vehicle, the bag did not crush permanently! After test the bag still measured in excess of 32" thick. The rebound on this test was quite severe, to the point the test vehicle did not come to rest on top of the attenuator bag.

It had been theorized that the bag fabric was capable of storing energy during the critical impact and returning it to the vehicle in the form of rebound. These two tests (#34 and #35) seemed to demonstrate the two extremes of that hypothesis. In order to minimize this energy storage mechanism a simple method of relieving the fabric stretch requirement was to leave "fullness" in the bag by not filling it completely. On Test #38 and #43 this technique produced an acceptable impact attenuation of a 13,300 ft-lb impact. Because the rebound energies of these tests were on the order of 10% of the initial energy it was believed that the fabric energy storage mechanism had been resolved. Two questions still remained in the investigation; what was the minimum operation time of the system as constructed and where was the 10% rebound energy being stored?

SECTION XIII

MINIMUM OPERATING TIME

The operation of the polyurethane foam impact attenuation system in an elapsed time of 120 seconds had been well demonstrated by 14 Sep 76. It was desirable to determine if the operating time could be reduced and the effect of doing so. A series of three tests were conducted on 14 Sep 76 to investigate the shorter operating time. The three impact tests (#40, #41, and #42) were conducted under identical conditions using the previous 20 ft^3 bag subjected to 7770 ft-lb impacts. The sole parameter which was varied with the tests was the operating times (time from initiation to impact).

Test #40 (14 Sep 76)	7770 ft-lbs operating time 6000 sec.
Test #41 (14 Sep 76)	7770 ft-lbs operating time 120 sec. (baseline tests)
Test #42 (14 Sep 76)	7770 ft-lb impact operating time 60 sec.

In each of these three tests the filling time was 18 sec. The foam nominal rise time was 30 sec. for a theoretical fill-expansion time of 48 sec. The 60 second minimum operating time test (#42) was identical in performance and pulse shape to the 120 sec operating time test (#41). The chemists had theorized that once full expansion had been ahcieved (in this case at 48 seconds) there would be no differences in material properties for the following 10 minutes or so. Only after a considerable cooling off period would the foam properties become significantly different. This difference was evident in the 6000 second case in which both the peak deceleration and the pulse shape were markedly different (i.e., a higher rate of onset of acceleration). An attenuation system operating time of 60 seconds had been demonstrated.

SECTION XIV

CONCLUDING TESTS

A subsequent series of tests were conducted between 21 Sep 76 and 22 Oct 76. The tests #44 through #48 constitute a quick look at further development needs of the system for future application. A real time documentary film of the foaming process was made as well as some minor manifold flow work. The 40 ft^3 bag had been designed against a 30,000 ft-lb impact and an evaluation at this energy level was desired. Additionally an extrusion mechanism had been noted in earlier testing and a further investigation was desired. The tests were as follows:

Test #44 (21 Sep 76)	Documentary film of 70 lb/min flow rate
Test #45 (29 Sep 76)	19,000 ft-lb impact 75% bag with bladder, max acceleration was 11 g's with moderate bounce
Test #46 (6 Oct 76)	Flow rate on manifold, 3/8" orifice could sustain 60 lbs/min flow rate
Test #47 (21 Oct 76)	28,800 ft-lb impact, bag was designed with 30 in^2 extrusion parts. No extrusion noted, bag ruptured violently due to weakened structure.
Test #48 (22 Oct 76)	28,800 ft-lb impact, max acceleration of 11 g's, moderate rebound.

The primary result of these tests was that the bag which had been designed by the theoretical analysis did in fact attenuate the impact at a level approaching the design level. The bag design had been predicted on a 30,000 ft-lb impact and had been successfully demonstrated at the 28,000 ft-lb energy level. Test #48 is especially important because it demonstrated that a deployable polyurethane ground impact attenuation system was capable of attenuating (energy management) 100% of the impact energy of a 28,000 ft-lb impact. The acceleration versus time plot for this uniaxial impact is shown in Figure 31.

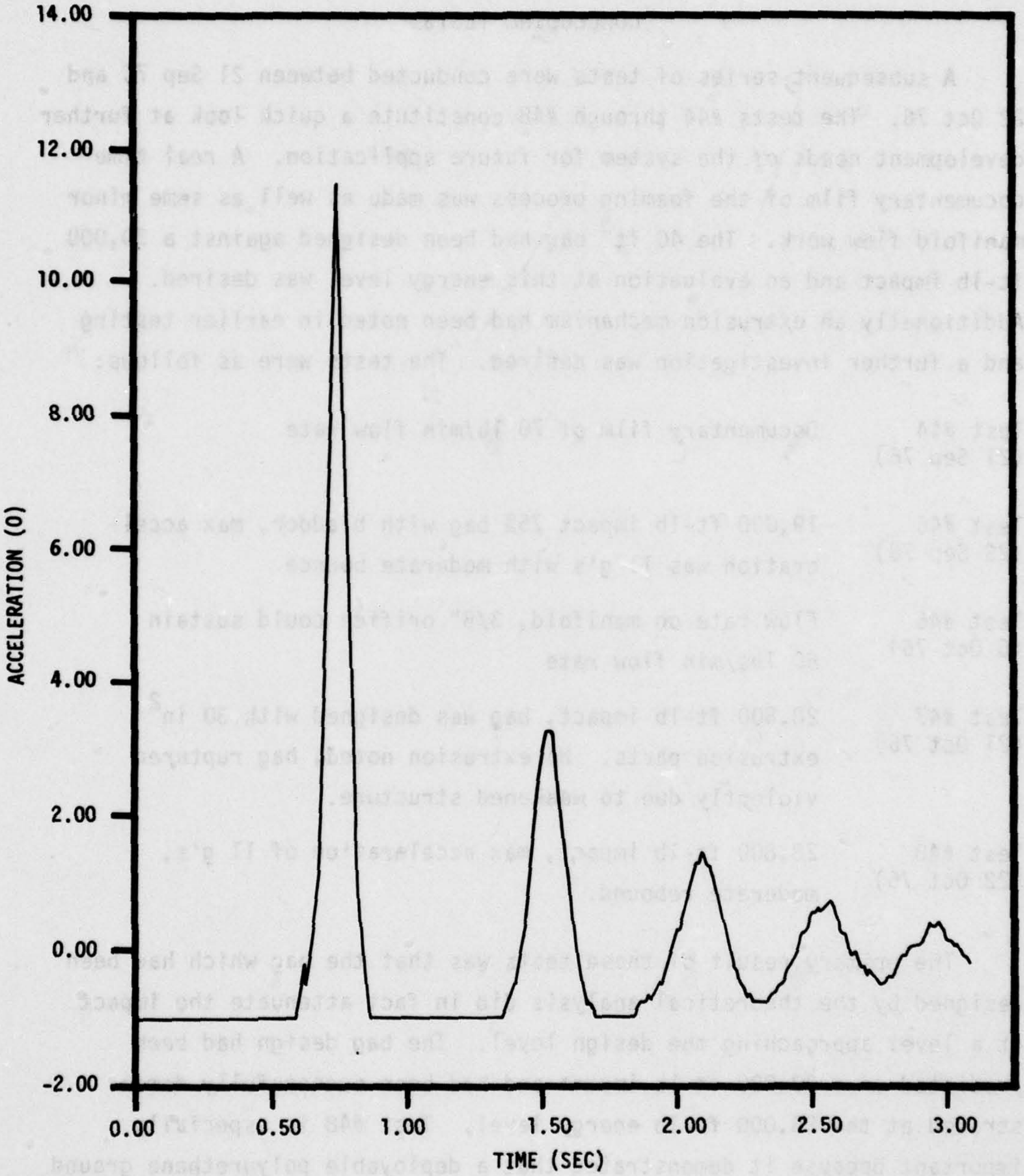


Figure 31. Test No. 48 Acceleration vs. Time

SECTION XV

HYPOTHESIZED SYSTEM REVISITED

In Section V an advanced impact attenuation system based on plastic foam was hypothesized. A test and analysis of such a system was performed and some comparisons can be made.

1. SYSTEM EMBODIMENT

The deployable polyurethane foam ground impact attenuation system hardware is shown in Figure 32. The hardware shown in this figure includes everything necessary to deploy the foam attenuator except valves, activator, mounting brackets and hatch covers. The total weight of the components shown (including 25 lbs of chemicals) is 37-1/2 lbs, allowing 3 pounds for valves and 5 pounds for a hatch cover and bracketry gives an estimated system weight of 45 pounds. The functional equivalent of this system was demonstrated in Test #48 to be capable of attenuating 28,800 ft-lbs of impact energy. These two values yield a system specific energy absorption (SSEA) value of 640 ft-lbs (energy attenuated divided by total system weight). Allowing for estimation errors the deployable polyurethane foam ground impact attenuation system has a SSEA of 600 (ft-lb)/lb. This represents an improvement in the state-of-the-art of impact attenuation systems of doubling the SSEA of 300 (ft-lb)/lb associated with a conventional airbag system (Reference 1). Further, this system was investigated using parameters associated with the AQM-34V ground impact and has been demonstrated capable of attenuating the energy level associated with that impact.

It was stated in Section II that a solution for the AQM-34V ground impact problem could only be determined in terms of life cycle costs with and without an attenuation system. The life cycle cost of the attenuation system was shown to affect the definition of a "solution" to the ground impact problem. Although an estimation of the total life cycle costs of a deployable polyurethane foam ground impact attenuation system is beyond the scope of this report some feel for the price per unit procurement costs can be approximated. The hardware items shown in Figure 32 are commercially available equipment items and their price

Figure 32. Breadboard Hardware

can be accurately estimated. The following system as costed out does not reflect a final operational system but rather a breadboard version which would function but not necessarily fit the operational problem.

Estimated System Price

6 nozzles @ $.50 each	$3.00
24' - 1/8" tubing @ $.05/ft	$1.20
2 manifolds @ $3 parts + $5 labor	$8.00
2 tanks @ $15 each	$30.00
25 lbs of chemicals @ $2/1b	$50.00
1 Bag @ $25 parts + $40 labor	$65.00
2 - 3/8" valves + activators	$40.00(estimated).
Estimated Breadboard System Price	$200.00

This system is based on a totally disposable unit which is thrown away and replaced with each use. When compared with average damage costs on the order of $17,000 per landing the foam attenuation system has a high potential payoff. Even if this estimated system price were to grow by a factor of fifty times by the time on operational system was in use, the payoff is still high.

SECTION XVI

CONCLUSIONS

1. A deployable polyurethane foam ground impact attenuation system is emimently feasible using 1976 technology.

2. The system is a major advancement in the state-of-the-art of impact attenuation systems for aerospace vehicles in general.

3. The system has the potential for high payoffs to the Air Force through reduction of damage to RPV's.

4. The system offers the operational commands increased flexibility of operations by eliminating the MARS helicopter operational restrictions.

5. The management concept of combining both research and operational parameters in a single investigation is highly workable in the area of impact attenuation.

APPENDIX

AFFDL-TR-78-145
Volume I

AN IMPACT ATTENUATION BIBLIOGRAPHY

DECEMBER 1975

STEPHEN R. MEHAFFIE

Library numbers (where specified) are in reference to the cataloging system of the Parachute Databank maintained by AFFDL/FER.

1947

1. January 1947
Parachute Load Arrester (Pressure Inflated Canopy Type)
Hatton, M.
TSEAP-7-1-522, AD 45523, January 1947
Library No. 9421.002

1948

1. October 1948
Evaluation of Parabag
Barnes, R.W.
MCREXE-672-23A
Air Material Command, Wright Field
Comment: Only known copy is in Parachute Databank

1949

1. March 1949
Final Report; Investigation of Recovery Systems for Pilotless Aircraft and Components
Anon
ATI55649
R-0140
U.S. Naval Air Development Station

2. June 1949
Human Exposures to Linear-Deceleration, Pt. I - Preliminary Survey of Aft-Facing Seated Position
Stapp, John Paul
AF TR No. 5915, Pt. 1, ATI 71065, June 1949
Library No. 9410.016

AD-A070 077 AIR FORCE FLIGHT DYNAMICS LAB WRIGHT-PATTERSON AFB OH F/G 1/3
INVESTIGATION OF A DEPLOYABLE POLYURETHANE FOAM GROUND IMPACT A--ETC(U)
JAN 79 S R MEHAFFIE
UNCLASSIFIED AFFDL-TR-78-145-VOL-1 NL

2 OF 2
AD
A070077

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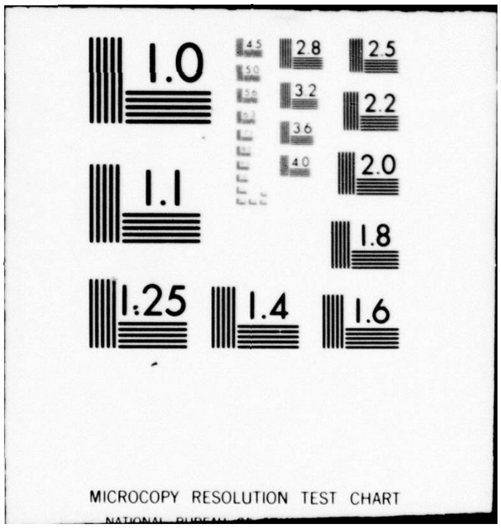

MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF

3. September 1949
Experimental Evaluation of Explosive Parachute Load Retarding Systems
Ewing, E.G.
ATI 115167
R-13
Radioplane Co.

4. October 1949
Development, Test and Evaluation of Components of Systems for the Recovery of Pilotless Aircraft
Anon
R-31
Radioplane Co.
Comment: Not in Parachute Databank

1951

1. March 1951
Handbook for the Design of Guided Missile Recovery Systems
Anon
Radioplane Co.
Comment: Not in Parachute Databank

2. September 1951
Measurement of Parachute Deployment and Load Impact Forces During D4 Bulldozer Drop
Berndt, R.J.
WCEE-672-40L
Wright Air Development Center
Comment: Only known copy is in Parachute Databank

3. September 1951
Development of Cargo Platform Landing Shock Absorbers
Setzko, J.F.
Stanley Aviation Corp.
Comment: Only known copy is in Parachute Databank

4. December 1951
Human Exposures to Linear Deceleration. Part 2 - The Forward-Facing Position and the Development of a Crash Harness
Stapp, John Paul
AF TR No. 5915, Pt. 2, ATI 136 452, December 1951
Library No. 9410.015

1953

1. February 1953
Development of an Inorganic Foamed-In-Place Material
Chakoumakos, C.
DDC No.: 9120
Department of the Navy

2. March 1953
Development of an Inorganic Foamed-In-Place Material
Chakoumakos, C.
DDC No.: 10362
Department of the Navy

3. June 1953
Air Mat Bumper Pads - Matador Recovery
Thome, T.L.
Rept. No.: 234
General Tire and Rubber
Comment: Not in Parachute Databank

4. September 1953
Evaluation of Airbag Decelerator by Drop Tests
Madaffer, M.C.
WADC-TN-WCLE-53-147, AD 857 024, September 1953
Library No. 9422.001

5. September 1953
Studies Toward Development of Expandable Plastics
Altamura, M.R.
DDC No.: 21519
U.S. Rubber

6. December 1953
Studies Toward Development of Expandable Plastics
Altamura, M.R.
DDC No.: 27774
U.S. Rubber

7. December 1953
Evaluation of Three Types of Airbag Decelerators by Drop Tests
Madaffer, M.C.
TN WCLE-54-11, AD 857 025, December 1953
Library No. 9422.032

1954

1. March 1954
Studies Toward Development of Expandable Plastics
Altamura, M.R.
DDC No.: 31985
U.S. Rubber

2. June 1954
Studies Toward Development of Expandable Plastics
Ponti, M.A.
DDC No.: 37641
U.S. Rubber

3. September 1954
Airbag Decelerators for C-130 Load Platform, Instrumented Tests of
Berndt, R.J.
WADC
Comment: Only known copy is in Parachute Databank

1955

1. June 1955
X-7A Supersonic Ramjet Test Vehicle Parachute Recovery System
Anon
DDC No.: 95744
WADC-55-162
Lockheed Aircraft Corp.

2. July 1955
Cushioning for Airdrop, Part I
Anon
University of Texas
Comment: Only known copy is in Parachute Databank

3. December 1955
Air Drop Cost Analysis
Turnbow, J.W.
University of Texas
Comment: Only known copy is in Parachute Databank

1956

1. January 1956
Study, Ground Impact Decelerator Systems
Howard, E.P.
#1589
Radioplane Co.
Comment: Not in Parachute Databank

2. January 1956
Performance Characteristics of Paper Honeycomb Cushioning Materials Impacted Under a Heavy Weight High Impact Shock Machine
Sabbagh, E.N.
WADC-TR-55-343
Wright Air Development Center
Comment: Only known copy is in Parachute Databank

3. July 1956
Unpublished Stress-Strain Dynamic Impact Curves for Various Cushioning Materials
Goodman, A.
Sandia Corp.
Comment: Only known copy is in Parachute Databank

4. August 1956
Cushioning for Air Drop, Part III - Characteristics of Paper Honeycomb Under Dynamic Loading
Turnbow, James W.; Matlock, Hudson; Thompson, J. Neils
AD 112 164, August 1956
Library No. 9422.040

5. November 1956
Theoretical Analysis of a Landing Snubber, for Use with Parachutes
Moore, W.L.; Morgan, C.W.
AD 122 375, November 1956
Library No. 9421.004

6. November 1956
Theoretical Analysis of a Landing Snubber for Use with Parachutes
Moore, W.L.
University of Texas
Comment: Only known copy is in Parachute Databank

7. December 1956
Cushioning for Air Drop, Part V - Theoretical and Experimental Investigations of Fluid-Filled Metal Cylinders for Use as Energy Absorbers on Impact
Morgan, Carl W.; Moore, Walter L.
AD 122 376, December 1956
Library No. 9422.039

8. December 1956
Development & Test of Landing Deceleration System for GAM-72 Missile
Rubinstein, S.
Radioplane Company
Comment: Only known copy is in Parachute Databank

1957

1. March 1957
Characteristics of Foamed Plastic Under Dynamic Loading
Turnbow, J.W.
University of Texas
Comment: Only known copy is in Parachute Databank

2. June 1957
Cushioning for Air Drop, Part VIII - Dynamic Stress Strain Characteristics of Various Materials
AD 141 943, June 1957
Library No. 9422.041

3. June 1957
Preliminary Design of XQ-4A Landing Bags
Scheel, W.
Radioplane Co.
Comment: Not in Parachute Databank

4. August 1957
Energy Absorbing Materials & Systems
Matlock, H.
University of Texas
Comment: Only known copy is in Parachute Databank

5. September 1957
Studies Toward Development of Expandable Plastics
Amidon, R.W.
DDC No.: 50091
U.S. Rubber

6. October 1957
Preliminary Tests on a Non-Pressurized Air Bag
Matlock, H.
University of Texas
Comment: Only known copy is in Parachute Databank

1958

1. March 1958
Development of Foamed in Place Plastic Energy Absorbing Materials
Bryant, R.C.
Atlantic Research Corporation
Comment: Not in Parachute Databank

2. April 1958
Further Developments of Airbags as Landing Shock Absorbers
Harwood, K.
Mech. Eng 257
Royal Aircraft Establishment
Comment: Only known copy is in Parachute Databank

3. July 1958
Development of High Velocity Aerial Delivery System
Hill, R.D.
DDC No.: 209642
Yuma Test Station

4. September 1958
Brooks & Perkins Side Rail Restraining Aerial Delivery System
Marshall, C.W.
DDC No.: 152289
AFFTC-TN-58-15
El Centro

5. December 1958
Brooks & Perkins Dual Rail Aerial Delivery System Tests in the C-130
Marshall, C.W.
DDC No.: 205483
AFFTC-TR-58-7

1959

1. February 1959
Study of Guided Missile Structural Design Criteria
Valand, W.B.
DDC No.: 155888
WADC-TR-57-140
Midwest Research Institute

2. March 1959
Investigation of Design Criteria for Cushioning Materials
Olevitch, A.
DDC No.: 201227
WADC-TR-58-639

3. May 1959
Development of a Paperboard Honeycomb Decelerator for Use with Large Platforms in Aerial Delivery Systems
Bixby, H.W.
WADC-TR-59-776, AD 240 234, May 1959
Library No. 9422.033

4. May 1959
Energy Absorption Characteristics of Paper Honeycomb
Karnes, C.H.
University of Texas
Comment: Only Known copy is in Parachute Databank

5. May 1959
The Effect of Moisture Content and Impact Velocity on Energy Absorption Characteristics of Paper Honeycomb
Karnes, C.H.
University of Texas
Comment: Only known copy is in Parachute Databank

6. May 1959
Parachute Recovery System Tests USAF Q-2C Drone Missile
Myers, E.C.
DDC No.: 215533

7. June 1959
Study of Design Criteria for Landing Shock Absorption Devices for Recoverable Flight Vehicle
Anon
WCLEHD-18
WADC, Wright Field
Comment: Not in Parachute Databank

8. June 1959
   Water Landing Characteristics of a Reentry Capsule
   McGehee, J.R.
   NASA Memo 5-23-591
   NASA
   Comment: Only known copy is in Parachute Databank

9. August 1959
   The Energy Dissipating Characteristics of Airbags
   Turnbow, J.W.
   University of Texas
   Comment: Only known copy is in Parachute Databank

10. September 1959
    Effects of Water Landing Impact on an Orbital Capsule from the Standpoint of Occupant Protection
    Hatch, H.G.
    NASA TN-D-39
    NASA
    Comment: Only known copy is in Parachute Databank

11. October 1959
    Optimization Study of Parachute Size & Deceleration Bag Size to Determine Optimum Rate of Descent
    Dodge, C.W.
    Stanley No. 1103
    Stanley Aviation Corp.
    Comment: Not in Parachute Databank

12. October 1959
    Limited Investigation of Crushable Structures for Acceleration Protection of Occupants of Vehicles at Low Impact Speeds
    O'Bryan, Thomas C.; Hatch, Howard, G., Jr.
    NASA TND-158, AD 227 649, October 1959
    Library No. 9422.011

13. October 1959
    Water Landing Impact Accelerations for Three Models of Reentry Capsules
    Vaughan, V.L.
    NASA-TN-D-145
    NASA
    Comment: Only known copy is in Parachute Databank

14. November 1959
    Development of a Paperboard Honeycomb Decelerator for Use with Large Platforms in Aerial Delivery Systems
    Anon
    Radioplane Co.
    Comment: Not in Parachute Databank

1960

1. 1960
Landing Systems Development History
Anon
NASA
Comments: Preliminary Notes to Gemini. Only known copy in Parachute Databank

2. 1960
Analytical Study of Soft Landings on Gas Filled Bags
Esgar, J.B.
NASA-TR-R-75
NASA
Comments: Only known copy is in Parachute Databank

3. February 1960
TM-76, MACE Landing Mat Design
Idomis, K.
Glenn L. Martin Co., Baltimore
Comment: Not in Parachute Databank

4. April 1960
Gas Dynamics of an Inflated Sphere Striking a Surface
Howe, J.T.
DDC No. 253 289
NASA-TN-D-315
NASA Ames

5. April 1960
An Analysis of the Impact Motion of an Inflated Sphere Landing Vehicle
Martin, Dale E.; Howe, John T.
NASA-TN-D-314, AD 235 290, April 1960
Library No. 9422.012

6. June 1960
The Impact Response of a Single-Degree-of-Freedom System with Viscous Damping
Luke, R.R.
AD 246 942, June 1960
Library No. 9410.003

7. June 1960
Decelerator Bag Study
Tomcsak, S.L.
WADC-TR-59-775, AD 243 159, June 1960
Library No. 9422.003

8. August 1960
The Response of a Two-Degree-of-Freedom Undamped System Subjected to Impulsive Loading
Richter, A.P.
AD 246 944, August 1960
Library No. 9410.002

9. September 1960
Analytical Study of Soft Landings on Gas Filled Bags
Esgar, J.B.
DDC No. 242357
NASA-TR-R-75
NASA

10. September 1960
Landing Energy Dissipation for Manned Reentry Vehicles
Fisher, L.J.
N 62-71027/NASA-TN-D-453
NASA

11. September 1960
A Study of the Plastic Deformation of a Single-Degree-of-Freedom System Subjected to Impulsive Loading
Huckabay, J.D.
University of Texas
Comment: Only known copy is in Parachute Databank

12. September 1960
High Velocity Impact Cushioning - Part VI 108C and 100C Foamed Plastics
Shield, R.
University of Texas
Comment: Only known copy is in Parachute Databank

13. October 1960
Landing Impact Characteristics of Load Alleviating Struts on a Model of a Winged Space Vehicle
Blanchard, V.J.
N 62-T1115/NASA-TN-D-541
NASA Langley

14. November 1960
Landing Characteristics of a Reentry Capsule With a Torus-Shaped Air Bag for Load Alleviation
McGehee, J.R.
NASA-TN-D-628
NASA Langley

1961

1. February 1961
Landing Characteristics and Flotation Properties of a Reentry Capsule
Vaughan, V.L.
N 62-71227/NASA-TN-71227
NASA Langley

2. March 1961
Study of Soft Recovery
Knacke, T.W.
DDC No.: 255766
Air Research and Development Co.

3. May 1961
Effect of a Load-Alleviating Structure on the Landing Behavior of a Reentry Capsule Model
Hoffman, E.L.
N 62-71385/NASA-TN-D-811
NASA Langley

4. August 1961
Design of Cushioning Systems for Air Delivery of Equipment
Ellis, B.C.
University of Texas
Comment: Only known copy is in Parachute Databank

5. September 1961
Landing Characteristics of a Lenticular-Shaped Reentry Vehicle
Blanchard, V.J.
N 62-71514, NASA-TN-D-940

6. December 1961
Landing Impact Dissipation System
Fisher, L.J.
DDC No.: 268136
NASA-TN-D-975
NASA Langley

1962

1. 1962
Aerohydromechanic Theory of Wing in a Non-Stationary Flow (Selected Parts)
Nekrasov, A.I.
FTD-TT-64-777, AD 610 /91, 1962
Library No. 9421.003

2. January 1962
An Analytical Study of an Undamped Nonlinear Single-Degree-of-Freedom System Subjected to Impulsive Loading
Fowler, Wallace T.
AD 276 690, January 1962
Library No. 9410.036

3. January 1962
The Effects of Acceleration Pulse Parameters on the Permanent Deformation of a Damped Single-Degree-of-Freedom System
Reifel, M.D.
University of Texas
Comment: Only known copy is in Parachute Databank

4. January 1962
Study of Design Criteria for Landing Shock Absorption Devices for Recoverable Flight Vehicles
Simonson, J.R.
ASD-TR-61-583, AD 273 096, January 1962
Library No. 9410.004

5. March 1962
Rocket Cushioning Device Feasibility Study
Anon
Stencil Aero Engineering Corp.
Comment: Only known copy is in Parachute Databank

6. March 1962
Model Investigation of the Landing Characteristics of a Reentry Spacecraft with a Vertical-Cylinder Air Bag for Load Alleviation
McGehee, John R.; Vaughan, Victor L., Jr.
NASA-TN-D-1027, AD 272 616, March 1962
Library No. 9422.019

7. March 1962
Energy Absorption of a Specific Aluminum Honeycomb
Schell, Edward H.
ASD-TR-61-726, March 1962, AD 277 797
Library No. 9422.043

8. April 1962
Propagation of Compressive Stresses Through a Plastically Deforming Material
Backman, M.E.
NAVWEPS 7896
Comment: Only known copy is in Parachute Databank

9. April 1962
Theory of High-Speed-Impact Attenuation by Gas Bags
Howe, J.T.
NASA-TN-D-1298
NASA Ames

10. June 1962
Survey of Energy Absorption Devices for Soft Landing of Space Vehicles
Esgar, J.B.
NASA-TN-D-1308
Comment: Only known copy is in Parachute Databank

11. July 1962
Fragility Studies Part VI, Personnel Carrier M113
Fowler, W.
University of Texas
Comment: Only known copy is in Parachute Databank

12. July 1962
PAD Assisted Parachute System for Aerial Delivery of Cargo, Dynamic Crane Drop Demonstration
Harkins, L.G.
Test Report T62-13-1
Frankford Arsenal
Comment: Only known copy is in Parachute Databank

13. October 1962
A Preliminary Experimental Investigation of an Energy-Absorption Process Employing Frangible Metal Tubing
McGehee, J.R.
NASA-TN-D-1477

14. October 1962
Impact Determinations - Final Report
Ripperger, E.A.
AD 400 638
Library No. 9422.042

<u>1963</u>

1. February 1963
A Theoretical Approach to Air Bag Shock Absorber Design
Browning, A.C.
Mech. Eng 369
Royal Aircraft Establishment
Comment: Only known copy is in Parachute Databank

2. March 1963
Propellant Actuated Device (PAD) Assisted Parachute System for Aerial Delivery of Cargo
Litz, C.J.
DDC No.: 415 227
Frankford Arsenal

3. April 1963
Earth Landing Systems for Manned Spacecraft
Kiker, J.W.
DDC No.: 427 671
AGARD-446
AGARD

4. May 1963
Investigation of Crew Escape System Surface Impact Techniques for Advanced Aerospace Vehicles
Slowik, J.; Weir, W.
ASD-TDR-63-173, AD 411 946, May 1963
Library No. 9410.001

5. July 1963
Final Report on the Skirt Jet Landing Decelerator Program
Dickinson, W.A.
Northrop Ventura 2802
Comment: Only known copy is in Parachute Databank

6. August 1963
Investigation of the Landing Characteristics of a Reentry Vehicle Having a Canted Multiple Air-Bag Load-Alleviation
Stubbs, Sandy M.; McGehee, John R.
NASA TN D-1934, N63-18772, August 1963

7. September 1963
Flight Vehicle Structural Design Criteria, Recovery Phase
Anon
DDC No.: 423012
ASD-TDR-63-453
AFFDL

8. November 1963
Evaluation of Thiokol Foam and Syrofoam Elements for F-111 Escape Pod Impact System
Anon
DDC No.: 431458
McDonnell

9. December 1963
Modified Apollo Logistics Spacecraft Study, Volume IV: Earth Landing System
Tinnan, L.M.
X64-14079/SID-63-1461-4
North American Aviation Inc.

1964

1. January 1964
Further Studies of the Response to Shock Landing of Vehicles Cushioned for Aerial Delivery
Ford, C.A.
University of Texas
Comment: Only known copy is in Parachute Databank

2. February 1964
Energy Dissipation Characteristics of Hand-Expanded Paper Honeycomb
Maschi, A.P.
U.S. Army Natick Labs
Comment: Only known copy is in Parachute Databank

3. April 1964
RCD-MS Systems Rocket Cushioning Device Applied to Modular Seat
Anon
AD 440 161, April 1964
Library No. 9421.001

4. April 1964
Attenuation of Landing Impact for Manned Spacecraft
McCullough, Jerry E.; Stafford, Frank A.; Benson, Harold E.
NASA CR-53291, N65-35265, April 1964
Library No. 9410.013

5. May 1964
Tutorial Session in Biodynamics
Stapp, John P.
A65-10732
Library No. 9410

6. June 1964
Retrorocket-Parachute Landing System Study for Earth and Martian Entry Vehicles
Anon
X64-15980/NASA CR 58306
Northrop Corporation

7. July 1964
Airdrop Impact Capability of the Shillelagh Missile Container
Anon
DDC No.: 455971
ADED 64-4
U.S. Army Natick Labs

8. December 1964
Ground Impact Shock Mitigation M-151 Utility Vehicle (JEEP)
Watson, H.
DDC No.: 463236
U.S. Army Natick Labs

1965

1. 1965
Conference on Langley Research Related to Apollo Mission
Anon
X66-19941 through X66-19978

2. March 1965
Dynamic Model Investigation of the Landing Characteristics of a Manned Spacecraft
Thompson, Wm. C.
NASA TN D-2497, N65-17536, March 1965
Library No. 9410.012

3. June 1965
Qualification, Evaluation of the Mechanical Energy Attenuating Device Designed for the Modular Zero-Zero Escape System
Nelson, Richard W.
TR-2-65, AD 476 723 L, June 1965
Library No. 9422.009

4. October 1965
Parachute and Retrorocket Landing System for Vertical Descent
October 1965, A65-33556
French, Kenneth E.
Library No. 9421

1966

1. January 1966
Landing Characteristics of the Apollo Spacecraft with Deployed-Heat-Shield Impact Attenuation Systems
Stubbs, Sandy M.
NASA TN D-3059, N66-14901, January 1966
Library No. 9422.025

2. February 1966
Final Report on a Parachute Recovery System for a Recorder Capsule
Anon
NASA-CR-75647, N66-27928, February 1966
Library No. 9422.022

3. February 1966
UH1B/D Armored Helicopter Seat Test Program
Reed, W.H.
DDC No.: 711983
USAAVSCOM-TR-70-9
Aerojet General Corp.

4. February 1966
Armored Crew Seat Drop Test Program
Reed, W.H.
DDC No.: 711984
USAAVSCOM-TR-70-8
Bell Helicopter Co.

5. March 1966
Airdrop Impact Capability of the Redeye Missile in Models 2 and 3
Tripak Containers
Antkowiak, Henry E.
Report No. 66-13-AD, AD 480 880, March 1966
Library No. 9422.010

6. May 1966
Airdrop Impact Capability of the Redeye Missile Tripak Container (Production Model)
Maschi, Angelo P.
Report No. 66-45 AD, AD 485 104, May 1966
Library No. 9422.014

7. July 1966
Parachute and Cushion Landing System
French, Kenneth E.
July 1966, A66-35626
Library No. 9422

8. September 1966
The "Skirt Jet" Impact Attenuation System
Ewing, Edgar G.; Frank, George
A66-40598
Library No. 9421

9. September 1966
Reduction and Presentation of Shock Data
Kasuba, John A.
Report No. DPS-2152, AD 878 690L, September 1966
Library No. 9410.008

10. September 1966
Ground Proximity Airdrop System
Michal, J.L.
DDC No.: 837338
Stencel Aero Engineering Corp.

11. October 1966
Impact Energy Absorption Properties of Crushable Materials
Conn, Andrew F.
RM-315, AD 814 736 L, October 1966
Library No. 9422.006

12. October 1966
Low Level Personnel Delivery Capsule
Deering, J.O.
DDC No.: 80624
SEG-TR-66-10
Lockheed Georgia

13. November 1966
Landing Characteristics of a Dynamic Model of the HL-10 Manned Lifting Entry Vehicle
Stubbs, Sandy M.
NASA TN D-3570, N67-10786, November 1966
Library No. 9410.014

1967

1. 1967
An Expandable Gas Bag Concept for a Stowable Omnidirectional Multiple-Impact Landing System
McGehee, J.R.
NASA-TM-X-59623, N68-33736, 1967
Library No. 9422.005

2. February 1967
Design of Cushioning Systems for Airdrop
Gionfriddo, Maurice P.
Report No. 67-59-AD, AD 655 280, February 1967
Library No. 9422.018

3. March 1967
Study and Design of Armored Aircrew Crash Survival Seat
Anderson, Leon R.; Grimes, Glenn R.; Rigers, Olan A.
USAAVLABS TR 67-2, AD 812 994L, March 1967
Library No. 9422.028

4. March 1967
Comparative Evaluation of Paper Honeycomb Testing
Guyton, W.L.
DDC No.: 830508
USA-NLABS-TR-68-52
Texas University at Austin

5. March 1967
Gemini Landing System Development Program, Volume I: Full Scale Investigation
Norman, L.C.
N67-19278
NASA

6. March 1967
Gemini Land Landing System Development Program, Volume II: Supporting Investigations
Norman, L.C.
N67-19279/NASA-TN-D-3870
NASA

7. August 1967
Ground Impact Shock Mitigation
Ripperger, E.A.
EMRL-TR-1029, AD 830 179, August 1967
Library No. 9422.007

8. October 1967
Dynamic Model Investigation of Touchdown Stability of Lunar Landing Vehicle
Herr, R.W.
NASA-TN-D-4215

1968

1. 1968
Shock and Vibration Technical Design Guide, Volume I and Volume II
Henderson, T. Bruce
FR68-10-671, AD 844 559, 1968
Library No. 9410.025

2. March 1968
Water Pressures and Accelerations During Landing of a Dynamic Model of the Apollo Spacecraft with a Deployed-Heat-Shield Impact-Attenuation System
Stubbs, Sandy M.
NASA TN D-4275, N68-18822, March 1968
Library No. 9422.027

3. May 1968
Silicate Foam for Airdrop Cushioning
Baker, Jack E., Jr.; Mallow, Wm. A.
Rpt. No. 68-46-AD, AD 669 666, May 1968
Library No. 9422.015

4. May 1968
Dynamic Stability of Space Vehicles, Volume 12: Reentry Vehicle Landing Ability & Control
Kuchta
N68-24945
General Dynamics Corporation

5. June 1968
Dynamic Structural Data Analysis
Anon
MTP 5-2-025, AD 719 672, June 1968
Library No. 9410.024

6. July 1968
MARS Hard Lander Capsule Study. Volume 3 Capsule Parametric Study
Anon
N68-35983/NASA-CR-66678-4
General Electric Co.

7. September 1968
A Parachute Retrorocket System for Low Altitude Airdrop of Cargo and Other Special Applications
Chakoian, George; Michal, Joseph L.
AIAA Paper No. 68-956, September 1968, A68-42029
Library No. 9421

8. December 1968
An Impact Energy-Absorbing Strut Employing Tube Cutting
Warner, R.W.
NASA-TN-D-4941
NASA Ames

1969

1. 1969
The Properties of a Mechanical System with a Dynamic Shock Absorber
Peterka, F.
FTD-HT-23-426-70, AD 877 033, 1969
Library No. 9410.010

2. January 1969
Emergency Earth Orbital Escape Device Study, Volume 2b - Spacecraft System Design
Anon
X69-31584
Lockheed Missiles & Space Co.

3. January 1969
The Effects of Moisture Content on the Energy Dissipating Characteristics of Paper Honeycomb
Ripperger, E.A.; Hannon, Gary J.
TR-69-67-AD, AD 687 338, January 1969
Library No. 9422.017

4. March 1969
Airdrop Impact Capability of the Redeye Missile Unipak Container
Antkowiak, Henry E.
Report No. 69-72-AD, AD 853 098L, March 1969
Library No. 9422.013

5. March 1969
Modular Honeycomb Concept for Preparation of Loads for Delivery by Airdrop
Falcone, J.F.
DDC No.: 688582
U.S. Army Natick Labs

6. April 1969
Apollo Pad Abort Land Impact Tests
Reese, Terrence G.; Rosen, J. David
NASA-TM-X-64365, N70-34714, April 1969
Library No. 9422.020

7. May 1969
Analytical Investigation of an Inflatable Landing System Having Ominidirectional and Multiple Impact Capabilities
McGehee, J.R.
NASA-TN-D-5236, N69-26223, May 1969
Library No. 9422.004

8. June 1969
Low Onset-Rate Energy Absorber
Keathley, Wm. H.; Wesselski, Clarence J.
TM-X-64444, N70-35706, June 1969
Library No. 9422.023

9. June 1969
Shock Absorber for Parachuted Load
Tkashev, F.D.; Pichugin, A.A.; Minaev, E.N.
FSTC-HT-23-395-69, AD 691 005, June 1969
Library No. 9422.002

10. July 1969
Behavior of Soils Under Impact Loading
Hustad, Paul A.; Cox, Wm. R.
N70-15392, July 1969
Library No. 9422.030

11. August 1969
Proceedings of the Collison Investigation Methodology Symposium
Anon
PB 196 531, August 1969
Library No. 9410.022

12. November 1969
The Determination of Soil Properties in Situ
Campbell, David B.; Hudson, W. Ronald
Research Rept. 98-7, PB 196 439, November 1969
Library No. 9410.018

13. November 1969
A Parachute Retrorocket Recovery System for Airdrop of Heavy Loads
Chakoian, C.
DDC No.: 699342
USA-NLABS-TR-70-34

14. December 1969
The Effect of Airdrop Impact on Complex Structures
Jan, Song Fong; Ripperger, E.A.
Report No. 70-55 AD, AD 711 555, December 1969
Library No. 9422.029

15. December 1969
Variations in the Crushing Strength of Paper Honeycomb
USA-NLABS-TR-70-57-AD, AD 711 557, December 1969
Ripperger, E.A.
Library No. 9422.008

16. December 1969
The Behavior of Sands Under Seismic Loading Conditions
Silver, Marshall L.; Seed, H. Bolton
Report No. EERC 69-16, AD 714 982, December 1969
Library No. 9410.011

1970

1. January 1970
An Impact-Energy Attenuating Device Combined with Guardrail-like Structures
Woolam, W.E.
PB 190 555 (N71-30296), January 1970
Library No. 9422.034

2. February 1970
Airdrop Impact Capability of the Redeye Missile Monopak Container
Antkowiak, Henry E.
Report No. 70-53-AD, AD 872 201L, February 1970
Library No. 9422.016

3. February 1970
Investigation of Impact of Rigid and Elastic Bodies with Water
Chuang, Sheng-Lun
Report No. 3248, AD 702 727, February 1970
Library No. 9410.006

4. February 1970
The Aerodynamic Characteristics of Large Angled Cones With Retrorockets
Jarvinen, Philip O.; Adams, Richard H.
NASA CR-12973, N72-12973, February 1970
Library No. 9421.005

5. February 1970
Helicopter Escape and Personnel Survival System Exhaust Plume Impingement Study
McCarten, R.M.
DDC No.: 866919
NWC-TP-4874
Naval Weapons Center, China Lake

6. February 1970
Test of Low Altitude Parachute Extraction System, 1528 LAPES
Thomas, P.J.
DDC No.: 872245
USAAESWBD-AB-2169

7. March 1970
Energy Absorbing Structure
Keathley, Wm. H.; Wesselski, Clarence J.
NASA Case MSC-12279-1, N70-35679, March 1970
Library No. 9422.024

8. April 1970
Fabrication of a Compartmented Spherical Gas Bag Landing System
Anon
NASA CR-66944, April 1970, N70-30198
Library No. 9422.044

9. April 1970
Landing Impact Attenuation of Non-Surface-Planing Landers
Jones, R.H.
NASA SP-8046, N70-38294, April 1970
Library No. 9410.007

10. May 1970
Mechanical Shock
Anon
DDC No.: 872806
MTP-2-1-006
Army Test & Evaluation Command, Aberdeen Proving Grounds

11. June 1970
Nonlinear Dynamic Analysis of Structures. Volume I - Nonlinear Damping in Structures
Chang, C.S.
LMSC/HREC D149171-1, N71-13098, June 1970
Library No. 9410.019

12. June 1970
Approximate Analytical Models for Landing Energy Absorption, Including the Effect of Penetration by the Payload into its Crushable Casing
Warner, Robert W.
NASA TN D-5833, N60-28800, June 1970
Library No. 9422.021

13. September 1970
Land Impact of the Apollo Command Module
Benson, Harold E.
AIAA Paper No. 70-1165, September 1970, A70-41847
Library No. 9422

14. September 1970
Advanced Development of Lumped Mass, Finite Difference Method for Dynamic Beam Analysis
Brooks, Robert P.
NAEC-ENG-7676, AD 715 112, September 1970
Library No. 9410.029

15. November 1970
Penetration Resistance of Soils; Report 1, Tests with Circular Footings in Air Dry Sands
Green, Andrew J.
TR-M-70-14, Rpt. 1, AD 715 979, November 1970
Library No. 9410.009

16. November 1970
High-Impact Dynamic Response Analysis of Nonlinear Structures
Gupta, K.K.
TR 32-1498, N71-21024, November 1970
Library No. 9410.017

17. November 1970
Application of Analog/Hybrid and Hybrid Computers to the Study of Shock Mitigation Systems
Patterson, C.L., Jr.
NSRD4A-6-28/70, AD 877 216, November 1970
Library No. 9410.005

18. December 1970
Minimum Dynamic Response of a Cantilever Bar
Brach, Raymond M.; Alderson, Robert G.
AD 721 669, December 1970
Library No. 9410.028

19. December 1970
Fuel-Optimal Retrothrusted Soft Landing Through an Atmosphere
Juncosa, M.L.
R-515-PR, AD 718 405, December 1970
Library No. 9421.007

20. December 1970
Parachute Retrorocket Airdrop System
Michal, J.L.
DDC No.: 736 361
USA-NLABS-TR-72-16
Stencel Aero Engineering Corporation

1971

1. 1971
NASTRAN - A Summary of the Functions and Capabilities of the NASA Structural Analysis Computer System
Butler, Thomas G.; Michel, Douglas
NASA SP-260, N71-21559, 1971
Library No. 9410.027

2. January 1971
Analysis of Helicopter Structural Crashworthiness. Volume I - Mathematical Simulation and Experimental Verification for Helicopter Crashworthiness
Gatlin, Clifford I.; Goebel, Donald E.; Larsen, Stuart E.
USAAVLABS Tech. Rept. 70-71A, AD 880 680, January 1971
Library No. 9410.021

3. January 1971
Analysis of Helicopter Structural Crashworthiness. Volume II - User Manual for "Crash," A Computer Program for the Response of a Spring Mass System Subjected to One-Dimensional Impact Loading (UH-1D/H Helicopter Application)
Larsen, Stuart E.; Drummond, John K.
USAAVLABS Tech. Rpt. 70-71B, AD 880 678, January 1971
Library No. 9410.020

4. February 1971
A Mathematical Procedure for Predicting the Touchdown Dynamics of a Soft Landing Vehicle
Zupp, George A., Jr.; Doiron, Harold H.
NASA TN D-7045, N71-16768, February 1971
Library No. 9410.023

5. March 1971
The Influence of Changing End Conditions on the Resonant Response of Beams and Plates
Egle, D.M.
NASA CR-1736, N71-18647, March 1971
Library No. 9410.026

6. March 1971
On the Use of Modeling in a Structural Response Problem
McGovern, D.E.; Thunborg, S., Jr.
SC-RR-70-880, N71-27986, March 1971
Library No. 9422.031

7. March 1971
Investigation of Materials for Seat Cushion and Parachute Support Spacer Development
Stech, Ernest L.; Russell, G. Kenneth
ASD-TR-70-56, AD 723 302, March 1971
Library No. 9422.035

8. April 1971
Dimensional Instability - An Introduction
Maringer, R.E.
DMIC Memo 253, AD 721 198, April 1971
Library No. 9410.030

9. April 1971
A Study of Impact Test Effects Upon Foamed Plastic Containers
McDaniel, Don
RL-TR-71-2, AD 723 396, April 1971
Library No. 9422.031

10. July 1971
Impact on Complex Mechanical Structures
Jan, S.F.
USANLABS-72-49
U.S. Army Natick Labs

11. September 1971
Investigation of Technique for Conducting Landing Impact Tests at Simulated Planetary Gravity
Stubbs, S.M.
N71-36247/NASA-TN-D-6459
NASA

12. October 1971
Monte Carlo Simulation of the Apollo Command Module Land Landing
October 1971, A71-42776
Library No. 9422

13. October 1971
A Fortran V Program for Predicting the Dynamic Response of the Apollo Command Module to Earth Impact
Thomas, W.E., Jr.
NASA TN D-6539, N71-36589, October 1971
Library No. 9410.033

14. November 1971
Dynamic Response Index Modulation for Personnel Escape Systems
Destefano, L.A.
DDC No.: 892385
FA-M71-23-1
Frankford Arsenal

15. November 1971
Statistics Concerning the Apollo Command Module Water Landing, Including the Probability of Occurrence of Various Impact Conditions, Successful Impact, and Body X-Axis Loads
Whithah, Arthur M.; Howes, David B.
NASA TM X-2430, N72-11790, November 1971
Library No. 9410.032

16. December 1971
Linear Acceleration of Impact Type
Anon
DDC No.: 737090
AGARD-CP-88-71
AGARD

17. December 1971
A Statistical Investigation into the Development of Energy Absorber Design Criteria
Phillips, N.S.; Carr, Richard W.; Scranton, Richard S.
NADC-CS-7122, AD 749 333, December 1971
Library No. 9410.034

1972

1. September 1972
Bioastronautics Data Book
Parker, James; West, Vita R.
AD-749 887, September 1972
Library No. 9410.035

2. February 1972
Cushioned Para-Drop Platform
Anon
FSTC-HT-23-1267-71, AD 894 125L, February 1972
Library No. 9422.036

<u>1973</u>

1. 1973
   Design Analysis of a Parachute/Retrorocket Landing System for an Aircraft Crew Escape Module
   Babish, C.A.
   AFFDL/FER
   Comment: Only known copy is in Parachute Databank

2. February 1973
   An Active Optical Ground Sensor for a Parachute Retrorocket Airdrop System (PRADS)
   Ulrich, Reinhard R.; D'Onofrio, Anthony J.
   HDL-TM-73-2, AD-911 216L, February 1973
   Library No. 9421.006

3. March 1973
   The Crushing Strength of Paper Honeycomb
   Ripperger, E.A.; Briggs, W.R.
   TR 73-31-AD, AD 763 913, March 1973
   Library No. 9422.038

4. March 1973
   HEPS (Helicopter Escape and Personnel Survival) System
   Thomas, G.T.
   DDC No.: 911479
   WADC-73052-50
   Naval Air Development Center

5. April 1973
   Experimental Investigation of the Ground Impact Characteristics of a 1/4-Scale Model of an Aircraft Emergency Crew Escape Capsule
   Roberts, Edward O.; Peterson, Richard L.
   AFFDL-TR-72-142, AD-911 147L, April 1973
   Library No. 9422.037

6. May 1973
   Advanced Development of a Parachute Retrorocket Airdrop System
   Chakoian
   DDC No.: 765422
   USA-NLABS-TR-73-59

7. May 1973
   Experimental Investigation and Correlation of the Ground Impact Acceleration Characteristics of a Full Scale Capsule and a 1/4 Scale Model Aircraft Emergency Crew Escape Capsule System
   Peterson, R.L.; Roberts, E.O.
   AIAA Paper No. 73-480, May 1973, A73-31463
   Library No. 9410

1974

1. September 1974
Final Report: Crew Escape Module Retrorocket Motor
Anon
DDC No.: AD B002772
AFRPC-TR-74-32
Air Force Rocket Propulsion Lab

1975

1. October 1975
Aircraft Crashworthiness
Saczalski, Editor
International Symposium
Comment: Symposium proceedings reflecting state-of-the-art as of October 1975

REFERENCES

1. S. R. Mehaffie, A Minimum Weight Analysis of Aerospace Vehicle Recovery Systems, AFFDL-TR-77-26, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, June 1976.

2. Col. A. P. McHugh, Operations Evaluation of TAC Drone Ground Recovery, TAC-72E-089T, TAC/DR, Langley Air Force Base, Va. July 1973.

3. Col. A. P. McHugh, Actual Weight Report for AQM-34V, Serial No. 67-20423, C.I. No., 2081101-02, TRA No. 25544-3, Teledyne Ryan Aerospace, San Diego, CA 92112, January 1976.

4. Actual Weight Report for AQM-34V Serial No. 67-20335, C.I. No. 2081101-26, TRA No. 25544-4, Teledyne Ryan Aerospace, San Diego CA 92112, August 1976.

5. M. C. Whitney, Crew Escape Capsule Retrorocket Concept, AFFDL-TR-76-107, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, May 1977.

*U.S.Government Printing Office: 1979 — 657-002/578