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PROTOTYPE DEVELOPMENT
PASSIVE, SEAT-MOUNTED, LIMB RETENTION SYSTEM

Aircraft and Crew Systems Technology Directorate
NAVAL AIR DEVELOPMENT CENTER
Warminster, Pennsylvania 18974

STENCEL AERO ENGINEERING CORPORATION
Asheville, North Carolina 28803

MAY 1979

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It has been well documented that the predominant cause of injury (both major and minor) occurring from combat ejections during the Southeast Asia conflict was due to flailing of the extremities as a result of increased ejection speed. A prototype passive seat mounted limb retention system was developed and manufactured which does not require the aircrewman to wear any additional devices or fasten additional restraint connections. It will not, in anyway, compromise his movement in the cockpit or his control of the

aircraft. This functional prototype device will undergo feasibility testing to determine acceptability for further development.

FOREWORD

This technical report describes the work accomplished by Stencel Aero Engineering Corporation in accordance with the requirements of Naval Air Development Center Contract N62269-77-C-0251. The principal engineer was Mr. F. Terry Thomasson and he was supported by Mr. Ron Brevard, Project Engineer and Mr. Gary Bradley, Senior Designer.

The effort described was conducted for the Life Support Engineering Division of the Aircraft and Crew Systems Technology Directorate under the technical direction of Mr. Marc Schwartz. His constructive comments and guidance along with that provided by Mr. Cliff Woodward are gratefully acknowledged.

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Section 1

INTRODUCTION/SUMMARY

1.1 INTRODUCTION

This program has been sponsored by the Naval Air Systems Command, Code 340B. This report has been prepared and the development reported herein has been accomplished under Naval Air Development Center Contract N62269-77-C-0251. The effort was conducted under the engineering monitorship of the Life Support Engineering Division to fulfill the following contract objective:

> "The objective of the effort is to design, fabricate and deliver an experimental feasibility prototype of a passive, seat-mounted, restraint and protection system to provide future crewmen with a system which will reduce their physiological exposure to aerodynamic and deceleration forces during high-speed ejection up to 600 knots. This prototype will be developed for the NADC Maximum Performance Ejection Seat basic configuration for feasibility demonstration."

Impetus for this development effort has been provided primarily from the combat injury experience generated by the Southeast Asia conflict. Analyses of this experience document that the predominant probable cause of injury (both major and minor) during combat ejections was due to flailing of the extremities.

1.2 SUMMARY

This report provides a synopsis of the background of limb retention developments undertaken to eliminate limb flail injuries. As the first attempts to produce workable passive systems failed, none became operational. The limb flail problem was masked by the low ejection speeds characteristic of non-combat ejections and the lethal potential was never realized nor appreciated. So, the U. S. Navy entered the Southeast Asia conflict with escape systems which offered limited protection against limb flail injury.

This report synopsizes the combat injury experience as analyzed by two Navy contracted studies and reported by two reports referenced herein. Not only does the data show that limb flail injury was the predominant probable cause of combat ejection injuries, but it also documents the consequences of having no limb restraint versus the benefits derived when limb restraint is provided.

The severity of limb flail increases with increasing ejection speeds. The report compares the operational performance of the Southeast Asia combat aircraft, the current front-line aircraft and the performance envelope of the future to indicate that higher ejection speeds can be expected to be more prevalent.

This report provides justification for a passive limb retention system, one which does not require that the aircrewman wear additional devices or accomplish additional restraint connections.

This report presents a summary of the development of the experimental, feasibility prototype of a passive, seat-mounted, limb retention system as required by the aforementioned contract. The system conceived by Stencel Aero Engineering Corporation during the preproposal design effort went through three design iterations. The efforts, the problems addressed and the design approaches evaluated during each iteration are presented. The configuration and the sequence of operation of the prototype design which was successfully demonstrated is presented herein.

Finally, the conclusion and recommendations are enumerated in Section 5. These are summarized as follows:

Conclusions

- A limb retention system that is completely passive is feasible.
- The contracted effort successfully produced a functional prototype of a passive, seat-mounted limb retention system which is suitable for feasibility testing.
- The combat injury experience generated by the Southeast Asia conflict documents an urgent need for a limb retention system in all ejection seat systems.
- The feasibility prototype developed and demonstrated is a promising approach for providing protection against limb flail injuries.

Recommendations

- To prove feasibility, the prototype should be tested on the ejection tower and be exposed to 600 KEAS windblast.
- System development should be continued to obtain a design for live subject ejection tower tests and for ejection testing with the Maximum Performance Ejection Seat System.

- The next development effort should include the final design of the system components, and integration of the NADC head restraint system.

- A plan should be prepared for development completion, service release testing and operational installation of the passive, seat-mounted, limb retention system in all U. S. Navy high performance aircraft.

Section 2

BACKGROUND

2.1 LIMB FLAIL INJURY BACKGROUND

The limb flail injury condition has been masked by the low ejection speeds which are characteristic of non-combat ejections. In fact, there has been a limb flail injury problem since the inception of the ejection seat, and limb flail injuries occur throughout the ejection speed regime. Quoting Woodward and Schwartz [1]:

> "It should be understood that the limb flailing problem is one that can occur and does occur even at speeds as low as 120 knots. Naval Safety Center Data is full of limb flail occurrences between 100 and 400 knots, and range all the way from simple contusions and sprains to multiple dislocations and fractures. Therefore, we should think of it as an ejection problem, not just a 400- to 600-knot problem."

The number and severity of the consequences of the non-combat limb flail injuries were not great enough to excite analysis. Therefore, the potential for limb flail injury was not appreciated by the ejection seat designers nor by those responsible for the escape system requirements. Had the limb flail injury condition been analyzed and its lethal potential assessed, an urgent need for limb restraint would have been realized. Then, surely, the specification requirements for arm and leg restraint would have been made mandatory and the combat ejection statistics generated by the Southeast Asia conflict would have been very different.

Instead, the following scenario led to the combat ejection experience. The first ejection seats incorporated stirrups, into which the feet were placed as a pre-ejection function, and two side arm ejection controls, which were grasped to initiate ejection and to restrain the arms. The first high-speed ejections proved the inadequacy of these approaches to limb restraint, and this prompted the exploration of active arm and leg restraint designs.

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(1) Woodward, Clifford C., and Schwartz, Marcus. High "Q" Escape Protection Proceedings, 15th Annual SAFE Symposium: 220-224, 1977

The USAF tried several approaches which combine separate restraints for the head and limbs with the conventional torso restraint. Ball and socket connections for attachment of the helmet and boots to the seat structure as a pre-ejection function was one unsuccessful approach. Cables, attached to these same points, coupled with "take-up" reels were also explored. These approaches found limited use and eventually were discarded. Their acceptance by the aircrewmen was poor because they required extra effort to hook up and they impeded limb movement during normal flight. Also, because restraint of the total body was obtained by independent attachment of the individual body parts, relative movement between the torso and the extremities was produced during exposure to acceleration forces. This resulted in loading the attachment joints of the extremities which, in some cases, produced injuries.

The next natural step toward gaining total body restraint led to research into some very effective, but impractical, restraint designs - designs in which the torso was "welded" to the seat and the extremities were restrained positively with respect to the torso. Two of these were: An "iron maiden" concept where the aircrewman was completely contained within a rigid structure (exoskeleton), and another where the aircrewman would be completely surrounded by rigid foam or "foamed in place". While impractical for aircraft operational application, these concepts did demonstrate the degree of restraint which should be sought for the elimination of flail injuries.

Attempts to devise more practical means of obtaining total body restraint followed. Structural flight garments were designed and tested. These garments used broad woven fabric and/or an integral network of straps to provide the restraining force. These approaches succumbed because the garments were heavy and unwearable; required multiple attachments to seat structure to achieve adequate torso and extremity restraint; and, last but not least, the garments were poor parachute harnesses. While this effort was not successful in producing satisfactory extremity restraint, it did produce the conventional torso harness restraint garment.

Therefore, the initial Navy jet aircraft inventory incorporated ejection seats without positive means of extremity restraint. This situation was changed during the time period 1956-1962 when the Navy accomplished a large-scale retrofit of the Martin-Baker ejection seat. The Martin-Baker seat was presented to the U. S. Navy with an active leg restraint as an integral part of its design configuration. However, this act did not reflect complete enlightenment toward the limb flail problem because U. S. industry was still permitted to develop ejection seats having no means of extremity restraint.

There was a single exception. The North American HS-1 (High Speed - 1) ejection system was designed and developed to include both passive leg restraint and active arm restraint. But, the HS-1 was required to include these restraints because of the increased design ejection speed specified for it (746 KEAS, 1905 PSF) versus that specified for other seats (600 KEAS, 1220 PSF). Thus, the need for limb flail protection continued to be thought of as a requirement only for very high ejection speeds, and no effort was undertaken to develop suitable means of arm and leg retention for all ejection seat systems.

Thus, the Navy entered combat with: A-4 and A-7 aircraft equipped with ESCAPAC seats having no means of limb restraint; F-4, F-8, and A-6 aircraft equipped with Martin-Baker ejection systems having a leg restraint garter subsystem, but no arm restraint; and one aircraft, the RA-5C, equipped with the HS-1 ejection seat which has active arm and passive leg restraint. However, while reviewing the combat limb flail data, to be presented next, keep in mind that both the Martin-Baker leg garters and the HS-1 arm restraint (vest sleeves and restraint cords) had to be donned and hooked up by the aircrewman.

2.2 COMBAT INJURY EXPERIENCE

The combat injury experience presented in this section has been extracted from the reports (2)(3) of two major studies of Navy Air Combat escape and survival in Southeast Asia. The first report (2) provides the results of analyses of data from aircrewmen who were successfully recovered following ejection and from aircrewmen who are repatriated POWs (Prisoners of War). The second report (3) augments the first with additional data and analysis. Most importantly, this report adds what information is available about the ejections of those aircrewmen classified as MIA/KIA (Missing in Action/Killed in Action). The limb flail injury experience presented in these reports is of primary interest to this study. The data pertinent to this problem is synopsized below as documentation of the need for limb retention in all ejection seat escape systems. However, the totality of the data contained in these reports is considered to be

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(2) Every, Martin G., and Parker, James F., Jr., Biomedical Aspects of Aircraft Escape and Survival Under Combat Conditions. Final Report, Office of Naval Research Contract No. N00014-72-C-101, Task No. NR 105-667, March 1976.

(3) Every, Martin G., A Summary of Navy Air Combat Escape and Survival. Final Report, Office of Naval Research Contract N00014-72-C-101, Task No. NR 105-667, February 1977.

of important impact to all aspects of ensuring successful escape and survival of aircrewmen. The reports should be studied by all who are responsible for the safety and survival of aircrewmen. The specifications, designs, and, in some cases, procedures should be revised as necessary to eliminate all injury potential which has been proven to exist.

The report [3] documents the following combat ejection injury experience:

Major Injury Resulting in Fatality	36%
Major Injury With Survival	24%
Minor or No Injury	40%

The report states that the major fatal injury rate (36% + 24% = 60%) is approximately twice the rate (30%) experienced for current non-combat ejections (1971-1975 time period).

The reports document that the predominant probable cause of injury (both major and minor) during combat ejections was due to flailing of the extremities. Table I presents a comparison of this data for all ejections and also for the higher speed ejections. The term higher speed is not defined in the reports, but can be assumed to pertain to ejections above 400 KEAS.

TABLE I

PROBABLE CAUSES OF KNOWN INJURY (POW GROUP)

	All Speeds	Higher Speeds
Flail	33%	60%
Enemy Inflicted	17%	*
Ejection Seat G Forces	14%	15%
Struck Object	13%	8%
Parachute Landing	11%	*
Fire	10%	*
Parachute Opening Shock	2%	*
Unknown or Other	-	17%

* Included as Unknown or Other

(3) ibid.

The data shows that one-third of all ejectees who were injured sustained a flail injury and that this cause was twice as significant as the second ranked cause. As would be expected, the significance of flail injuries became greater at the higher ejection speeds, and this cause was four times as prevalent as the next ranked cause. Therefore, flail injury, which was of such little significance during non-combat ejection experience, became overridingly the greatest source of injury during combat.

The reason for this is found by a comparison of combat versus non-combat ejection speed history. Figure 1 from the second report [3] provides this comparison in graphic form.

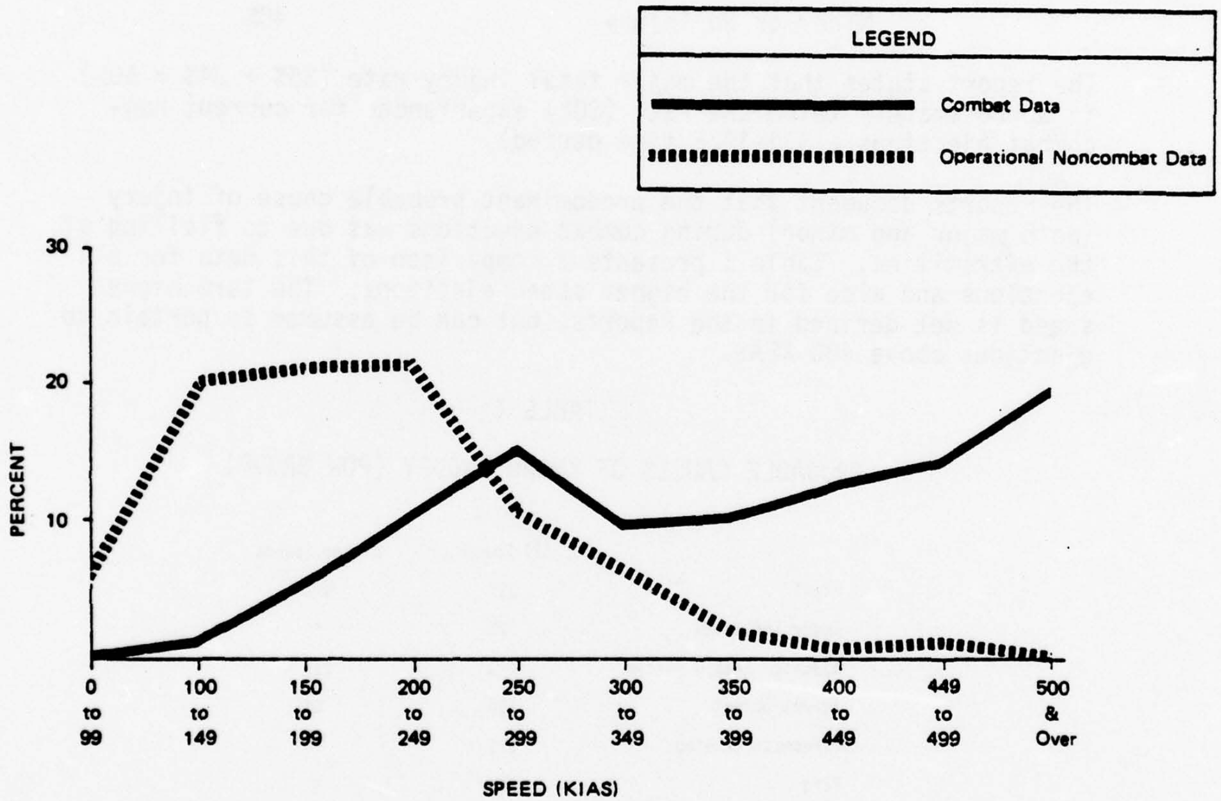

FIGURE 1 COMBAT VERSUS NON-COMBAT EJECTION SPEEDS

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(3) ibid.

A much greater percentage of combat ejections occurred at high speed. The second report [3] provides the following breakdown (Table II) of the percentage of ejectees at each speed regime:

TABLE II

KNOWN EJECTION SPEEDS VERSUS
CASUALTY STATUS (NON-FATAL EJECTIONS)
CASUALTY STATUS PERCENT

	Recovered (102 Cases)	POW'S (116 Cases)	MIA/KIA (24 Cases)	Total Recovered POW'S MIA/KIA'S	Non-Combat
0- 99	0	0	0	0	6.4
100-199	13.7	4.3	0	7.9	42.7
200-299	41.2	14.0	12.5	25.5	34.5
300-399	18.6	21.6	16.7	19.8	11.4
400-499	20.6	32.8	33.3	27.6	3.9
500 and Over	5.9	27.6	37.5	19.3	1.1

Adding the percentages for 400-499 and 500 and over together shows that 46.9% of the combat ejections occurred at speeds over 400 knots versus 5.0% for non-combat ejections. But these data show an additional trend when the data for the separate categories - Recovered, POW's, MIA/KIA - is compared. As the prevalency of ejections over 400 knots increased dramatically for each category from 26.5% for "Recovered", to 60.4% for "POW's", to 70.8% for the "MIA/KIA" category, the chance of recovery and ultimate survival appears to be related to ejection speed.

The data analysis in the first report [2] produced the Figure 2 graph showing the percentage of survivors sustaining a major injury versus ejection speed.

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(2) ibid.

(3) ibid.

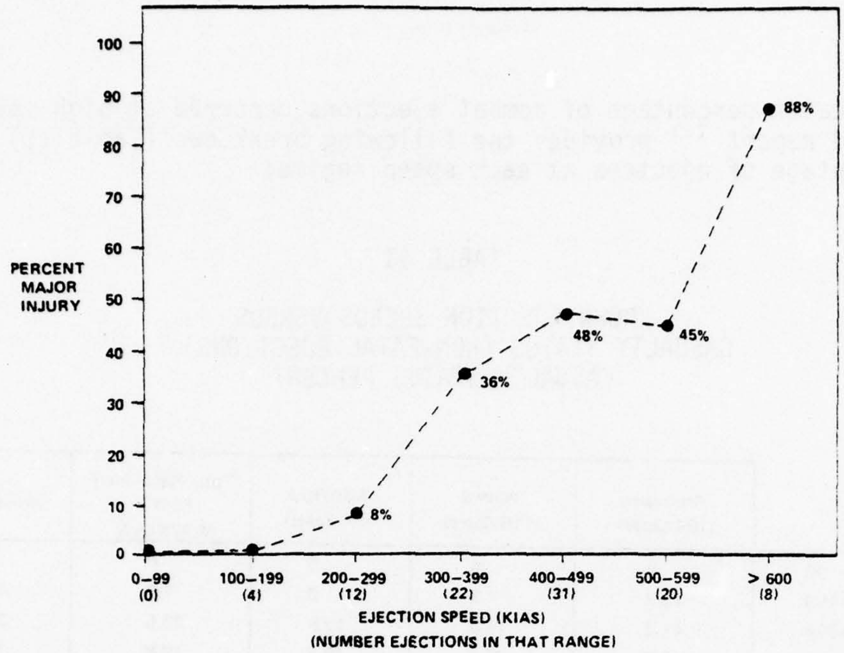

FIGURE 2 PERCENT OF SURVIVORS SUSTAINING A MAJOR INJURY VERSUS EJECTION SPEED

The data analysis also proved that, for the POW group, the majority of their major injuries were due to flailing of the extremities (Figure 3).

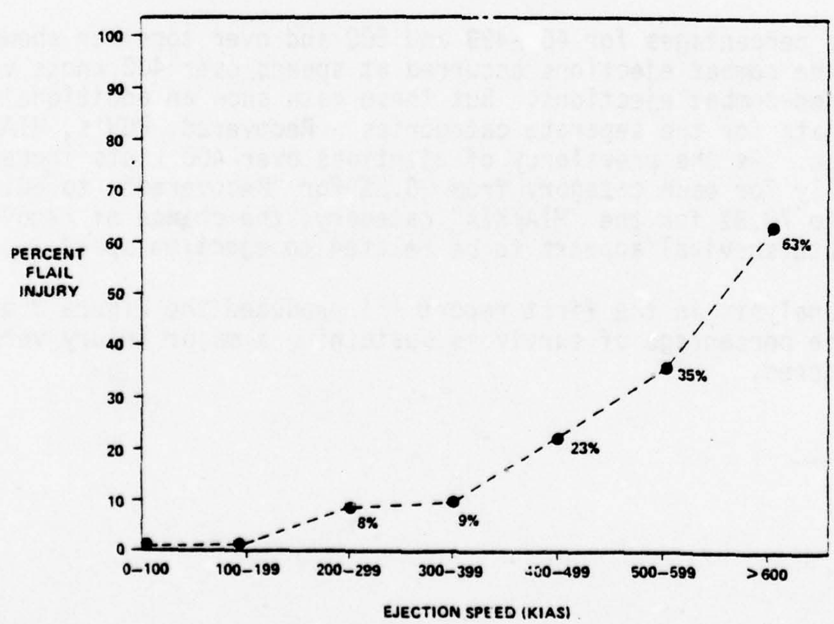

FIGURE 3 INCIDENCE OF MAJOR FLAIL INJURY VERSUS EJECTION SPEED

The first report [2] also presents the following data on the types, frequencies and location of the flail injuries which occurred. Table III provides the number of flail injuries by injury type and for comparison the number of the same type of injury from all causes.

TABLE III

TYPES AND FREQUENCIES OF MAJOR POW FLAIL AND EJECTION INJURIES*

Type of Injury	Flail Only Frequency	All Ejection Injuries
Dislocations	20	21
Fractures		
Simple	20	31
Compound	4	5
Torn ligaments or muscles or severe sprains	9	9

*Includes only known flail and ejection injuries; excludes all spinal-compression fractures.

It can be seen that the greatest number of dislocations, fractures and lesser injuries are produced by flailing.

The percentage of the location of the flail injuries is illustrated by Figure 4.

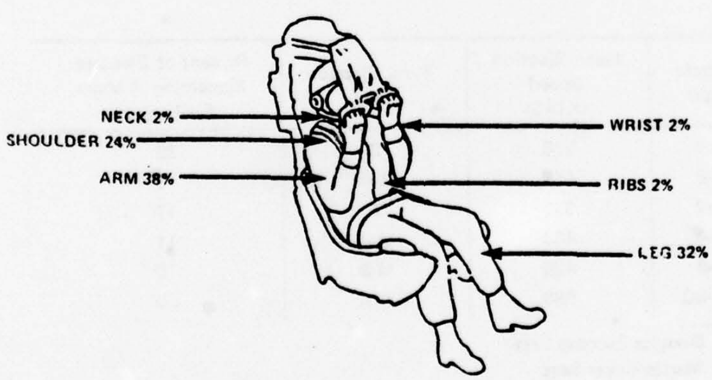

FIGURE 4 GENERAL LOCATION OF MAJOR FLAIL INJURIES

(2) ibid.

Flailing of the arm resulted in 64% of the injuries and flailing of the leg 32%. Head flailing produced 2% of the injuries, and the final 2% was assigned to rib involvement.

The reports (2) (3) provide much biomedical reasoning regarding the types and characteristics of the injuries experienced in combat. For the purpose of this study, it is sufficient to summarize this reasoning: First, by quoting a pertinent phrase from the first report (2), "... the loads of unsupported limbs may exceed the strength of major joints."; and by stating that the result of this condition is dislocations which, along with the fractures and ligament/muscular injuries, made escape and evasion and, in many cases survival, impossible. From the combat injury experience related by the reports, it is reasonable to conclude that flail injuries sustained during ejection were the direct cause of the capture and/or death of many Naval aircrewmen.

The first report (2) also provides data which can be used to obtain an assessment of the effectiveness of the limb retention devices which were used in combat. Also, a comparison can be made with ejection data where no limb retention was incorporated. Table IV relates the percentage of ejectees sustaining a major flail injury to seat type and also to the mean ejection speed. The latter relationship is important because, as flail injury has been proven to be related to ejection speed, any seat-to-seat assessment must also be related to ejection speed.

TABLE IV

PERCENT OF POW SURVIVORS SUSTAINING MAJOR FLAIL INJURY BY AIRCRAFT TYPE

Aircraft Type	Mean Ejection Speed (KIAS)	Type Ejection Seat	Percent of Ejectees Sustaining A Major Flail Injury
A-4	378	D	36
A-6	408	M-B	9
A-7	337	D	17
F-4	403	M-B	11
F-8	420	M-B	0
RA-5C	588	N.A.	50

D = Douglas Escapac Seat
M-B = Martin-Baker Seat
N.A. = North American Seat

(2) ibid.

(3) ibid.

The conclusion could be hastily drawn from Table IV that the North American HS-1 seat in the RA-5C provided the worst protection against flail injury, but the opposite is true. Examining Table V, which compares extremity injury rates for the upper (arms/shoulders) and lower (legs) extremities, shows that 40% of the flail injuries experienced in the RA-5C were to the upper extremity, and no flail injuries were sustained in the lower extremities.

TABLE V

POW EJECTION EXTREMITY FLAIL INJURY RATES*

	Douglas Seat A-4 & A-7 45 Ejections	Martin-Baker F-4, A-6 & F-8 49 Ejections	North American RA-5C 10 Ejections
Upper Extremity Flail Rate	24%	8%	40%
Lower Extremity Flail Rate	20%	4%	0%

$$^{*}\% = \left(\frac{\text{Number of persons suffering major flail injury}}{\text{Number of persons ejecting with a specific seat}}\right)$$

This means that even though the mean ejection speed for the RA-5C was the highest, the passive leg retention system worked superbly and flawlessly. The RA-5C data presents an interesting and important contrast because it appears to indicate that the arm restraint garment was ineffective due to its design. But, it is more likely that the garment was not worn by most aircrewmen because it impeded normal aircraft operations.

The Martin-Baker leg restraint garter system also was near perfect in preventing flail injuries, which indicates not only an effective design, but also good aircrew discipline concerning its use.

On the other hand, even though aircraft incorporating the ESCAPAC seat had the lowest mean ejection speeds, a high percentage of flail injuries occurred to both the upper and lower extremities. This reflects the result of providing no means of limb restraint.

TABLE VI

COMPARISON OF POW EJECTION SEAT MAJOR FLAIL INJURY RATE BY AIR SPEED

Ejection Speed KIAS	Percent Major Flail, by Ejection Seat Type	
	Martin-Baker 48 Cases	Douglas 41 Cases
0-300	0	14.3
301-450	8	25
451+	13	64
All Speeds	8	32

Table VI provides a comparison of major flail injury rate by ejection speed for the Martin-Baker and ESCAPAC ejectees. The consequences of not providing any means of limb retention are strongly illustrated. Not only were limb flail injuries much more prevalent in the ESCAPAC seat, but they also occurred even at the low ejection speeds.

2.3 AIRCRAFT PERFORMANCE IMPACT ON THE NEED FOR LIMB RESTRAINT

The Southeast Asia combat experience was accrued flying in aircraft designed to the performance capabilities achievable in the 1955-1965 time frame.

The current front-line operational aircraft (F-14, F-15, F-16, and the soon to be operational F-18) outperform the combat tested aircraft by a large margin. Their performance capabilities make normal, non-combat flight operations at the extremes of their speed and acceleration envelope a commonplace occurrence.

The aircraft currently being designed for operational use in the 1981-1985 time frame are, of course, being configured to meet an even greater operational performance envelope, not only in terms of speed and altitude, but also in maneuvering capability. Their projected operational missions dictate normal operation at the extremes of their flight envelope.

Figure 5 presents the approximate flight speed/altitude envelope for the three generations of aircraft. The performance envelope for the future aircraft was established from data provided by airframe contractors and the Government in requests for future escape system design.

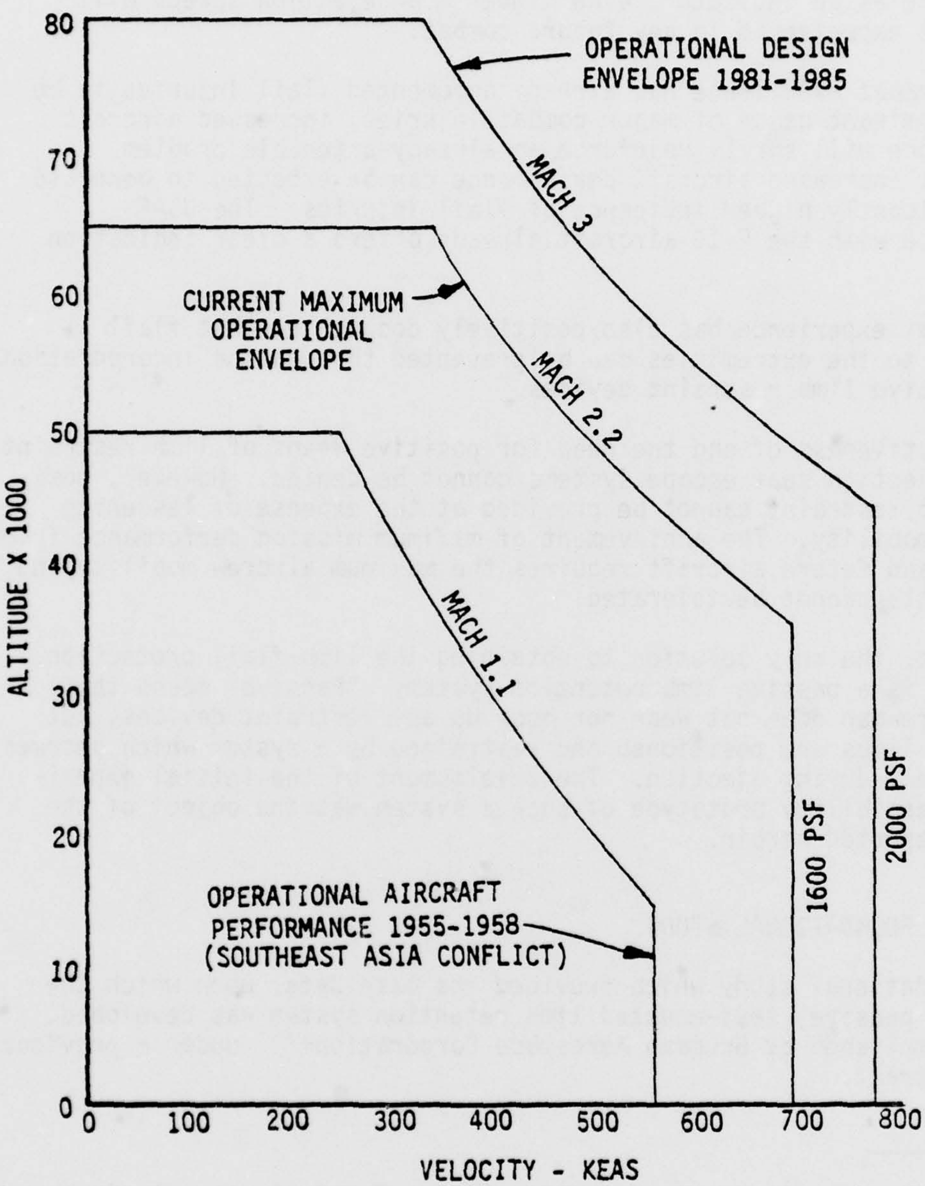

FIGURE 5 AIRCRAFT PERFORMANCE ENVELOPE COMPARISON

The increase in mission performance can reasonably be projected to result in an increase in the prevalence of non-combat ejections at the extremities of the flight envelope. Using the previous combat experience as an indicator, even higher mean ejection speeds will surely be experienced in any future combat.

As the combat experience has already documented flail injuries to be the predominant cause of major combat injuries, increased aircraft performance will surely reinforce an already untenable problem. Likewise, increased aircraft performance can be expected to generate a significantly higher incidence of flail injuries. The USAF experience with the F-15 aircraft already offers a clear indication of this.

The combat experience has also positively documented that flail injuries to the extremities can be prevented through the incorporation of effective limb restraint devices.

The effectiveness of and the need for positive means of limb restraint in all ejection seat escape systems cannot be denied. However, positive limb restraint cannot be provided at the expense of lessening aircrew mobility. The achievement of maximum mission performance from current and future aircraft requires the maximum aircrew mobility, and impediments cannot be tolerated.

Therefore, the only solution to obtaining the limb flail protection required is a passive limb retention system. "Passive" means that the aircrewman does not wear nor hook up any restraint devices, but that his limbs are positioned and restrained by a system which becomes active only during ejection. The development of the initial experimental feasibility prototype of such a system was the object of the effort reported herein.

2.4 THE FOUNDATIONAL STUDY

The foundational study which provided the base data, upon which the proposed passive, seat-mounted limb retention system was developed, was accomplished by Grumman Aerospace Corporation (4) under a previous NADC contract.

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(4) __________, Crewman's Retention System for Protection Against High Speed Ejection Up to 600 Knots, Grumman Aerospace Corporation. Technical Report No. NADC-76119-40, October 1976.

This study correctly analyzed the aerodynamic and inertial forces which work to dislodge the limbs. This effort defined the maximum restraint force requirements which must be resisted by the limb restraint system to ensure satisfactory restraint of the limbs. The requirements are stated in Table VII in Section 3. As the analysis was based upon a seat system which is virtually unstabilized during the critical period of entrance into the high dynamic pressure environment, these requirements are considered to represent a "worst case" condition.

The study also correctly treats the need for a stabilized seat as the first step in preventing flailing of the extremities.

Many and varied possible designs for limb restraint were formulated and evaluated during this foundational effort. These designs were then evaluated parametrically against a number of criteria applicable to the design and integration of limb restraint mechanisms. From this evaluation, several approaches were selected for further consideration.

The report presents several principal recommendations for escape system improvement. Specifically pertinent to the problem of limb flail prevention, the report recommends the development of an "Integrated Mission/Survival Garment System." As the nomenclature suggests, the system is a garment which would be designed to provide complete environmental and windblast protection. To obtain limb restraint, the garment does incorporate a network of webbings which are connected to receptacles on the ejection seat and power tensioned upon ejection.

Stencel appreciated the merits in obtaining limb restraint using flexible, rather than rigid mechanical, means. However, the requirement for a constant wear garment and for additional restraint hookup action by the aircrewman was considered unacceptable. It is considered that the approach to preventing limb flailing reported on herein achieves the intent of the flexible restraint, and, most importantly, does so without the need for an additional garment or additional attachments.

Section 3

DEVELOPMENT - PASSIVE, SEAT-MOUNTED, LIMB RETENTION SYSTEM

3.1 DEVELOPMENT SUMMARY

The development of an experimental feasibility prototype of a Passive, Seat-Mounted, Limb Retention System was accomplished under Naval Air Development Center Contract N62269-77-C-0251. This contract specified that Stencel Aero Engineering Corporation develop, test, fabricate and deliver the experimental prototype installed in the MPES (Maximum Performance Ejection Seat). The contract objective was met with the delivery of a completely functional and structurally sound prototype suitable for subsequent Government-conducted ejection tower and wind-blast testing.

To execute the contract work, Stencel conducted the empirical design and development effort reported herein. The effort was purposely planned as a cycle where design was followed by prototyping, which was followed by verification test and evaluation and the steps repeated to refine the design until a satisfactory design was achieved. There were two primary reasons for structuring the program in this manner: (1) The proposed design was such that it lent itself to more efficient solution through empirical rather than formal or "paper" design effort, and (2) The empirical approach provides the earliest determination of design viability and feasibility through "real time" identification and solution of problem areas.

The principal purpose of the effort was to devise a restraint system which would prevent limb flailing during ejections. However, mindful of the reasons previous attempts had failed, Stencel approached the problem from the total body restraint aspect. The beneficial results of this approach will be discussed in appropriate sections below.

The program commenced by completing and evaluating the design which was proposed. During the conduct of the program, the design went through three more iterations before a satisfactory experimental, feasibility prototype design was achieved. The conceptual design configuration of the limb restraint harness assembly remained unchanged. The technical problems occurred in the areas of restraint deployment and system stowage. Once solutions were successfully found, the limb restraint harness assembly functioned as well as predicted from the preproposal design effort. This is important because of the biomedical aspects of the limb restraint problem. The limb restraint concept is founded on previous research and contains some well-tested techniques. Therefore, the prototype system should be capable of rapid completion of development and qualification and should gain acceptance by the aeromedical community without great difficulty.

3.2 LIMB RETENTION SYSTEM DESIGN REQUIREMENTS/CRITERIA

The general design requirement for the system is best stated by contract objective:

> "The objective of the effort is to design, fabricate and deliver an experimental feasibility prototype of a passive, seat-mounted, restraint and protection system to provide future crewmen with a system which will reduce their physiological exposure to aerodynamic and deceleration forces during high-speed ejection up to 600 knots. This prototype will be developed for the NADC Maximum Performance Ejection Seat basic configuration for feasibility demonstration."

In lieu of design specifications, the contract Statement of Work specified the design requirements. These are synopsized as follows:

- As an optimum, no special attachments or disconnections shall be required by the crewmember for ingress and egress.
- As an optimum design goal, the system shall be capable of achieving arm and leg retraction or entrapment regardless of aircraft attitude, "G" environment or crewmember position at the time of ejection.
- The command ejection case, where the unprepared ejectee may be out of position at time of ejection, shall be considered and the arms and legs shall be captured in this case.
- The system shall ensure that both arms and legs are fully restrained prior to leaving the aircraft or immediately prior to limb exposure to windblast. The maximum allowable time for this should not exceed 0.25 to 0.30 second.
- The retraction or entrapment system and limb retention mechanism shall not cause any injury to the crewmember throughout the ejection to seat/man separation phase of the escape.

- The system must not impede positive seat/man separation under all ejection conditions.

- The system shall ultimately be capable of retaining the arms and legs against the maximum generated restraint forces shown in Table VII. The initial demonstrable concept need not conform to these maximum requirements for the initial prototype; however, the contractor should approach the design with these ultimate force requirements as the minimal acceptable criteria for advanced development models.

- The contractor shall have the option of considering any structural modifications, shaping and sizing of the MPES seat sides, front and headbox areas as necessary to fulfill the requirements as long as the overall dimensions remain in accordance with those specified in MIL-S-18471. The intent is to incorporate as much of the basic seat structure as possible as part of the passive ejection protection system. Retrofitting or hanging of components on the seat shall be avoided wherever possible.

- No modifications shall be permitted to any existing seat subcomponents, system packaging or hardware item location on the rear or bottom of the seat; nor are any changes in the guide rails, seat back angle, seat adjustment mechanism or survival gear desired. The only acceptable changes in structure and shape are in the crewman's seated occupied "living area", in conformance with the requirements stated above.

- The system shall be integrated into the seat in a manner which will not interfere with any other mechanical or operator function.

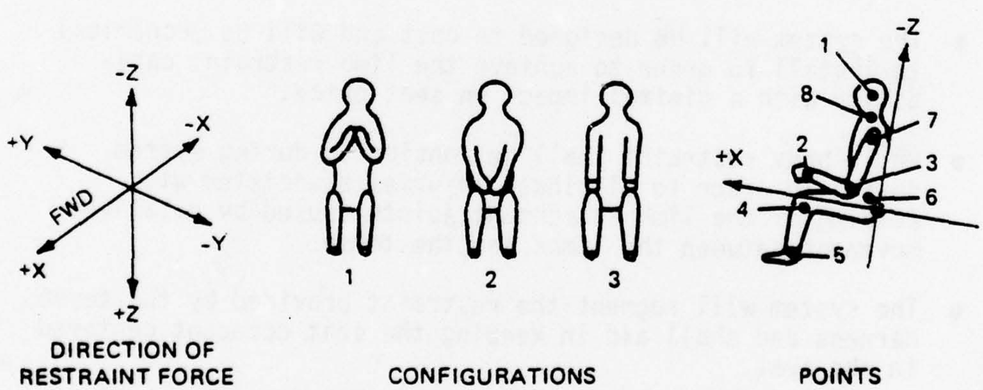
- The contractor must ensure that the limb retraction or entrapment system design will be compatible with the sequencing of the ballistic inertia reel which retracts and tightens the crewmember's upper torso restraint.

- The system shall ensure compatibility with all aircrew percentile population ranging from the 3rd through the 98th percentile.

TABLE VII

MAXIMUM RESTRAINT FORCES

POINT	CONFIGURATION	MAXIMUM FORCE IN POUNDS		
		X	Y	Z
1 HEAD	1	-260	±260	+570
	2	-260	±260	+570
	3	-260	±260	+570
2 WRIST	1	-205	±205	+113
	2	-154	±154	+100
	3	-154	±154	+100
3 ELBOW	1	-126	±126	+297
	2	-208	±208	+245
	3	-208	±208	+245
4 KNEE	1		±988	+766
	2	*	±988	+766
	3		±988	+766
5 ANKLE	1	-360	±957	
	2	-360	±957	**
	3	-360	±957	



* FORCE RESTRAINED BY SEAT-TORSO RESTRAINT SYSTEM.
** FORCE RESTRAINED BY KNEE RESTRAINT.

- The system design shall take into consideration all the flight gear worn by the crewmember to ensure system effectiveness.

- The contractor may utilize any known method or technique or any original design to meet the requirements.

Stencel augmented the above requirements by establishing the following criteria to govern the system design:

- The aircrewman will not be required to accomplish any connections or disconnections to obtain limb restraint.

- When integrated into the seat for normal flight, the system will be as unobtrusive as possible and virtually unnoticeable to the aircrewman.

- The system will be founded on current technology and will contain well-tested techniques to the maximum extent possible.

- The system will integrate into the MPES seat configuration with the minimum impact on basic seat structure.

- As a *design goal*, the system will be designed for ease of retrofit into the Stencel SIIIS-3 seat or any other operational seat system.

- The system will be designed to cost and will be economical to install in order to achieve the limb restraint capability with a minimal impact on seat price.

- Whole body restraint shall be considered during system design in order to eliminate injuries associated with loading of the limb attachment joints caused by relative movement between the limbs and the torso.

- The system will augment the restraint provided by the torso harness and shall aid in keeping the seat occupant centered in the seat.

It is considered that the experimental feasibility prototype of the passive, seat-mounted, limb retention system designed and developed under the contract and delivered for NADC evaluation is capable of ultimately meeting all of the above requirements and criteria.

3.3 PROPOSED LIMB RETENTION SYSTEM

Figure 6 depicts an artist's rendering of the system as proposed to NADC. This system contains the following major components: Shoulder Mounts or Epaulets, Continuous Restraint Straps, Arm Restraint Net, Upper Leg Restraint Strap, Inflatable Knee Grippers, Restraint Ratchets and Retraction Mechanism. The functions envisioned for each of these components are:

Shoulder Mounts or Epaulets (refer to Figure 7) are mounted to each riser to accomplish the following two purposes:

(1) To provide for stowage of the upper portion of each restraint strap and arm restraint net, and

(2) To ensure the initial travel of the restraint straps and nets are outboard and then around the shoulders, so as to sweep the arms inboard.

Continuous Restraint Straps (refer to Figure 7) run from the Epaulets down the torso, around the inside of the knees, through the knee grippers, around the calf and then through the restraint ratchets. These continuous restraint straps provide for five important functions:

(1) Receive and apply the deployment force for the arm restraint net (refer to Figure 7) and for the upper leg restraint straps (refer to Figure 8),

(2) Act as the main structural member of the limb restraint harness assembly,

(3) Apply the restraint tension force by being tensioned by either a strap retractor or by the motion of the seat up the rails,

(4) Anchor the arm restraint net, and

(5) With the aid of the knee gripper (refer to Figure 9), position and restrain the lower leg against movement.

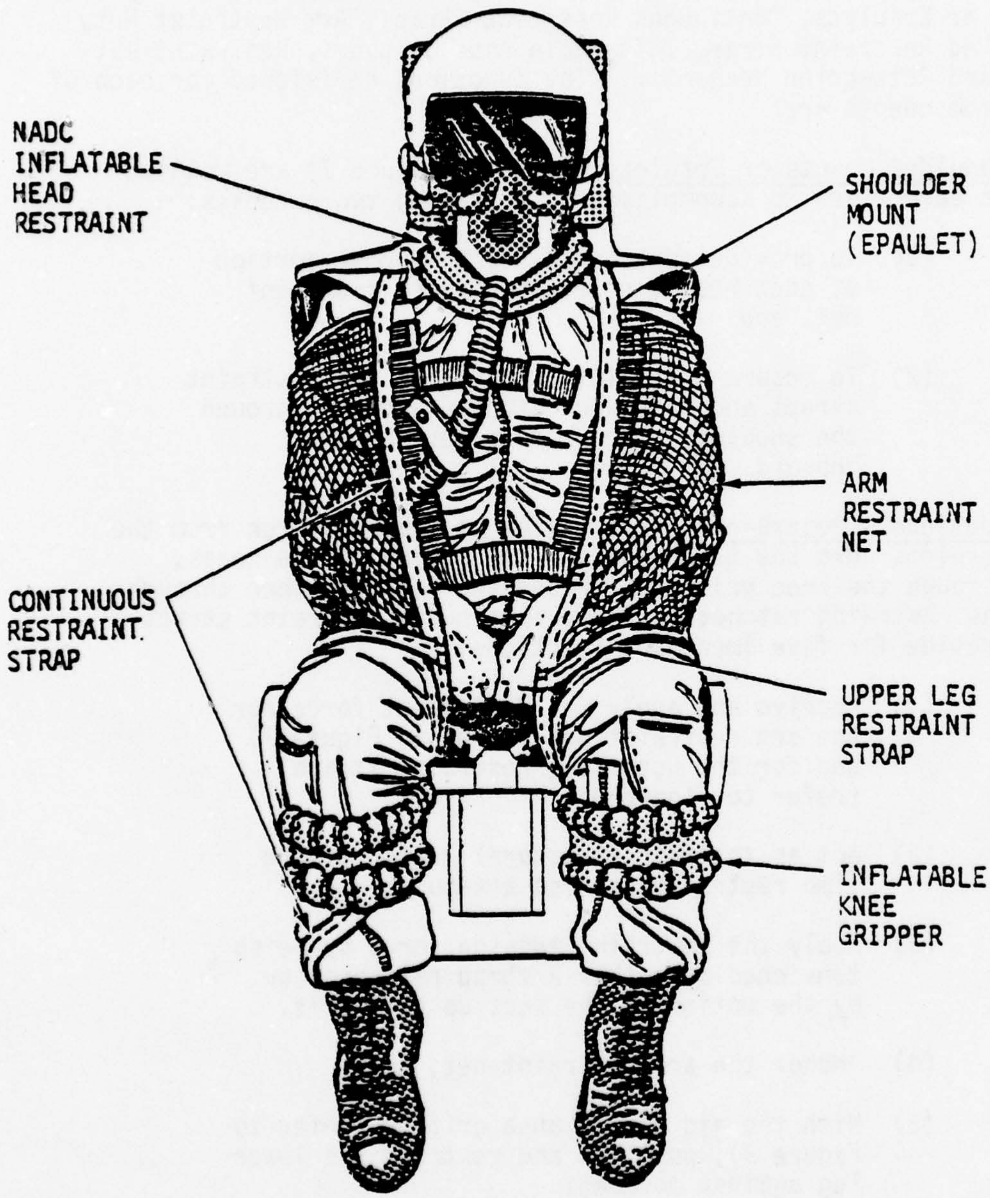


FIGURE 6 PROPOSED LIMB RETENTION SYSTEM

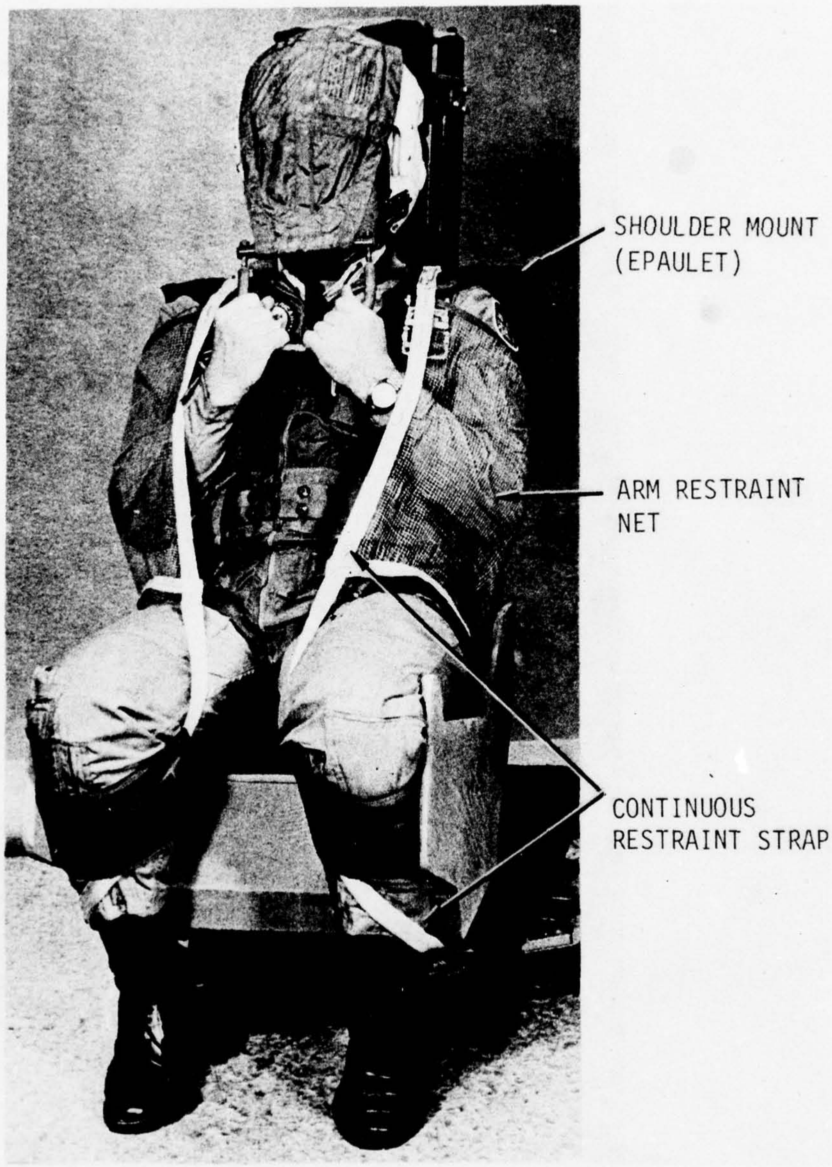


FIGURE 7 LIMB RETENTION SYSTEM - MAJOR COMPONENTS

FIGURE 8 LIMB RETENTION SYSTEM - DEPLOYED
MPES EJECTION CONTROL

INFLATABLE KNEE GRIPPER (SIMULATED)

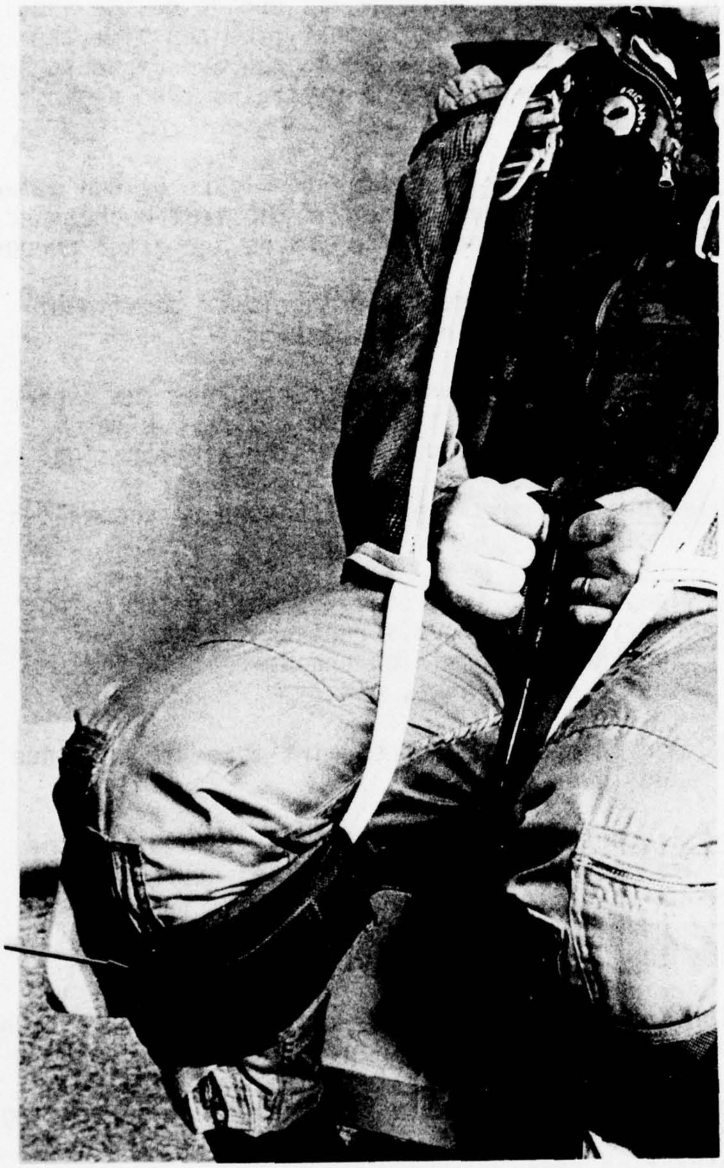


FIGURE 9 LIMB RETENTION SYSTEM - DEPLOYED CLOSE-UP

Arm Restraint Net (refer to Figure 7) is a single uninterrupted piece of netting running from one continuous restraint strap across the back of the seat to the other continuous restraint strap. When deployed, it encircles the shoulders and arms. During system deployment, the net aids the continuous restraint strap in sweeping the arms inboard and then positions the arms properly and restrains them against the windblast forces.

Upper Leg Restraint Straps (refer to Figure 8) run between an attachment at the rear corner of the seat bucket and each continuous restraint strap. The straps serve two purposes:

(1) To anchor and restrain the lower portion of the arm restraint net, and

(2) To provide a downward force across the upper legs preventing them from rising due to windblast or drogue-generated acceleration.

Inflatable Knee Grippers (refer to Figure 9) accomplish two critical functions:

(1) They inflate into position and, in so doing, carry the continuous restraint strap over the knee and position and hold it on the inside of the knee, and

(2) Aid in applying a restraint force to the knee and lower leg.

Restraint Ratchets (refer to Figure 8), similar to the ratchets used on SIIIS-3 and Martin-Baker seats, are installed on the bottom of the seat bucket to snub the continuous restraint strap and maintain the tension applied by the retraction mechanism.

Retraction Mechanism (not shown) applies tension to each continuous restraint strap to deploy the limb restraint harness assembly and to generate the restraining force. This mechanism can be either a "ripper" force generating device, as used in the SIIIS-3 seat system, or a powered strap retraction reel.

Figure 10 depicts the proposed limb retention system mock-up in the stowed position.

From the above description and the accompanying photographs, it can be appreciated that the proposed limb retention system was a unique, albeit simple, concept which was well-founded on existing technology and which consisted of well-tested techniques. While the overall concept was conceived by Stencel, credit should be given to Baer Automatic Systems for the knee gripper concept and to Payne, Incorporated, for their wind tunnel evaluation of the arm restraint net.

3.4 INITIAL PRELIMINARY DESIGN AND EVALUATION

The contracted effort started with a review of the proposed design and the establishment of the configuration/Work Breakdown Structure, Figure 11, to govern the system configuration and the design activities.*

An initial review of the design identified the areas of technical risk as: Positioning of the continuous restraint strap over and to the inside of the knee and capturing the arms when they are in other than an ejection ready position.

The initial design effort was concentrated on determining whether the "Baer hand" gripper element would accomplish the restraint strap positioning and whether it could augment the strap in holding the legs against the MPES side panel extensions. The gripper was invented by Baer for use as a finger element of a prehensile hand for industrial robots.

Figure 12 depicts the element at rest and after the introduction of gas pressure. Its unique bellows design results in a curling of the element upon the introduction of gas pressure on the order of 120 psi. One element was given to Stencel by NADC. The element was approximately seven inches in length. The element was tested to determine its capability to generate gripper "torque". The results are shown in Figure 13. From these results, it was determined that a single element would be of little use in restraining the legs against the force requirements specified. However, it was determined that the gripper would be usable

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* The configuration/Work Breakdown Structure shows a component, inflatable head restraint. As part of the overall system design, Stencel offered to attempt to integrate this NADC-developed device into the limb retention system. However, the system development did not proceed fast enough to allow effort in this area.

FIGURE 10 LIMB RETENTION SYSTEM - STOWED

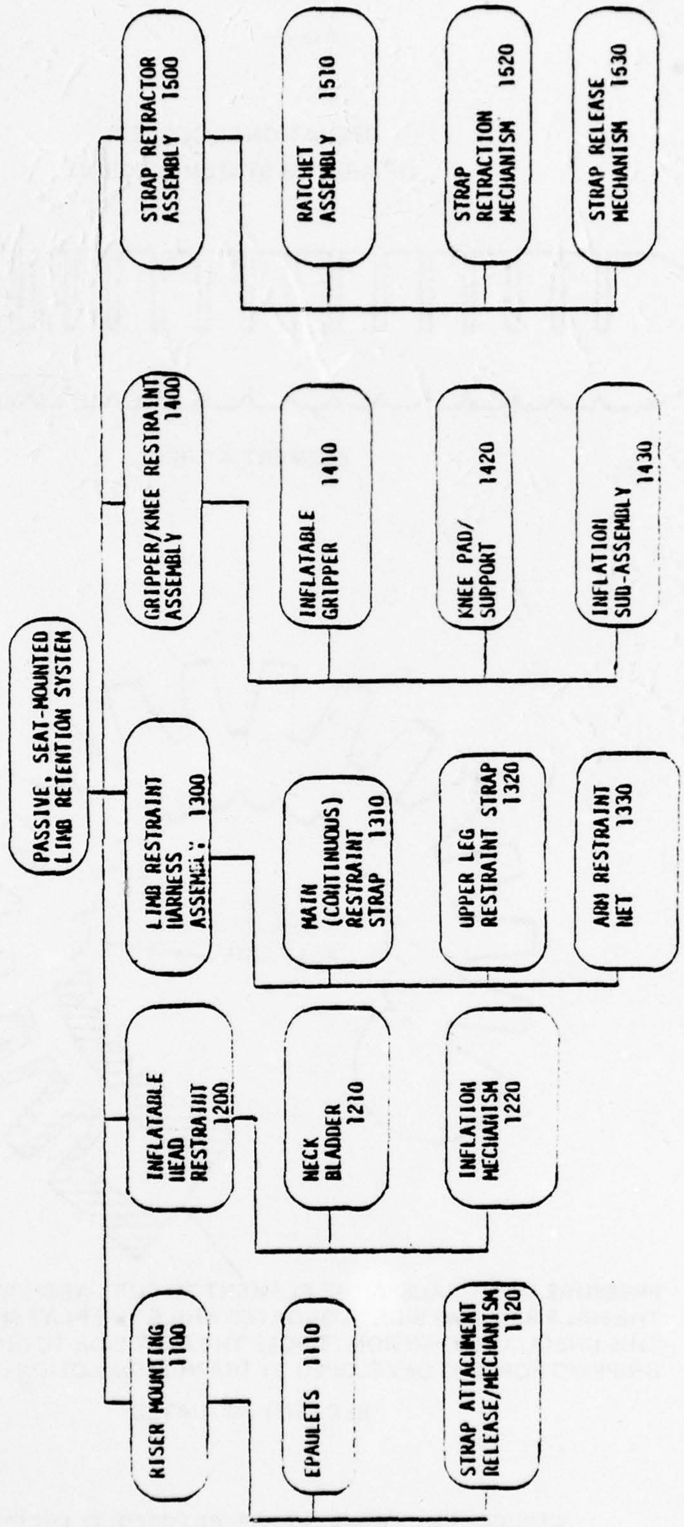

FIGURE 11 CONFIGURATION/WORK BREAKDOWN STRUCTURE

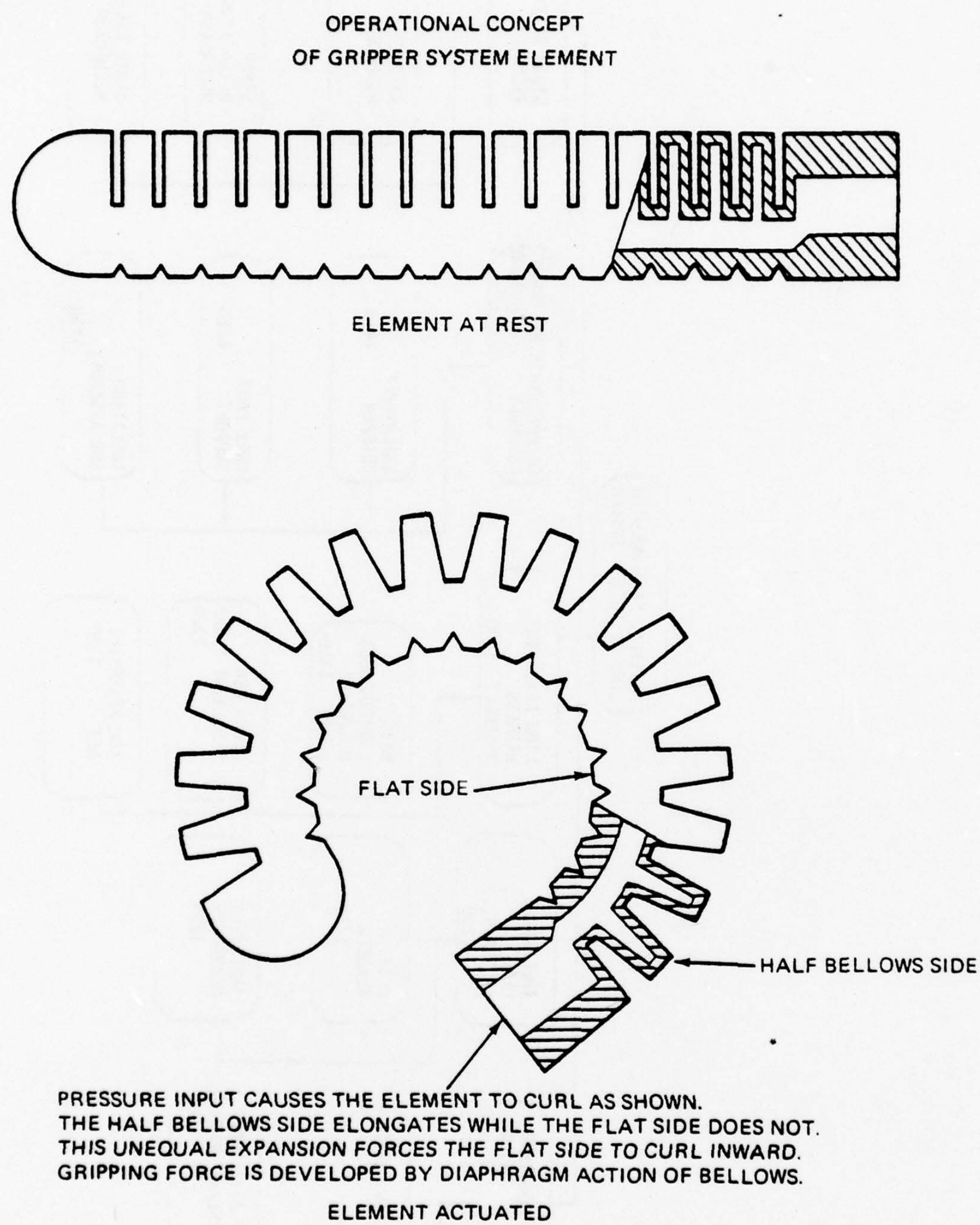

FIGURE 12 "BAER HAND" GRIPPER ELEMENT

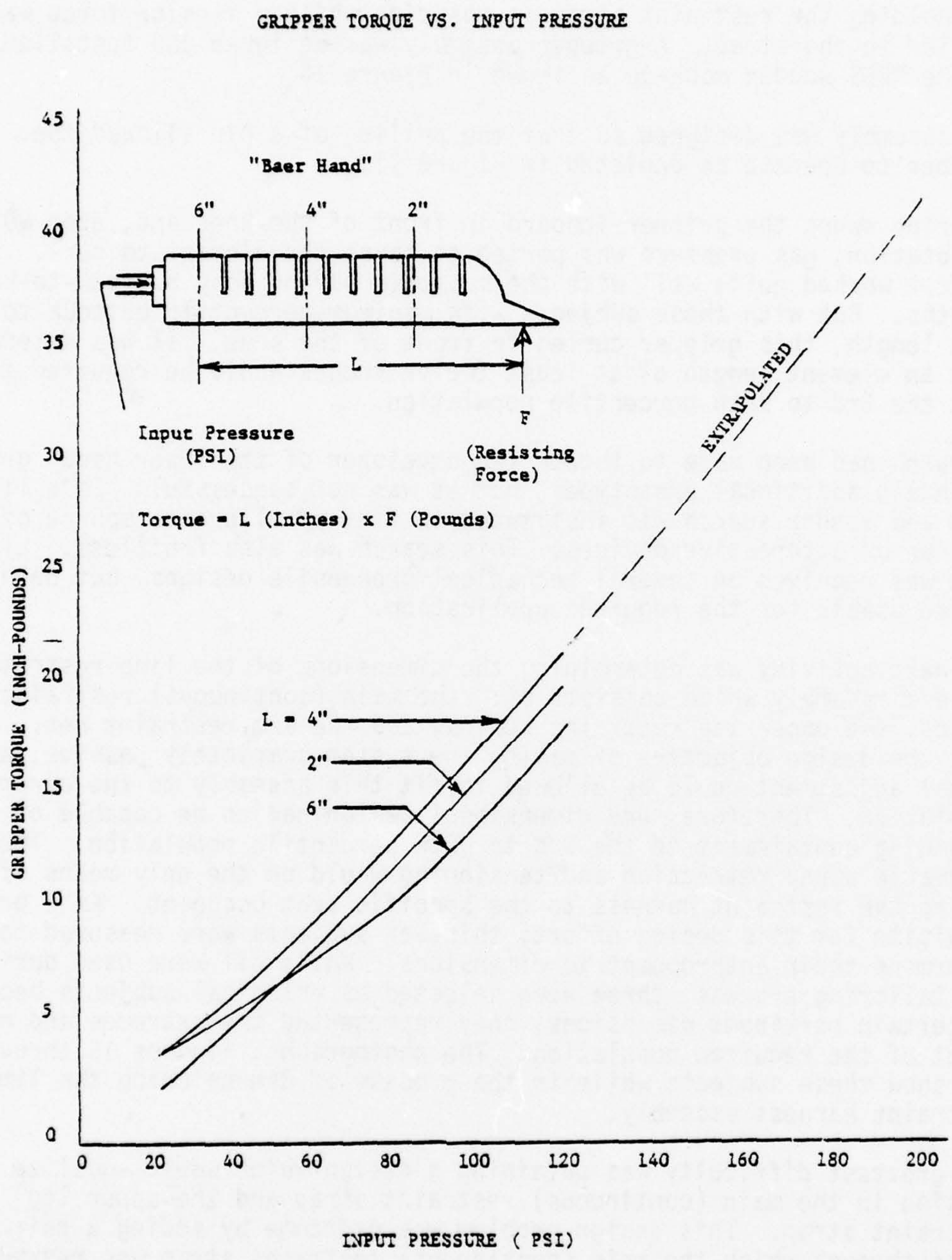

FIGURE 13 "BAER HAND" GRIPPER TORQUE

for holding the restraint strap in position while a tension force was applied to the strap. A gripper assembly was designed and installed on the MPES wooden mock-up as shown in Figure 14.

The assembly was designed so that the pulling of a pin allowed the gripper to operate as depicted in Figure 15.

A spring swung the gripper inboard in front of the knee and, upon 90° of rotation, gas pressure was ported to cause the element to curl. The concept worked quite well with the subjects having long buttock-to-knee lengths. But with those subjects with minimum percentile buttock-to-knee length, this gripper curled in front of the knee. It was determined that an element length of at least twelve inches would be required to suit the 3rd to 98th percentile population.

A search had been made to locate the developer of the "Baer hand" gripper to obtain additional prototypes, but it was not successful. So a literature and vendor search was instituted to find an alternate source of similar or alternative devices. This search was also fruitless. Literature was received on several mechanical prehensile designs, but none were judged usable for the required application.

The next activity was determining the dimensions of the limb restraint harness assembly which consists of: the main (continuous) restraint straps, the upper leg restraint straps, and the arm restraint net. To meet the design objective of making the system completely passive, no manual adjustment could be allowed to fit this assembly to the aircrew population. Therefore, one dimensional design had to be capable of providing containment to the 3rd to 98th percentile population. The automatic strap retraction and tensioning would be the only means of sizing the restraint harness to the specific seat occupant. As a prerequisite for this design effort, thirteen subjects were measured to determine their anthropometric dimensions. While all were used during the tailoring process, three were selected as principal subjects because, in certain pertinent dimensions, they represented the extremes and midpoint of the required population. The photographs, Figures 16 through 18, show these subjects while in the process of dimensioning the limb restraint harness assembly.

The greatest difficulty was obtaining a design which would equalize the tension in the main (continuous) restraint strap and the upper leg restraint strap. This design problem was overcome by adding a pair of rings through which the main (continuous) restraint strap was reeved. This configuration is shown in the photograph of Subject #2 (Figure 17). The rings are positioned on his right upper thigh.

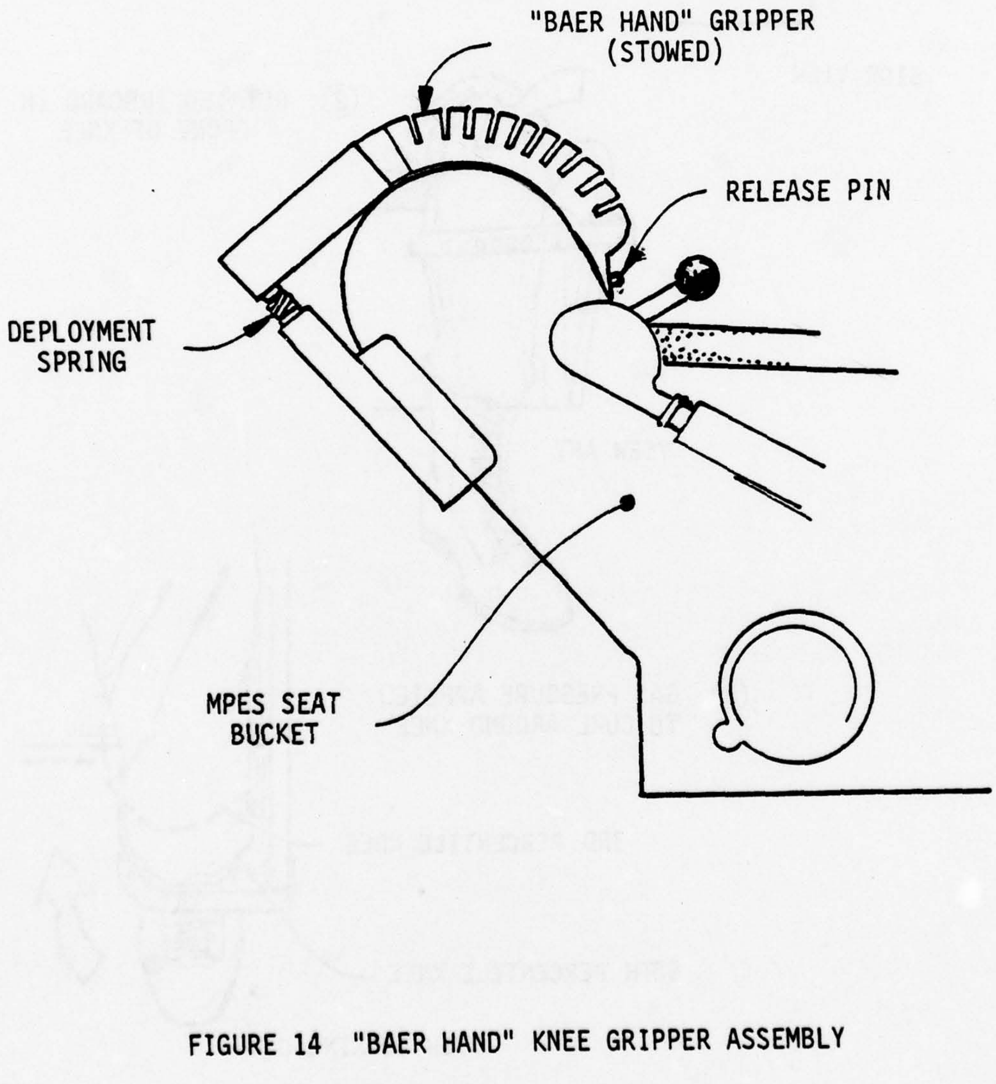

FIGURE 14 "BAER HAND" KNEE GRIPPER ASSEMBLY

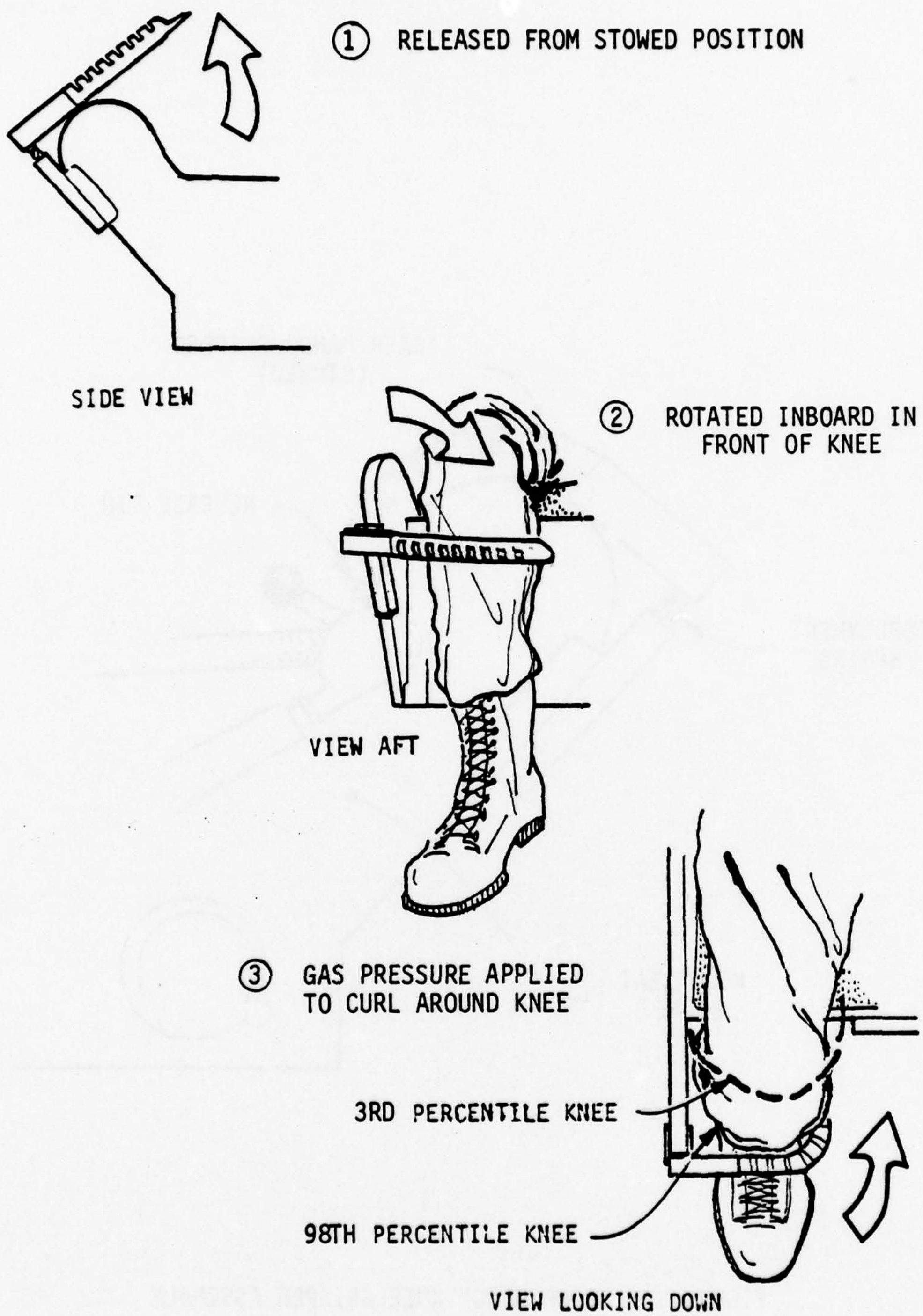

FIGURE 15 DEPLOYMENT SEQUENCE - "BAER HAND" KNEE GRIPPER ASSEMBLY

FIGURE 16 SUBJECT NO. 1
1ST-3RD PERCENTILE DIMENSIONS

FIGURE 17 SUBJECT NO. 2
40TH-60TH PERCENTILE DIMENSIONS

FIGURE 18 SUBJECT NO. 3
93RD-99TH PERCENTILE DIMENSIONS

The other design difficulty was sizing the arm restraint net to fit both small and large subjects. The net envelopes the subject and runs from one main restraint strap around behind and then to the opposite main restraint strap. A net fitted to the small percentile would contain the arms and shoulders of the large subject, but would apply tension in an outboard direction to the main restraint straps. This prevented the straps from reaching the proper position which is a straight line from the junction of the shoulder and neck to the inside of the knee. This problem was solved by a design compromise. The net was sized to favor the large percentile, which resulted in fullness in the elbow area of the smaller percentile. This compromise was considered to be acceptable because the purpose of the net is not to hold the arms in a specific position, but to contain the arms from egressing aftward.

An evaluation of the initial limb restraint harness assembly mock-up verified that this design would achieve that objective for the available population.

Conclusions from the evaluation of the initial preliminary design effort were that:

- A limb restraint harness assembly could be designed to fit the aircrew population from 3rd to 98th percentile without the need for manual adjustment.
- Strap tension could be equalized regardless of the specific seat occupant, providing their anthropometric dimensions were within the maxima and minima specified as standards for the 3rd through 98th percentile population.
- An alternative to the "Baer hand" gripper would have to be designed for use in the Gripper/Knee Restraint Assembly.

3.5 FIRST DESIGN ITERATION

The first design iteration started with the design of an inflatable bladder, to replace the "Baer hand", as the mechanism to deploy the strap over the knee and ended with an NADC review of a mock-up of the complete limb retention system.

Figure 19 shows the inflated shape and dimensions which were determined to be required for an inflatable bladder design to place the restraint strap inside of the knee. Patterns were made and several prototypes were fabricated of MIL-C-19002, Type I 6½-ounce per square yard, neoprene-coated nylon material. They were bonded with MIL-A-5030 adhesive and proved to have a maximum pressure capability of ten to fifteen psi.

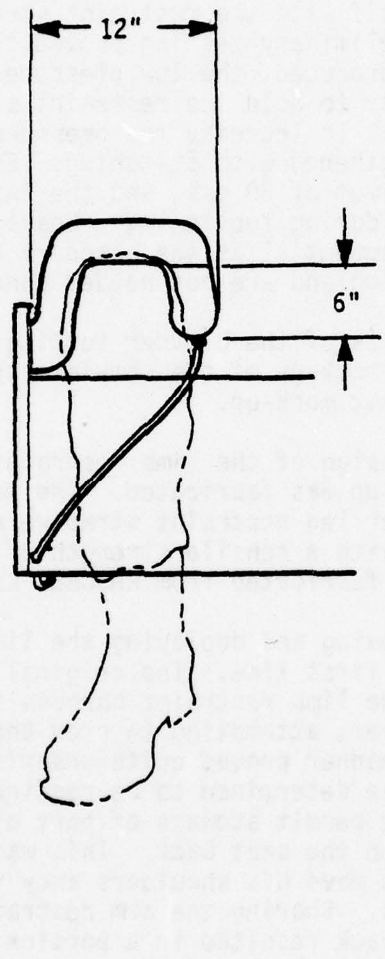

FIGURE 19 KNEE BLADDER DIMENSIONS

To achieve the desired position, it was determined that the inflation of the bladder had to be staged. As shown in the Figure 20 sequence, the bladder had to inflate from the root and extend vertically to clear the knee. Then it could inflate horizontally to the tip and thereby extend inboard to place the main restraint strap inside of the knee.

Several techniques were tried to achieve staged inflation. The most successful technique was that shown in the sequence. The bladder is stowed inside itself with the restraint strap attachment protruding from the tip. Preliminary testing proved that, while successful staging could be produced, the low pressure (10-15 psi) did not provide sufficient rigidity to hold the restraint strap into a fixed position during tensioning. To increase the pressure capacity, the adhesive joints were strengthened with stitching. Evaluations were made using shop air at a maximum of 30 psi, and the inflated bladders held the strap in position during tensioning. Leakage did occur, but this was considered inconsequential as the bladders accomplish their function at initial inflation and are not needed thereafter.

Based on the results of the bladder testing, it was decided to proceed with a functional mock-up of the complete system to be installed in the wooden MPES seat mock-up.

The preliminary design of the limb restraint harness assembly was completed and a mock-up was fabricated. The main (continuous) restraint strap and the upper leg restraint strap were fabricated of 3/4-inch wide Kevlar tape with a tensile strength of 3,500 pounds. The arm restraint net was fabricated from RASCHEL knit material.

The problem of stowing and deploying the limb restraint harness was addressed for the first time. The original proposed idea was to stow the majority of the limb restraint harness in the shoulder mounts (epaulets). However, attempting to stow the limb restraint harness assembly in this manner proved quite unsatisfactory. The harness geometry, which was determined to be required to gain adequate restraint, did not permit stowage of part of the restraint net in the epaulet and part on the seat back. This was because the seat occupant must be allowed to move his shoulders away from the seat back a distance of eighteen inches. Sharing the arm restraint net stowage between the epaulet and seat back resulted in a portion of the net being exposed between the occupant's back and the seat to allow for this movement. This arrangement was mocked-up, evaluated and rejected. The stowage concept was modified to stow the whole arm restraint net in a pad on the seat back. This necessitated adding an extra length to the main restraint strap. The resultant limb restraint harness geometry, in

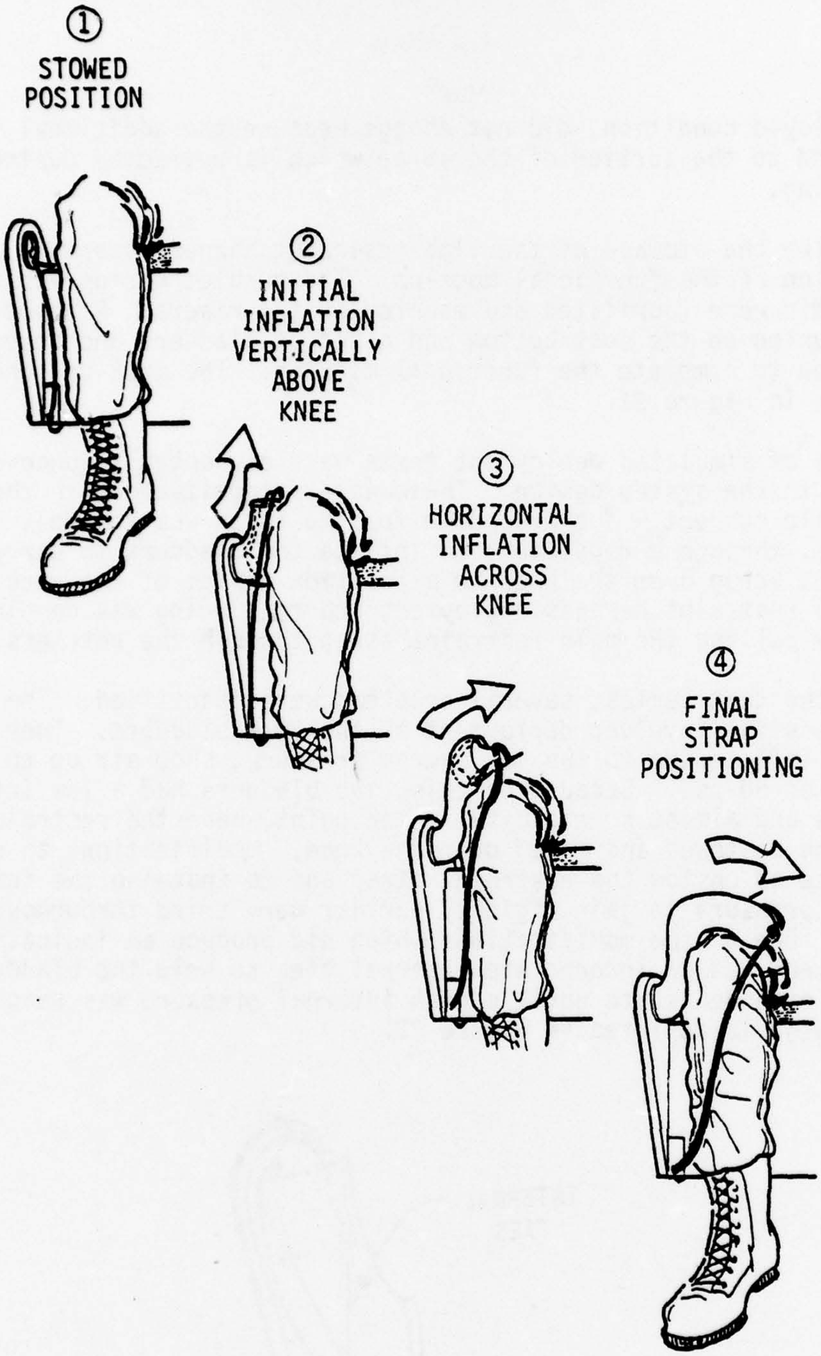

FIGURE 20 STAGED INFLATION CONCEPT
FOR THE INFLATABLE KNEE BLADDER

the deployed condition, did not change because the additional length was added to the portion of the strap which is retracted during tensioning.

Rectifying the stowage of the limb restraint harness assembly allowed completion of the functional mock-up. The epaulet design was finished and a pair were fabricated and mounted on the risers. Ratchet assemblies were mounted on the seat bottom and a set of bladders and hoses were installed to complete the functional mock-up. The mock-up configuration is shown in Figure 21.

A series of simulated deployment tests were conducted to uncover inadequacies in the system design. These were accomplished with the 50th percentile subject. The procedure for the tests was to apply shop air pressure, through a regulator, to inflate the bladders to carry the restraint strap over the knee to a position inside of the knee. Then the limb restraint harness deployment and tensioning was completed by manually pulling the main restraint strap through the ratchets.

During the test series, several problems were identified. The major problems still involved deployment of the knee bladders. They were slow to inflate due to the low source pressure, shop air up to a maximum of 80 psi. Because of this, the bladders had a low internal pressure and almost no rigidity at the point where the restraint strap was being unstowed and moved over the knee. Modifications to reduce the force to unstow the restraint strap and to increase the initial bladder pressure to gain rigidity earlier were tried throughout the series. One of the modifications which did produce an indication of an improvement was to incorporate internal ties to hold the bladder in a partial extended state until a high internal pressure was reached. This design is depicted in Figure 22.

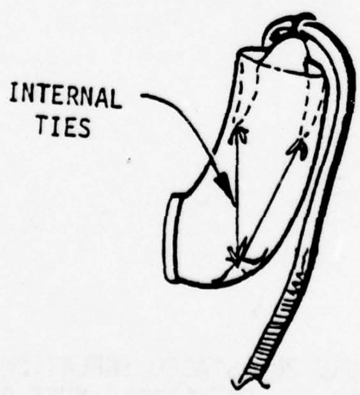

FIGURE 22 KNEE BLADDER INTERNAL RESTRAINING TIE CONCEPT

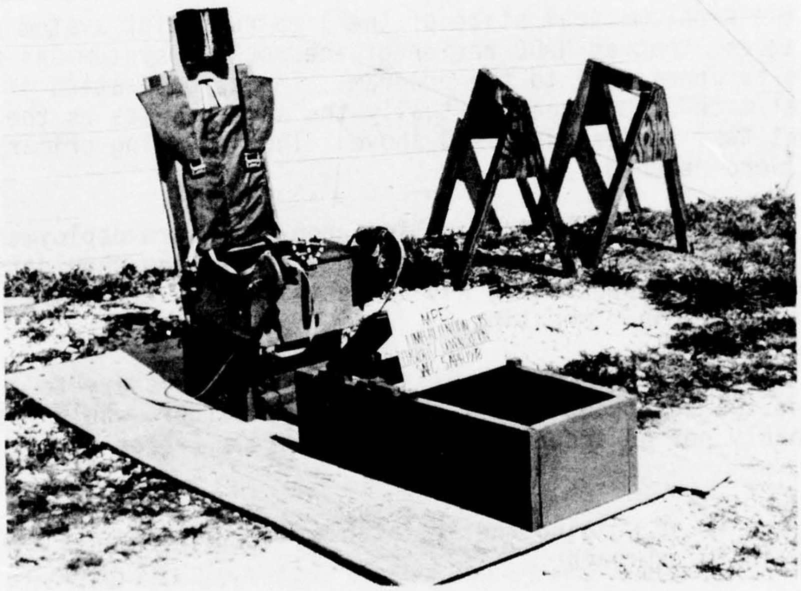

FIGURE 21 RESTRAINT SYSTEM MOCK-UP CONFIGURATION

The approach worked as predicted using a slow pressure rise. But, when the inflation process was speeded up by using high-pressure stored gas bottles, rupture of the bladder was usually experienced before failure of the ties. This design was still undergoing experimentation testing at the time of the NADC mock-up review.

A second problem identified by the simulated deployment testing was that repeatable deployment of the main restraint straps around the subject's shoulders was not demonstrated. The strap often fouled on the rear of the shoulders and would jam there when the restraint straps were tensioned. This problem was caused by insufficient stiffness of the epaulets and by the lack of stability of the mounting of the epaulets.

Despite the problematical state of the limb restraint system design, Stencel agreed that an NADC review of the mock-up system was necessary and would be beneficial to the program. The demonstration of the functional mock-up produced virtually the same results as the simulated deployment test series discussed above. The following primary conclusions were reached:

- The epaulets could not be relied upon to ensure deployment of the main restraint strap around and over the shoulders because the risers could not be restrained as necessary to gain a stable mounting.

- The large size of the epaulets, which was necessary to guide the strap deployment around the shoulder, would most probably not be acceptable to the aircrews (refer to Figure 21).

- The method of staging the inflatable knee bladder was not a reliable approach.

- All components of the limb retention system should be mounted on the seat structure.

- To ensure completion of limb positioning and restraint prior to exposure to the windblast, the limb restraint harness assembly must be deployed before initial seat motion.

- An independent powered strap retraction device should be investigated as an alternative to strap retraction by seat motion.

To the latter conclusion, Stencel responded that a vendor search to find a qualified powered strap retraction device had been made. The only qualified designs available were powered retraction inertia reels which were overdesigned and much too expensive to suit this application. Stencel agreed to examine a powered retraction design to meet the specific requirements of the limb retention system.

3.6 SECOND DESIGN ITERATION

The second design iteration started with a thorough review of the limb retention system design and the evaluation results, and a renewed effort to achieve a workable means of main restraint strap deployment and positioning. It ended with a second functional mock-up review at the Naval Air Development Center.

The review of the design and the evaluation results showed that while much effort had been expended and much had been learned, the critical design problems still remained to be solved. It was concluded that the limb restraint harness assembly was a satisfactory design for containment of the arms and for restraint of the legs, but that a reliable deployment approach still eluded solution.

The desire to introduce rigid mechanical members to deploy and position the main restraint strap became stronger. An example of such a design is the shepherd's crook shape mechanical leg retention device which was provided as a potential approach in the contract. This design was rejected, as were other mechanical approaches, because the device could act as a fulcrum over which bones could be broken. It would also have to be retracted after strap positioning to prevent interference with seat/man separation. This would necessitate the design of a complex mechanism to extend the device from a stowed position to a position above the knee, rotate into the strap holding position until strap tensioning was completed and then reverse the action to a retracted position prior to seat/man separation.

A compromise design was selected as the next approach to be investigated for deploying and positioning the lower portion of the main restraint strap. This device used mechanical means to unstow the restraint strap and elevate it above the knee and an inflatable bladder to carry the strap inboard across the knee. The sequence of operation is illustrated in Figure 23.

Gas pressure is introduced against a piston to force extension of the inner tube which includes a housing into which a bladder is stowed. At the full extended distance (x), determined based upon clearing the knee, the gas is ported into the bladder which inflates to carry the strap to the position required at strap tensioning.

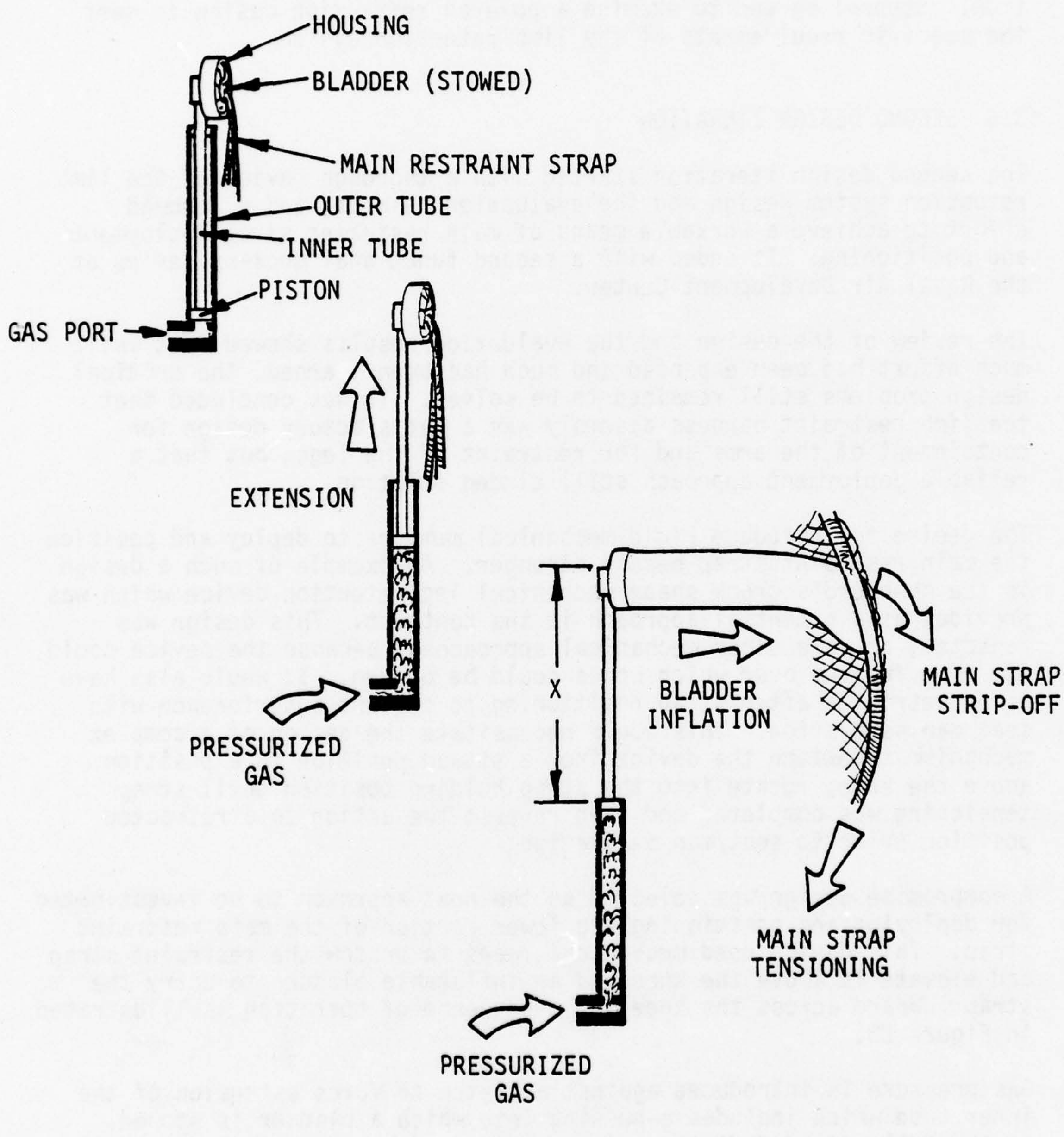

FIGURE 23 KNEE BLADDER/EXTENSION ASSEMBLY

As this action had to occur before seat motion, the aircrewmen's knees would be elevated as his feet were on the rudder pedals. To determine the dimension (x) required to clear the knees, measurements were taken of the subject population seated in a geometric mock-up of the MPES seat versus rudder pedal location. The dimensions for seat placement with respect to the rudder pedals and for rudder pedal throw were developed from several available aircraft crewstation drawings. Figures 24, 25 and 26 illustrate the 3rd, 50th, and 98th percentile subjects with the pedals adjusted in the most aftward position that the subject would use. The resultant measurements showed that at least eight inches of extension above the top of the seat side panel extension would be required to clear the knee.

A functional mock-up of the concept illustrated in Figure 23 was designed and fabricated to the eight-inch extended dimension. The mock-up was installed on the MPES side panel, tested, and performed successfully.

The problem of replacing the epaulets with a seat-mounted means of guiding the upper portion of the main restraint strap around the seat occupant's shoulders was then addressed. The MPES seat back width is approximately 17-1/4 inches. The bideltoid diameter (shoulder width) of the third percentile is 17.05 inches, of the 50th percentile 18.78 inches, and of the 98th percentile 20.64 inches. Therefore, for the limb restraint harness assembly to be deployed around the 98th percentile's shoulders from a stowed position on the seat sides, the main restraint strap would first have to be extended at least two inches outboard of each seat side surface. A simple lever mounted on each side and deployed by initial strap tensioning appeared to offer an easy solution. However, as the lever would have to be located at the highest point on the seat side, it would be in close proximity to the parachute risers. Stencel's experience during system testing has proven that the slightest protuberance in the riser area will result in fouling of and damage to the risers. Therefore, the mechanical lever was rejected in favor of a small inflatable extension (refer to Figure 27). This concept was mocked-up and evaluated with satisfactory results.

Stowage and deployment of the limb restraint harness assembly was addressed next. It was decided that the best approach would be to stow the limb restraint harness assembly in pouches mounted on each vertical face of the side panels. As in the first design iteration, it was again realized that the harness geometry required to provide adequate limb restraint was not dimensionally compatible with stowage. The distances between the fixed points are longer. In the deployed (restraint) position, each main restraint strap assumes the position

FIGURE 24
KNEE HEIGHT MEASUREMENT
3RD PERCENTILE SUBJECT

FIGURE 25
KNEE HEIGHT MEASUREMENT
50TH PERCENTILE SUBJECT

FIGURE 26
KNEE HEIGHT MEASUREMENT
98TH PERCENTILE SUBJECT

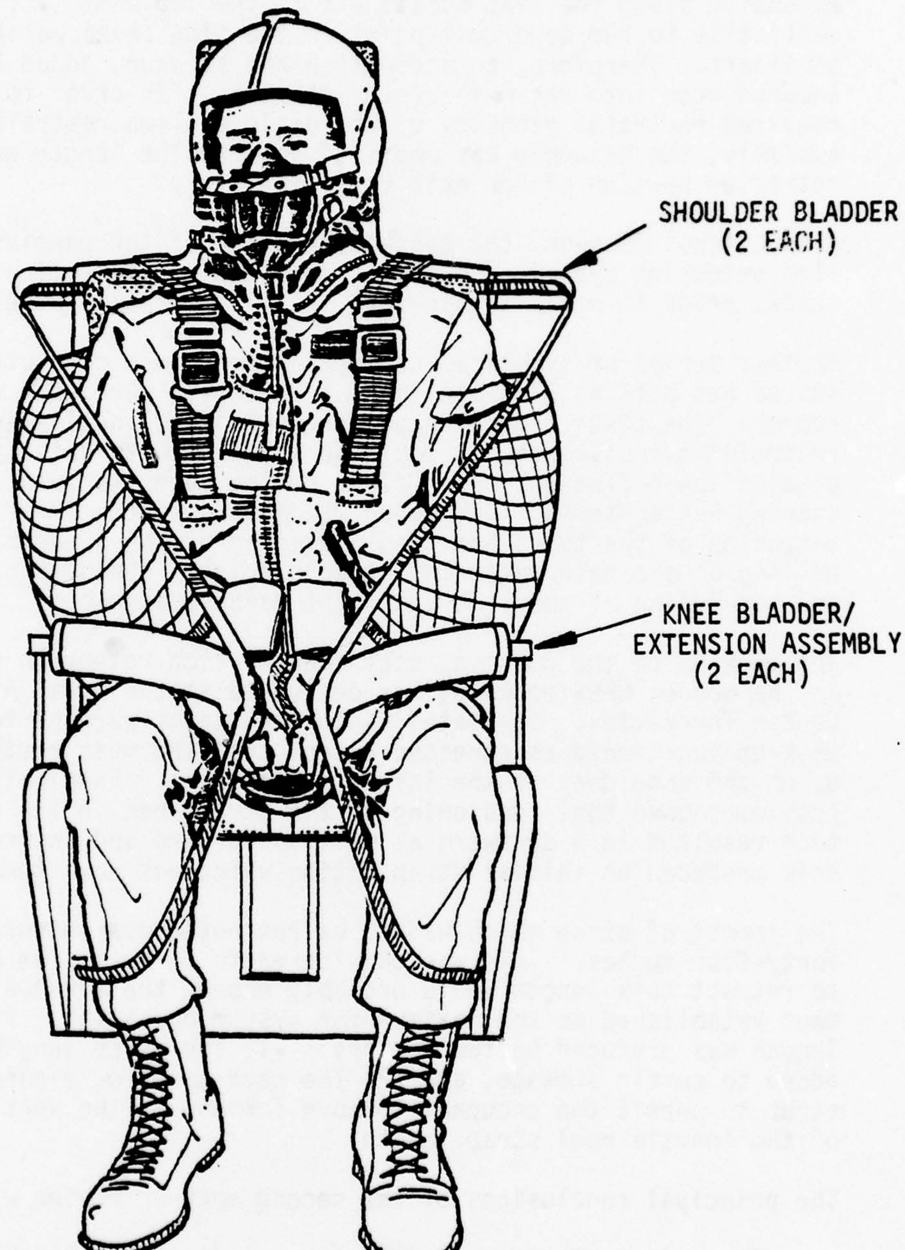

FIGURE 27 SYSTEM CONFIGURATION DEPLOYED -
SECOND DESIGN ITERATION

of the hypotenuse of a triangle which runs from the occupant's shoulders to the inside of his knees. In the stowed position, it must be long enough to run the length of the sides of the triangle, from front panel extension along the seat bucket aft to the lap belt fitting and then vertically to the uppermost point on the side panel behind the occupant's shoulders. Therefore, to accomplish the stowage, added length had to be incorporated into the main restraint strap. In order to maintain the required restraint geometry of the deployed limb restraint harness assembly, the assembly was modified so that the length was added to the retracted portion of the main restraint strap.

A functional mock-up, the second iteration of the passive seat-mounted limb retention system, was completed. The configuration in the deployed stage, prior to strap tensioning, is illustrated in Figure 27.

Another series of simulated deployment tests was conducted. High pressure stored gas bottles (4-cubic inch at 2500 psi) were used as the inflation source. The tests demonstrated that successful deployment of the limb restraint harness assembly could be achieved with this system design. By placing the inflation source close to the upper (shoulder) bladders, staging was achieved. The upper bladders inflated first, followed by extension of the tubes and then inflation of the lower bladders. Manual pulling of the main restraint strap completed deployment, positioning and tensioning of the limb restraint harness assembly.

The mock-up of the passive, seat-mounted limb retention system, installed in the wooden MPES mock-up, was delivered to the Naval Air Development Center for review. Simulated deployment tests were performed and the mock-up functioned as expected except that the main restraint strap hung up on the shoulders of the larger percentiles. Examination of this problem showed that tensioning of the strap when in its deployed attitude resulted in a downward as well as forward and inward force components. This produced an initial strap motion which was down toward the shoulders.

The amount of strap which had to be retracted was measured as being forty-four inches. This was considered to be excessive because the time to retract this length would probably exceed the 250-300 ms time requirement established as the maximum for system operation. The excessive length was produced by two factors: (1) The strap length which was added to permit stowage, and (2) The need to allow eighteen inches of strap to permit the occupant to move forward in the seat the full extent of the inertia reel strap length.

The principal conclusions of the second mock-up review were that:

- The main restraint strap must be positioned well above the shoulder level of all percentiles in order to ensure that unimpeded positioning of the strap would be reliably achieved.

- The changes made in the limb restraint harness assembly to accomplish stowage resulted in undesirable complexity.
- The length of strap which had to be retracted must be shortened to achieve system operation within the contractually established time requirement.
- The extension tubes of the lower (knee) bladder assembly could impede seat/man separation and a means of retracting them back to the stowed position should be investigated.

Stencel agreed to respond to these conclusions by accomplishing design changes prior to fabrication and delivery of the experimental feasibility prototype of the passive, seat-mounted, limb retention system.

3.7 THIRD AND LAST SYSTEM DESIGN ITERATION

The third design iteration proved to be the last effort required because it resulted in an acceptable functional experimental feasibility prototype of the passive, seat-mounted limb retention system. The effort started with another thorough design review to determine the design improvements needed to respond to the conclusions of the second mock-up review, and it ended with the delivery and successful demonstration of the contractually required prototype system.

After the system design review, a design effort was started to devise a method of retracting the lower (knee) bladder extension tubes. The approach involved the introduction of a second gas pressure signal above the piston and the opening of a port below the piston to vent the actuation pressure. While the mechanics of the approach are simple, the impact on the system design added undesirable complexity. It would require that a time delay initiator and another pressure source be introduced into the system.

This realization generated a reevaluation of the pure inflatable bladder to accomplish the function of over-the-knee strap positioning. The conclusion reached was that the general approach tried during the first design iteration was correct and that only the method of staging the bladder was unworkable. The inflating bladder had to be integrated into the system in a way which allowed it to be fully pressurized <u>before</u> it deployed the main restraint strap. Experimentation was accomplished which proved that this could be achieved by a proper stowage arrangement and the rapid introduction of high pressure gas. The initial knee bladders were fabricated of MIL-C-19002, Type I, 6½-ounce per square yard, neoprene-coated nylon material. They were cemented with adhesive and the seams were reinforced with stitching. This was necessary because the internal working pressure was 40-60 psi. The bladders were stowed in pockets on the side of a seat cushion. They inflated out of the pocket pointing aftward, and as the process continued to full pressure, they swept upward and forward towing the main restraint strap over and to a position immediately in front of the knee. The stowed position is shown in Figure 28. For added detail on the stowage arrangement, refer to the stowage instructions in Appendix A hereto.

The upper (shoulder) bladder was substantially changed from the second mock-up configuration. It was increased in size and made a modified "C" shape to provide two attachment legs to improve its stability when inflated. Several configurations of the bladder design were fabricated in the same manner as the knee bladders, and evaluation tests were conducted. The bladders, along with the upper portion of the main restraint strap and the arm restraint net, were stowed in pockets on either side of a back pad (refer to Figure 28). For additional detail on this stowage arrangement, refer again to Appendix A.

The upper portion of the main restraint strap was positioned along the leading edge of the bladder with Velcro. Inflation tests showed that the bladder positioned the main restraint strap forward and above the 98th percentile's shoulders and held it there preparatory to positioning.

One side of a full limb retention system was fabricated for testing. The inflation source, gas under high pressure, was positioned nearer the upper bladder so that it would complete its inflation slightly ahead of the knee bladder. After many adjustments, it was found that the limb retention harness would be fully deployed and properly positioned around the subject's torso solely by the force applied by the knee bladder (refer to Figure 29). Subsequent retraction and tensioning of the main restraint strap stripped the lower portion of the main restraint strap from the knee bladders to the leg restraint position across the subject's calves.

During the testing described above, several changes were made in the limb restraint harness assembly to overcome the deficiencies identified by the second mock-up review. The restraint strap routing was changed. The original harness had a main restraint strap running continuously from the occupant's shoulders to the knee, around the calf and then through the ratchets. The upper leg restraint strap was attached to the main strap and ran from it across the upper leg to the seat/lap belt release fitting. The redesigned harness shown in Figure 30 has a strap running from the shoulder attachment to a fitting inside of the upper leg and then across the upper leg to the seat/lap belt release fitting. To this fitting is attached a strap which runs past the inside of the knee, around the calf and then through the ratchets. While the basic restraint

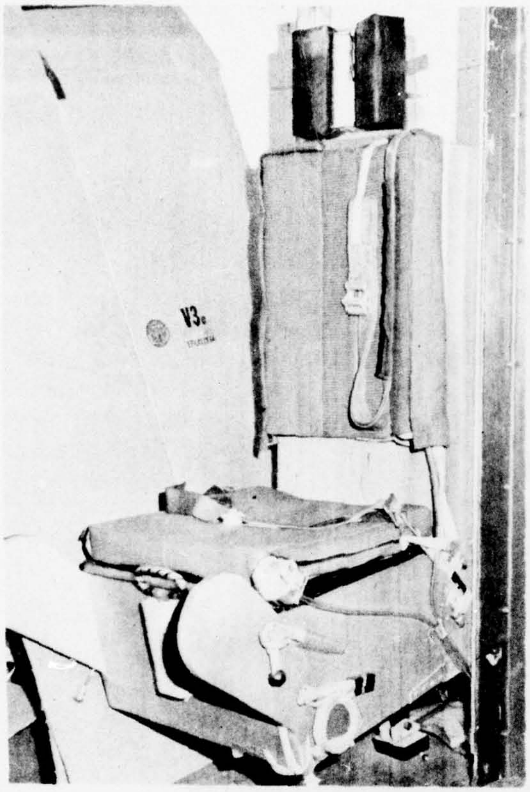

FIGURE 28 PROTOTYPE LIMB RETENTION SYSTEM STOWED

FIGURE 29 PROTOTYPE LIMB RETENTION SYSTEM DEPLOYED

FIGURE 30 LIMB RESTRAINT HARNESS ASSEMBLY - FINAL CONFIGURATION

configuration of the harness is not changed, this strap rerouting permitted stowage of the assembly without adding extra strap length.

Also, the need for an extra eighteen inches of strap to allow for forward movement in the seat was eliminated. This was simply done by adding a loop to the upper end of the restraint harness strap at the exit of the inertia reel strap. The loop allows the inertia reel strap to payout without disturbing the restraint harness strap which remains in position at the inertia reel strap exit. When the limb restraint harness assembly is deployed, the loop is pulled free and rides along the inertia reel strap until it is constrained at the junction of the inertia reel strap and riser.

The testing demonstrated that these design changes resulted in a reduction in the length of strap which has to be retracted from forty-four inches to fourteen inches. Retracting this length of strap can be most efficiently and economically accomplished using a force generating webbing ripper energized by initial seat motion. This is the design used in our SIIIS-3 seat. This approach was considered to be the most suitable for the planned ejection tower testing of the delivered prototype. Therefore, the design of a new powered strap retraction device was not completed under this program.

The experimental feasibility prototype of the passive, seat-mounted limb retention system was completed and installed in the prototype MPES seat structure. Several system actuations were made in order to demonstrate the system's functional reliability and deployment repeatability prior to contract delivery. The test results were completely satisfactory.

The prototype system was delivered to the Naval Air Development Center, and three successful demonstrations were accomplished before a number of NADC personnel. Figures 31 and 32 are copies of official U. S. Navy photographs taken at that demonstration. They show the system in the stowed configuration prior to actuation and deployed as it was being demonstrated.

After demonstrating the restraint function the third time, the question was raised as to how the limb restraint harness assembly would be released to permit separation of the ejectee from the seat. The release function is accomplished by the normal MPES functions of inertia reel strap cutting and lap belt release. To demonstrate this operation, these release functions were simulated. The upper ends of the restraint harness straps were separated from the inertia reel straps and the ends of the upper leg restraint strap were separated from the lap belt fittings. This permitted the subject to stand up and walk from the seat without any impediment.

FIGURE 31 PROTOTYPE SYSTEM STOWED

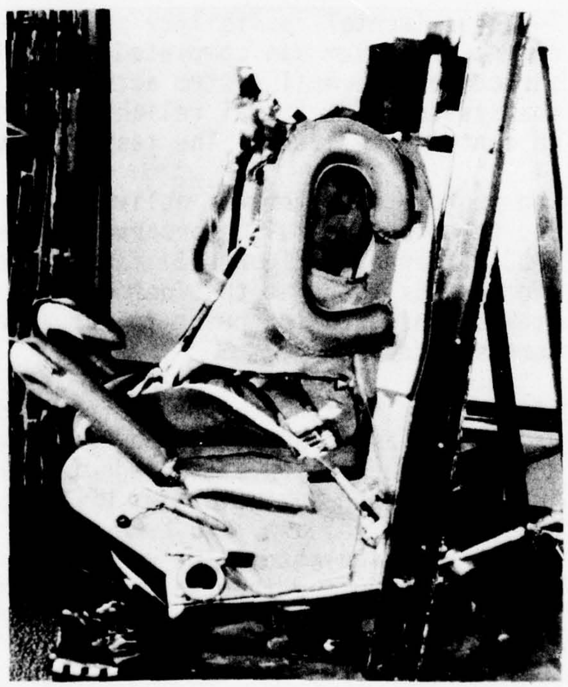

FIGURE 32 PROTOTYPE SYSTEM DEPLOYED

The final subject discussed at the demonstration was what pressure source would be used to actuate an operational system. Stencel responded that a pyrotechnic gas generator, similar to those being used to inflate automotive inflatable impact bags would be the preferred approach. Talley has demonstrated a small gas generator which inflates a one-cubic foot bag to 50 psig. This unit is approximately 4½ inches in diameter by 1½ inches thick and would integrate easily into the MPES seat system. As this unit provides over twice as much gas volume as required by the limb retention prototype, an actual unit designed for this application could be considerably smaller. The determination of the final inflation unit size should be made after the final inflatable volumes have been established.

The demonstration was concluded with a NADC statement that the next planned phase of the passive, seat-mounted, limb retention system would include feasibility testing of the prototype, first by ejection tower tests and then by exposure to windblast equivalent to 600 knots.

Section 4

SEQUENCE OF OPERATION - PASSIVE, SEAT-MOUNTED LIMB RETENTION SYSTEM

4.1 SYSTEM DESCRIPTION AND EJECTION SEQUENCE

The experimental feasibility prototype of the passive, seat mounted limb retention system produced by this effort is shown in Figure 31 in the stowed position in the MPES seat. The system is about to be actuated for the demonstration test at the Naval Air Development Center. As can be seen from this photograph, the system is completely seat mounted, primarily in the back and bottom cushions. The aircrewman is not required to don or hook up anything. In Figure 32 the system has been actuated and the limb restraint harness assembly has been deployed and tension has been applied to capture and restrain the arms and legs.

As Figure 32 illustrates, inflatable bladders are used to deploy a limb restraint harness assembly. The harness includes 3500 pound Kevlar straps and netting which accomplish the actual restraint. The bladders may be inflated by gas generators of the type used in inflated automotive impact systems or by high pressure stored gas.

The sequence of operation during an actual ejection would be as follows:

The Limb Retention System is initiated by actuation of the ejection control (Figure 33). In 150 milliseconds four bladders have inflated, two over the aircrewman's knees and two around his upper torso. This is accomplished just before the seat begins its travel up the rails. Simultaneously, the power retraction inertia reel pulls the upper torso to the seat back. The shoulder bladders inflate slightly ahead of the knee bladders, positioning the main restraint harness forward of and higher than the occupant's shoulders. The force applied by the inflating knee bladders causes the restraint straps to strip off of the shoulder bladders to positions down across his shoulders and with the aid of the restraint net sweeps the arms inboard and captures them. The initial seat motion causes the portion of the straps positioned over the knee to strip off of the knee bladders and to be tensioned across his upper legs and down the inside of each knee and across his calves as shown in Figure 34. The arm restraint netting, attached to the strap network, is tensioned around each arm cradling and restraining the elbows. It should be emphasized that, because the strap deployment motion is over and around the shoulders and the upper arms, the arms are swept inboard toward the center of the seat. This motion was selected because the position of the arms and hands cannot be predicted during sequenced crew ejections; but the location of the shoulders,

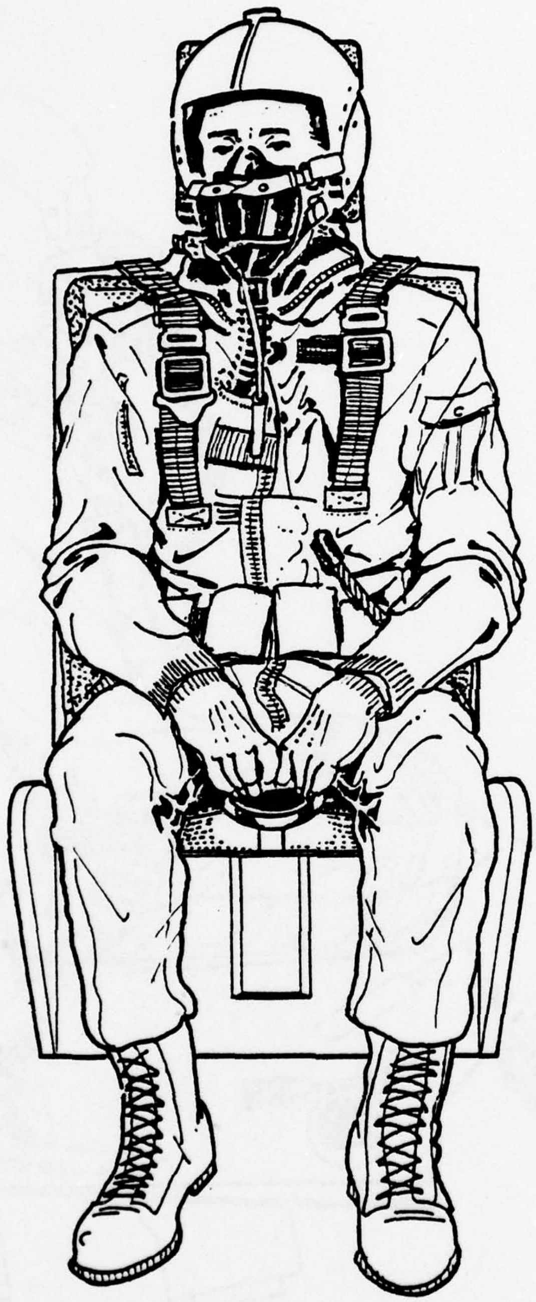

FIGURE 33 (1 of 2) EJECTION INITIATION

FIGURE 33 (2 of 2) EJECTION INITIATION

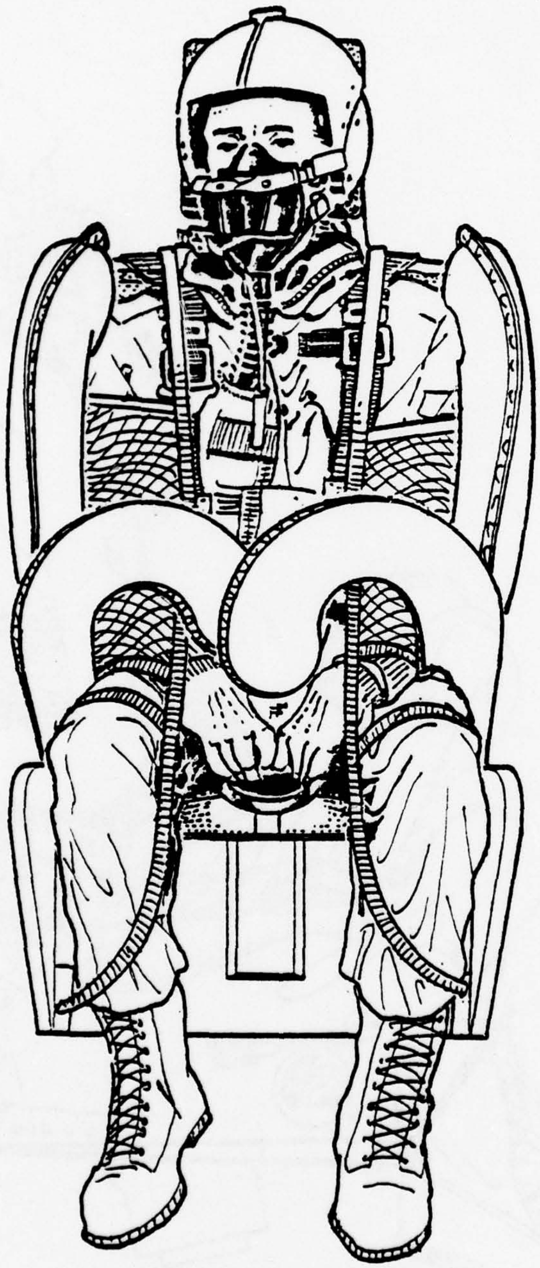

FIGURE 34 (1 of 2) SYSTEM AT INITIAL SEAT MOTION

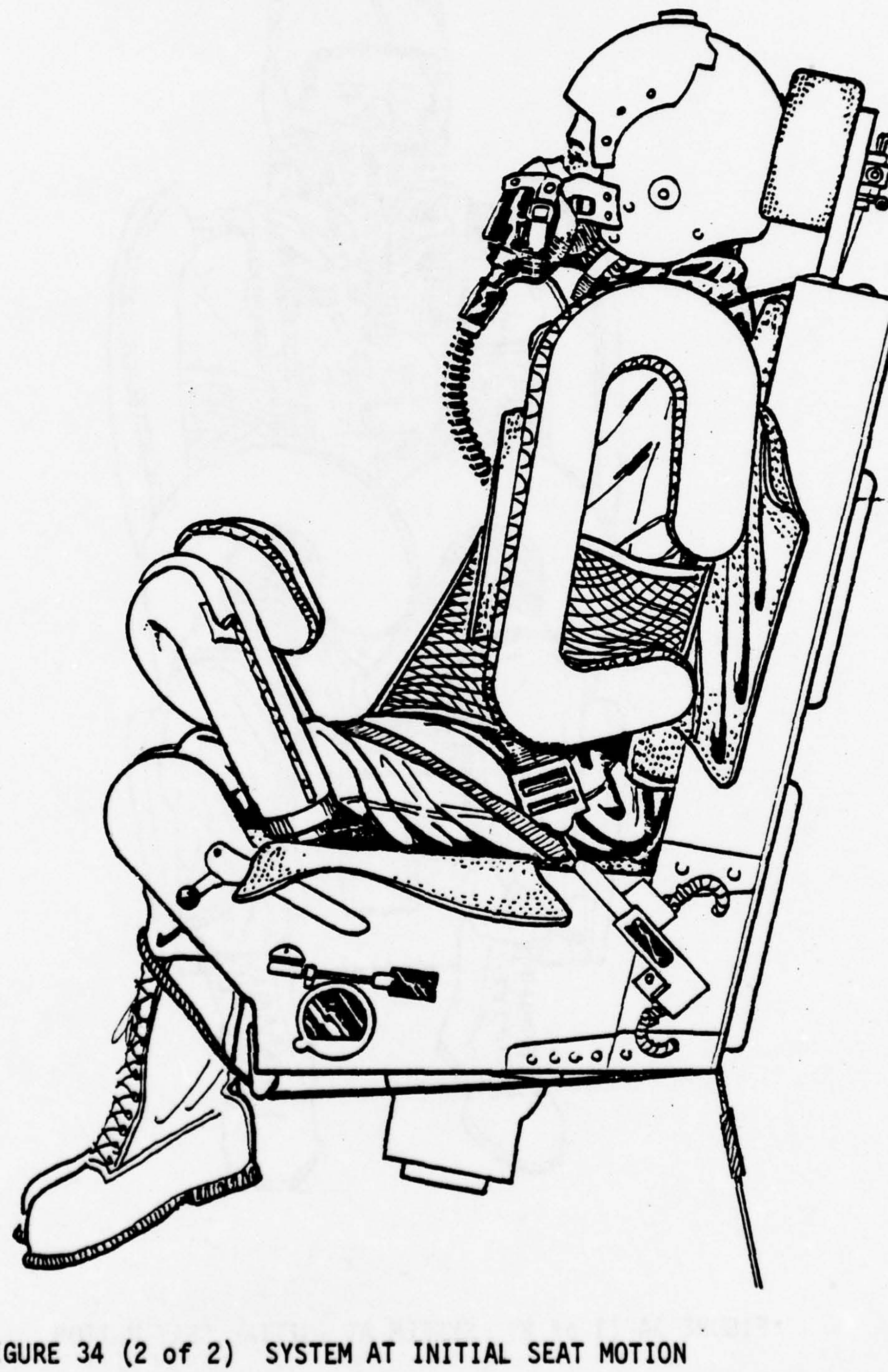

FIGURE 34 (2 of 2) SYSTEM AT INITIAL SEAT MOTION after powered haulback, is known. Further travel of the seat initiates a webbing "ripper" mechanism to generate a constant force to achieve leg retraction and to ensure that adequate, but noninjurious, tension force is imparted to the straps. When the "ripper" separates, detaching the cockpit portion of the restraint straps, a strap snubber ensures that the tension force is maintained by preventing the straps from loosening.

As the seat leaves the aircraft and enters the windstream (Figure 35), the bladders have deflated and either trail into or are torn loose by the windstream. The strap and netting retain the limbs - the legs against the seat side panel extensions, and the arms in toward the center of the seat and pinned to his body. The netting prevents the elbows and arms from egressing rearward into the windstream.

The restraint is maintained up to the point of seat/man separation when the restraint straps are released by the normal action of inertia reel strap cutting and lap belt release. The limb restraint harness assembly remains with the seat after seat/man separation to preclude interference with survival kit deployment and subsequent survival actions. (Figure 36).

In the final passive seat mounted limb retention system, the strap retraction and tensioning could be accomplished by a powered strap retraction device. This would permit completion of all deployment, strap positioning and restraint actions prior to initial seat motion.

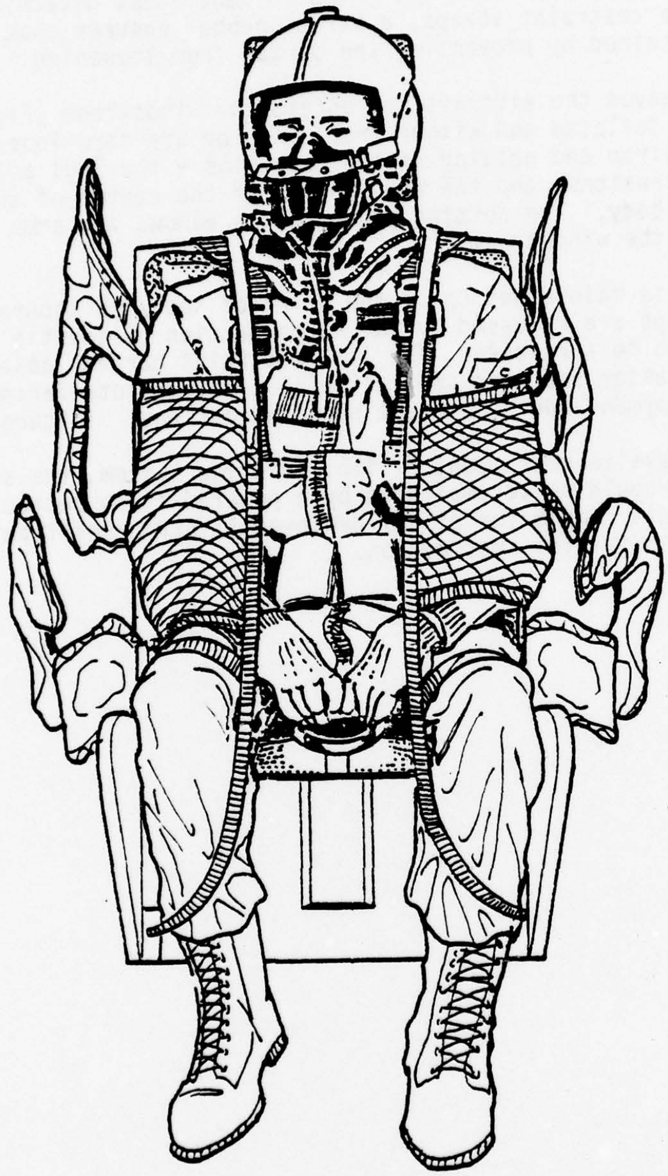

FIGURE 35 (1 of 2) SYSTEM AT ENTRANCE TO WINDSTREAM

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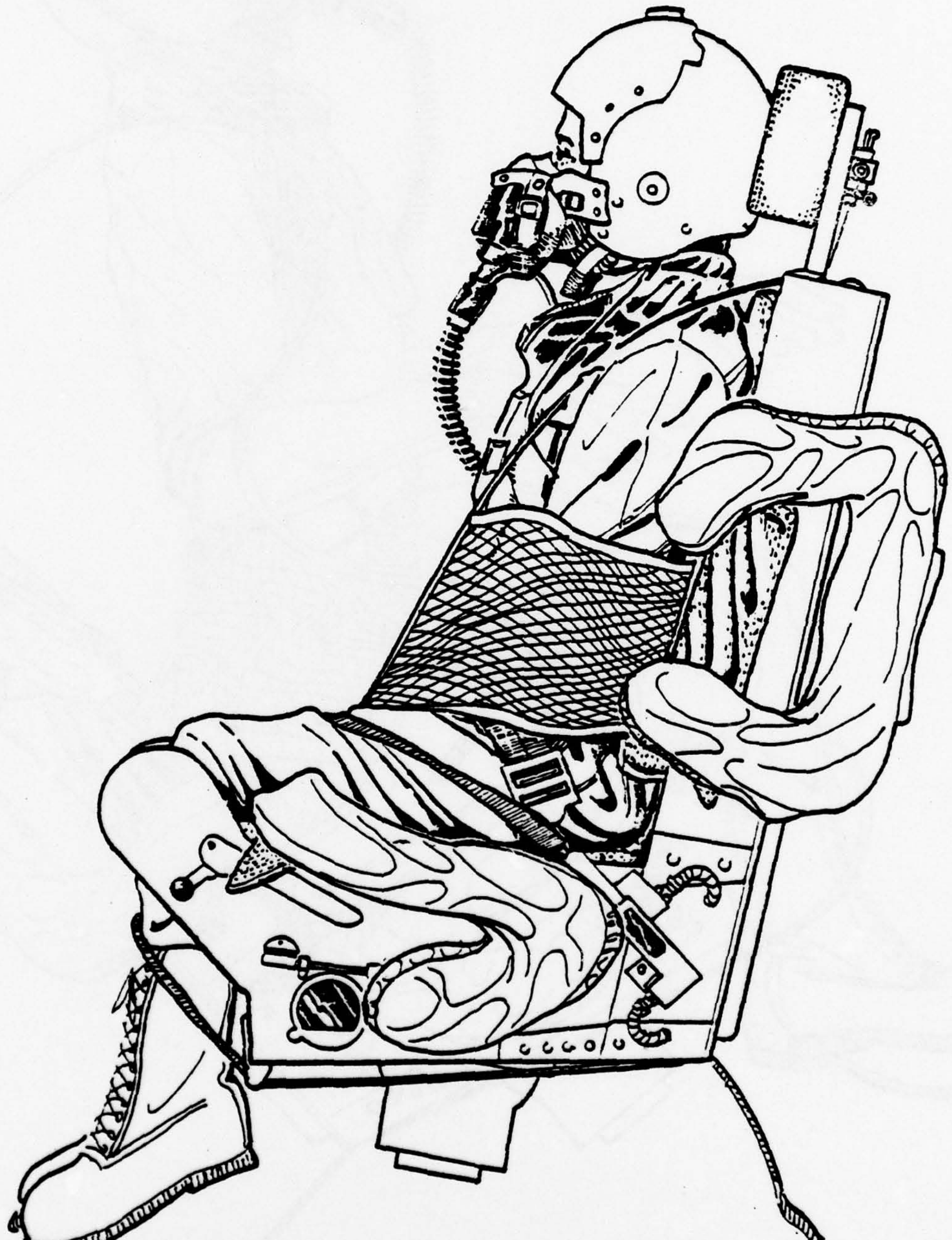

FIGURE 35 (2 of 2) SYSTEM AT ENTRANCE TO WINDSTREAM

FIGURE 36 SYSTEM RELEASE AT SEAT/MAN SEPARATION

Section 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The development effort accomplished under Naval Air Development Center Contract N62269-77-C-0251 and the research and analysis into the combat injury experience in Southeast Asia provide a basis for the following conclusions:

- A limb retention system that is completely passive is feasible. Restraint of the limbs can be achieved without requiring the aircrewman to wear any additional garments nor accomplish any added connections or disconnections upon aircraft ingress or egress.

- The development effort completed under the contract cited above successfully produced a functional, experimental feasibility prototype of a passive, seat-mounted limb retention system as required by the contract.

- The combat injury experience generated by the Southeast Asia conflict documents an urgent need for a limb retention system in all ejection seat systems. Restraint of the arms as well as the legs is required, and, to prevent all flail injuries, positive restraint of the head must also be accomplished.

- The feasibility prototype developed and demonstrated under the program is a promising approach for providing protection against limb flail injuries in all operational escape systems. It is considered to be capable of further development to meet all of the requirements and criteria enumerated in Section 3.

5.2 RECOMMENDATIONS

The following recommendations are made based upon the successful effort reported herein and on the conclusions stated above:

- The design of the prototype passive, seat-mounted, limb retention system delivered to NADC should be verified and its feasibility demonstrated by ejection tower testing and by exposure to windblast equivalent to 600 KEAS.

- Contingent upon the feasibility testing, the development should be continued to produce a design suitable for verification testing through ejection tower testing with live subjects and incorporation on the ejection tests planned for the Maximum Performance Ejection Seat System.

- The next development effort for the passive, seat-mounted, limb retention system should include the following major activities:

  Final design of the inflatable deployment components including the selection of a more weight efficient coated fabric.

  Design of a self-contained inflation source which is compatible with the limb retention system design and the MPES seat configuration.

  Design and testing of a powered strap retraction device to meet the requirements of the limb retention system.

  Final design of the limb restraint harness assembly and its stowage in the MPES seat.

  Design and development of the NADC head restraint device as an integral part of the limb retention system.

- A plan be prepared for the completion of development, design verification testing and service release testing, and operational installation of the passive, seat-mounted, limb retention system in all U. S. Navy high performance aircraft.

APPENDIX A

RIGGING AND PACKING INSTRUCTIONS

FOR

PROTOTYPE PASSIVE, SEAT-MOUNTED

LIMB RETENTION SYSTEM

1.0 INTRODUCTION

The passive, seat-mounted, limb retention system provides protection against limb flail injuries during ejection. The system is completely seat-mounted and is stowed primarily in the back and bottom cushions of the ejection seat. Once stowed, the system deploys automatically upon ejection initiation and provides restraint of the ejectee's arms and legs without the necessity of any manual connections or other pre-ejection operations.

2.0 REQUIRED GROUND SUPPORT EQUIPMENT

A standard air pump having an inflation and a vacuum capability is required to aid in rigging and packing the system.

3.0 RIGGING AND PACKING PROCEDURES

The rigging and packing procedures required to stow the prototype limb retention system are described and illustrated in the following text and photographs.

Figures 1 and 2 illustrate the prototype system in the deployed state. The system consists of two knee bladders, two shoulder bladders, a limb restraint harness assembly, dual webbing ratchets, and two force generating "ripper" assemblies. Inflation of the prototype system is accomplished by a stored gas source which is connected to the four bladders by tubing.

3.1 The initial step in rigging the system is to connect the tubing to an air pump and inflate the bladders to 15-20 psi pressure.

3.2 Insert the end of the lower portion of the restraint strap on each side through the ratchets mounted on the bottom of the seat bucket (as shown in Figures 1 and 2) and connect the inserted end to the webbing "ripper" assembly.

3.3 Rig each side of the lower portion of the restraint strap to the knee bladder by mating the Velcro halves. Start at the inboard tip of each bladder and follow the contour. Fold the Velcro tabs at each end of the bladder contour over the strap to lock the strap in place. The completed rigging is illustrated in Figures 1 and 2.

FIGURE 1

FIGURE 2

3.4 Attach each side of the upper restraint harness strap to the lower portion of the restraint strap. Insert the loop on the lower end through the roller assembly and secure the loop at the lap belt seat attachment as shown in Figure 2.

3.5 Attach the upper end of the restraint harness assembly to the inertia reel. Disconnect the inertia reel straps at their riser attachment and slip the loop in the upper end of the restraint harness, each side, over the inertia reel straps. Reconnect the inertia reel straps to each riser. The completed rigging is illustrated in Figure 3.

3.6 Place the air pump in the vacuum mode and evacuate the air in the bladders as illustrated in Figure 4.

3.7 Ensure that each side of the restraint harness assembly is rigged as illustrated in Figure 5 prior to starting the packing.

3.8 Start the packing of each side of the restraint harness assembly and inflatable bladders by packing the knee bladder and attached restraint straps first. Lift the knee bladder up and turn the bladder edge with strap attached aftward, placing a 90^0 twist at the base of the bladder as shown in Figure 6.

3.9 Retaining the 90^0 twist, lay the bladder aftward and down toward the seat cushion so that the edge with strap attached is parallel with the edge of the seat cushion. Place your left hand midway up the bladder and fold the bladder forward. These steps are illustrated in Figure 7 and the completed fold is shown in Figure 8.

3.10 As illustrated in Figure 9, fold the lower edge of the bladder up and place the folded edge parallel to and at the bottom edge of the seat cushion flap junction.

3.11 As illustrated in Figure 10, take the portion of the bladder above that just folded in Step 3.10 and fold it down over the previously folded portion. Then fold the tip end of the bladder up as shown in Figure 10.

FIGURE 3

FIGURE 4

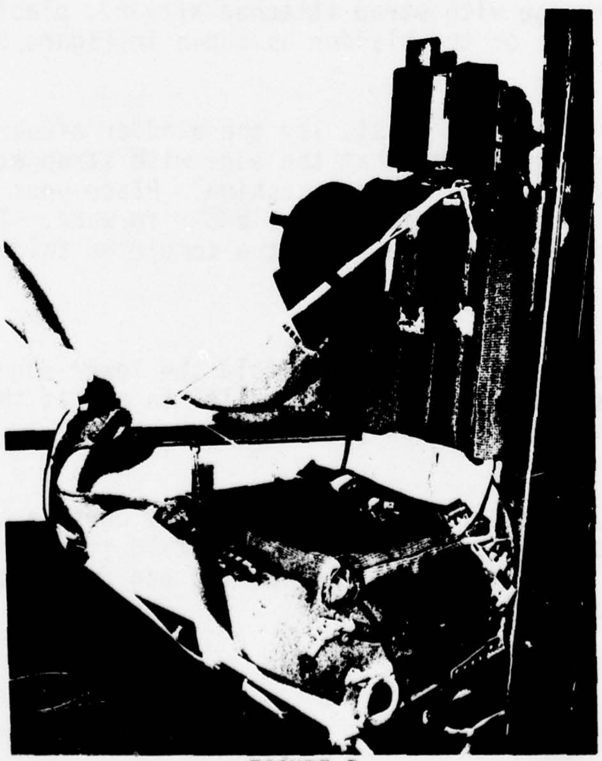

FIGURE 5

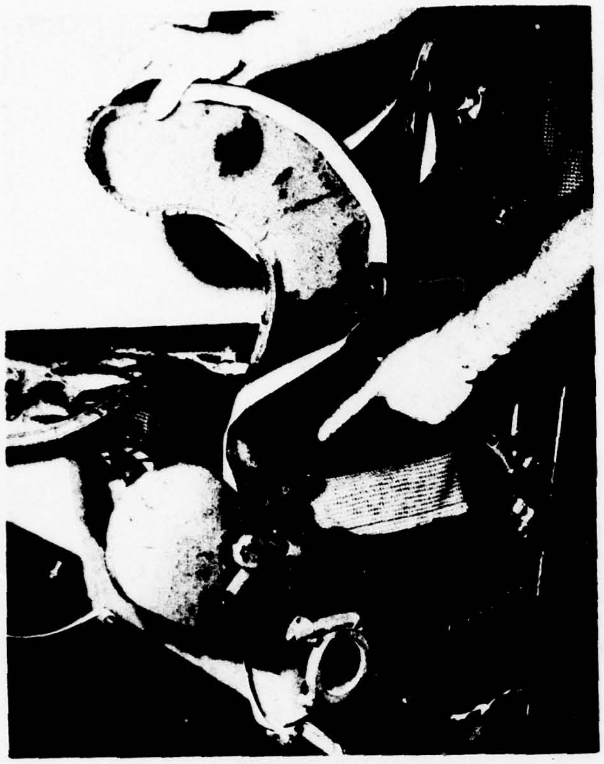

FIGURE 6

FIGURE 7

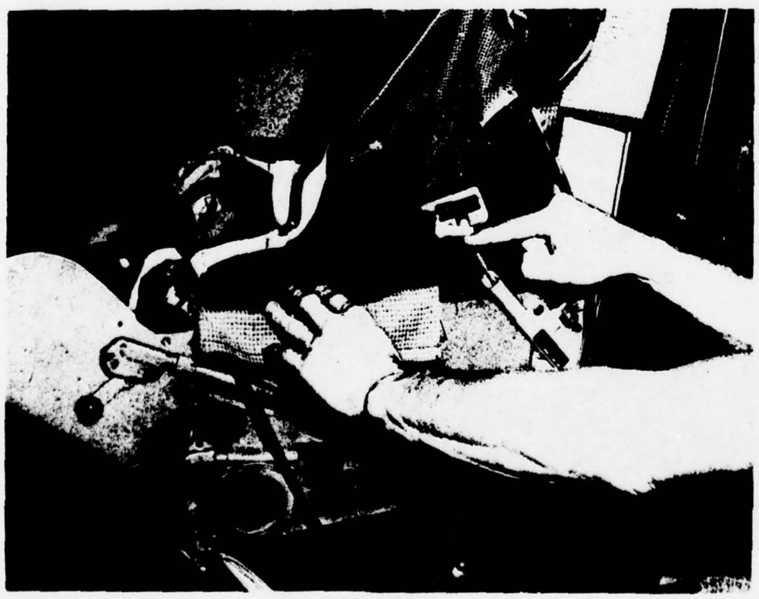

FIGURE 8

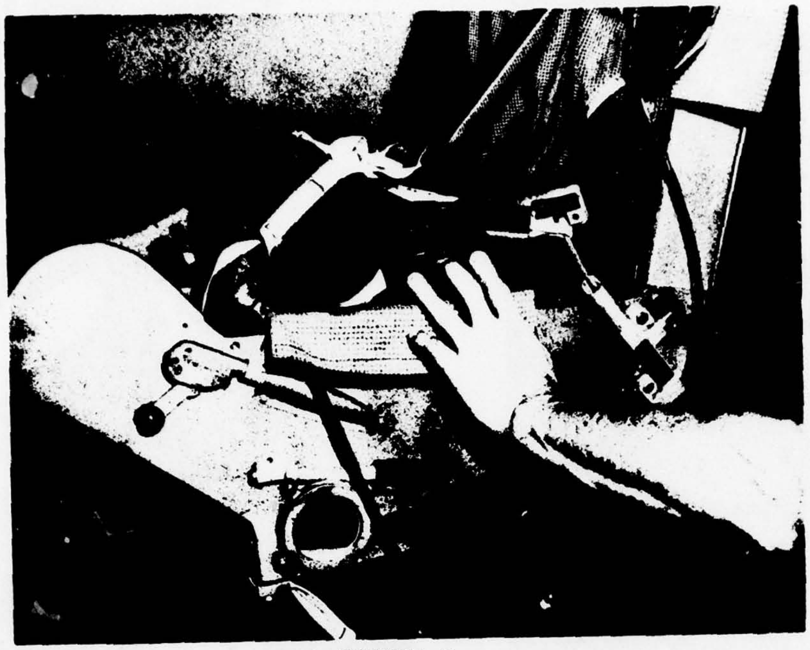

FIGURE 9

FIGURE 10

3.12 Retain the folded bladder with the left hand as shown in Figure 11 and position the strap and roller assembly as shown.

3.13 Place the portion of the bladder being held in the left hand along the bottom edge of the seat cushion at the junction of the flap and tuck the upper portion down behind as shown in Figure 12. Ensure that the strap and roller assembly lies between the folded bladder and the cushion as shown in Figure 12.

3.14 As shown in Figure 13, close the seat cushion flaps over the folded bladder and strap starting at the rear and working forward. The completed packing arrangement and strap position should be as shown in Figure 14.

3.15 Repeat Steps 3.8 through 3.14 to stow the other knee bladder and the attached restraint straps.

3.16 The rigging and packing of the shoulder bladders and the attached portion of the restraint harness assembly is started as illustrated in Figure 15. Extend the bladder forward and mate the Velcro on the strap to the Velcro on the leading edge of the bladder and fold the locking tap over the strap as illustrated.

3.17 With the bladder extended forward, grasp the bag as shown in Figure 16 and start an accordion fold into the shape of a "W" when viewed from the top. Complete the accordion fold as shown in Figure 17. The completed fold should look as shown in Figure 18 with the leading edge of the bladder, with strap attached, facing forward.

3.18 As illustrated in Figure 19, tuck the arm restraint netting between the outboard and adjacent portions of the folded bladder. The completed folded bladder, with netting stowed, should look as shown in Figure 20.

3.19 Complete the stowage of the shoulder bladder and attached restraint harness assembly by securing the flaps of the back pad as shown in Figure 21. Start from the bottom and tuck in the bladder as necessary to close the flaps securely.

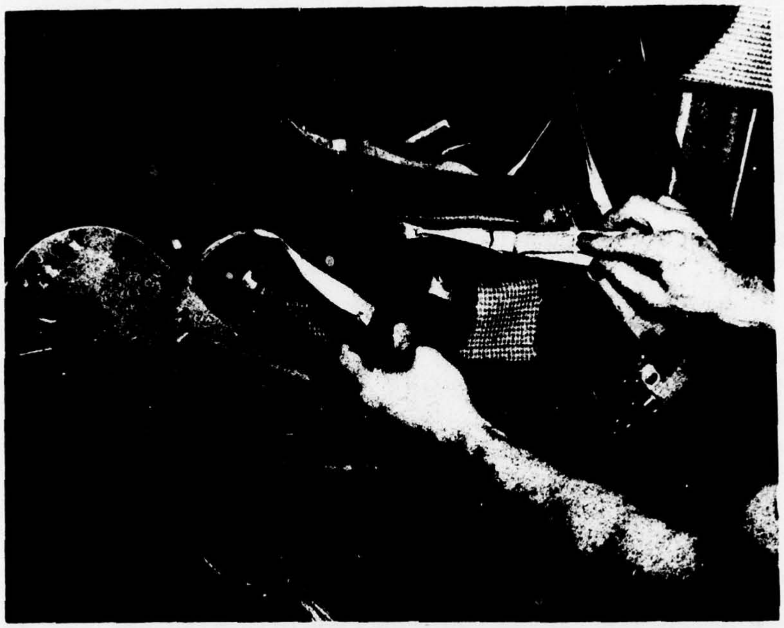

FIGURE 11

FIGURE 12

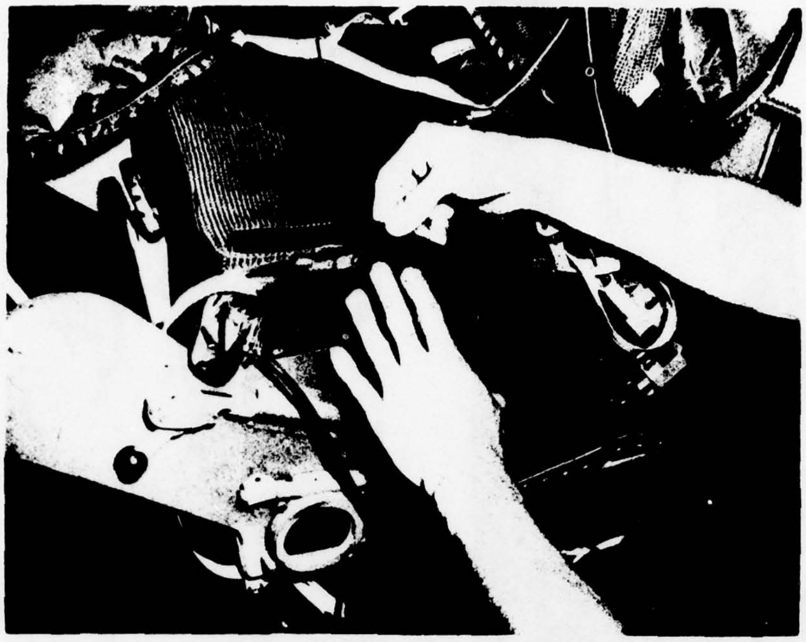

FIGURE 13

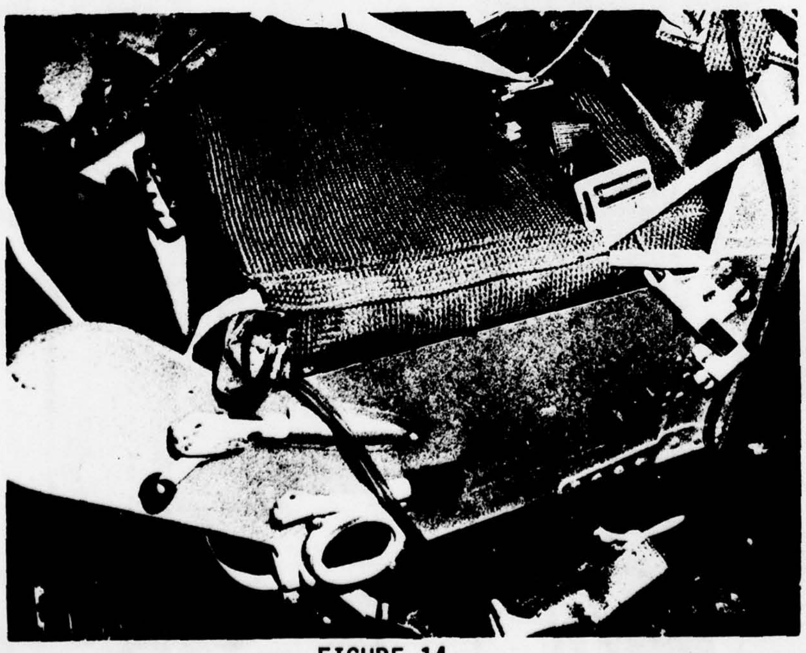

FIGURE 14

FIGURE 15

FIGURE 16

FIGURE 17

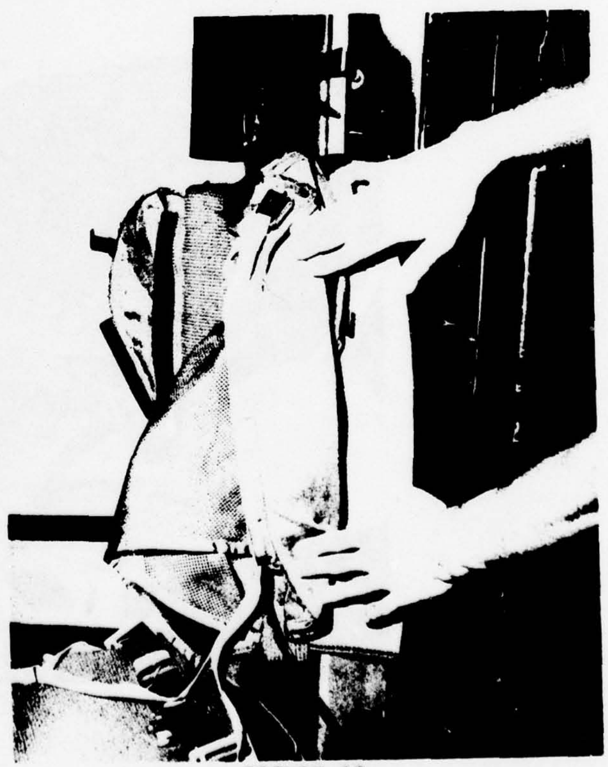

FIGURE 18

FIGURE 19

FIGURE 20

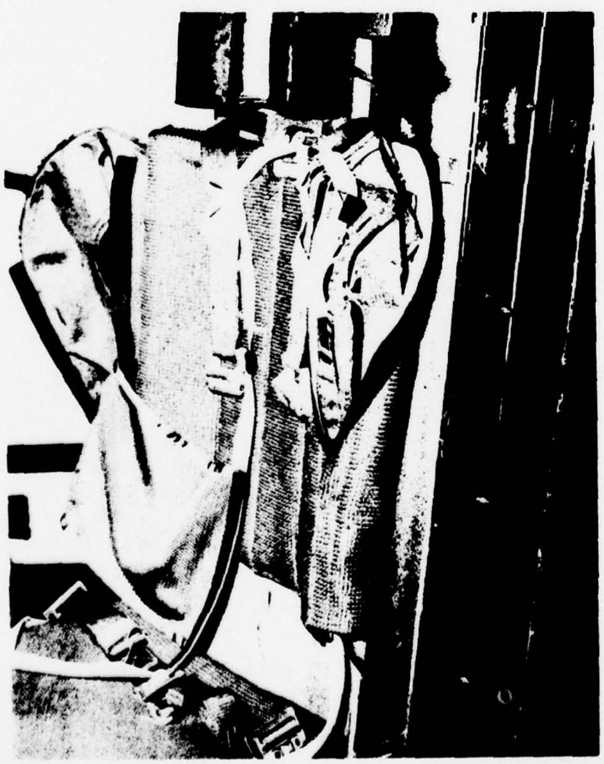

FIGURE 21

3.20 To complete the flap closure, fold the excess bladder material extending above the back pad down and tuck it in as shown in Figure 22, and then close the flaps.

3.21 Ensure that the end of the upper portion of the restraint strap passes over the riser as shown in Figure 23. Position the loop around the inertia reel strap as shown and then close the tab, attached to the back pad, over the strap to lock the strap into the position shown.

3.22 Repeat Steps 3.16 through 3.21 to stow the other shoulder bladder and the attached portions of the restraint harness assembly.

3.23 Check the completed stowage of the prototype limb retention system by comparing it to that illustrated in Figures 24, 25 and 26.

3.24 Remove the tubing attachments to the air pump and hook them to a suitable high pressure (700 psi per side) gas source for test and evaluation.

FIGURE 22

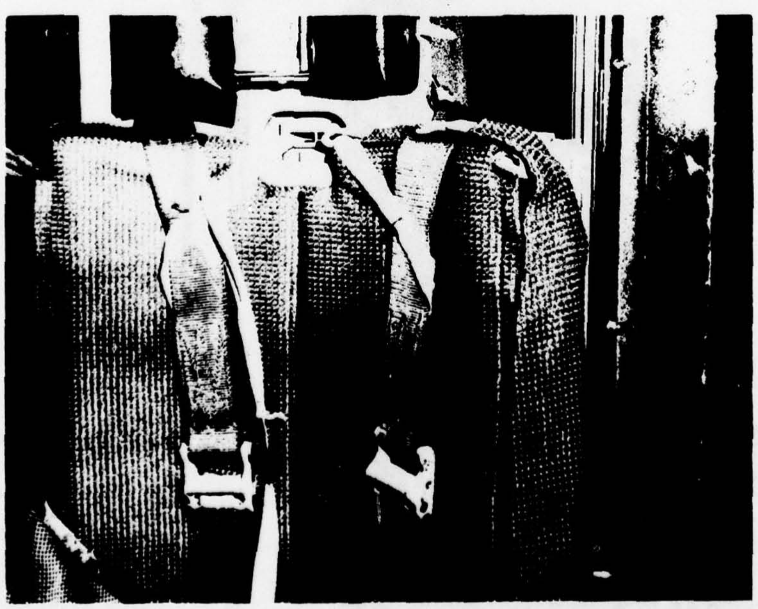

FIGURE 23

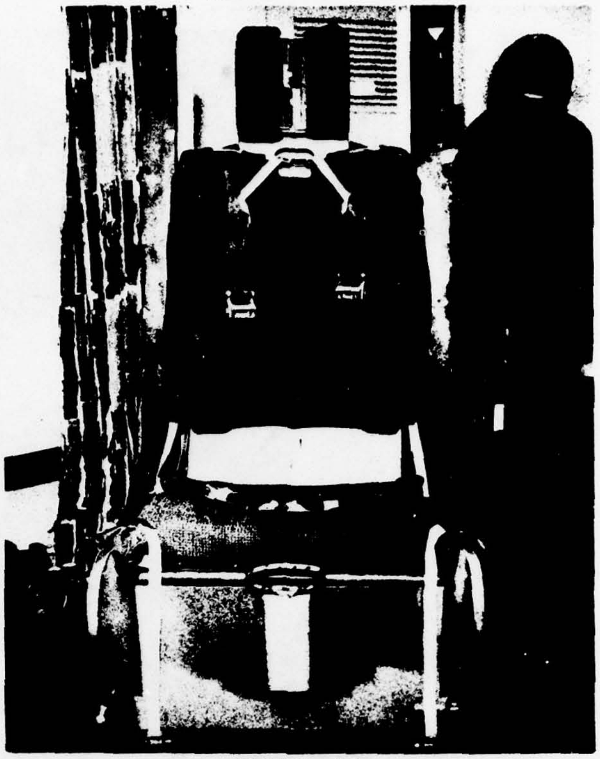

FIGURE 24

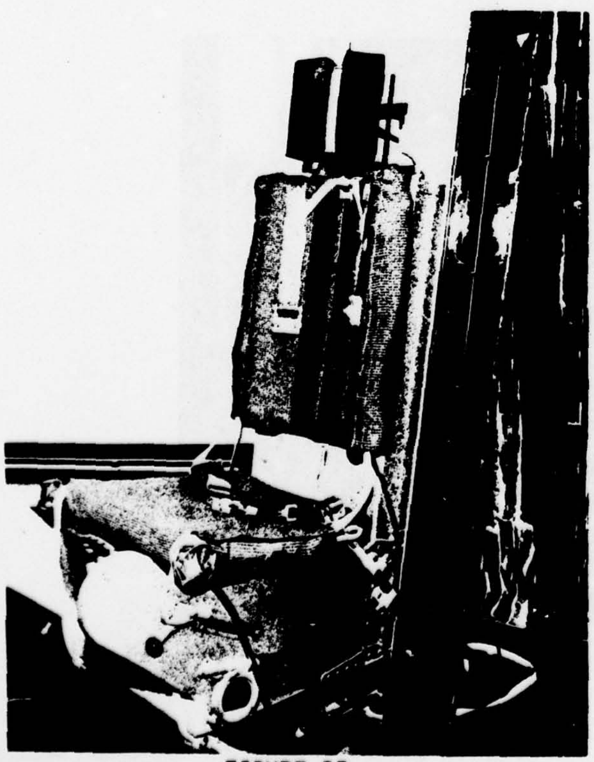

FIGURE 25

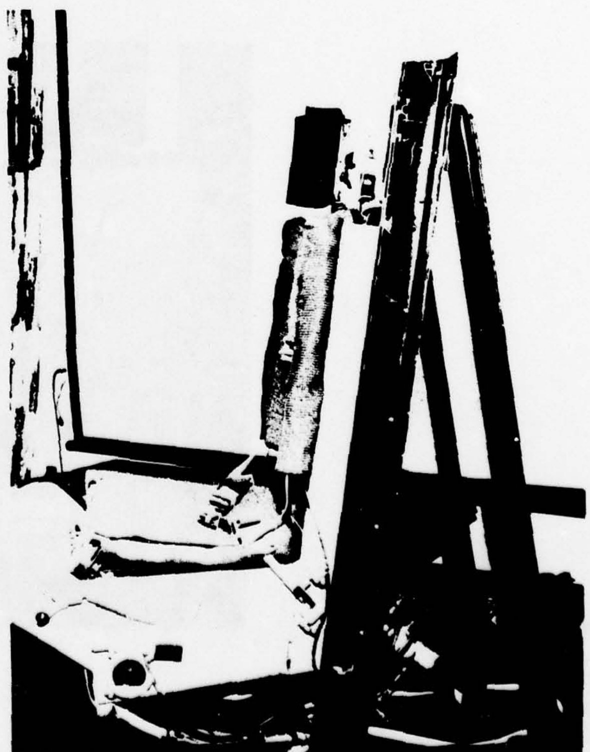

FIGURE 26

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NAVWPNCEN, China Lake, CA (4573)	1
NAVORDSTA, Indian Head, MD (5012).	1
NAVAIRTESTCEN, Patuxent River, MD 20670 (SY 71).	1
AVCO Corp. (Specialty Materials Div.), Lowell, MA	1
A.R.A. Inc., W. Covina, CA 91790	1
Bell Helicopter Textron, Fort Worth, TX 76101.	1
Boeing Aircraft Corp., Seattle, WA 98124	1
Boeing-Vertol Co., P. O. Box 16858, Phila., PA 19142	1
Budd Co., Fort Washington, PA 19034.	1
Douglas Aircraft Co., Long Beach, CA 90846	1
East-West Industries, Framingdale, NY 11735.	1
General Dynamics Corp., St. Louis, MO.	1
Grumman Aerospace Corp., Bethpage, NY 11714.	1
Hughes Helicopters, Culver City, CA 90230.	1
Lockheed Aircraft Corp., Burbank, CA 91503	1
North American Rockwell, Columbus, OH 43216.	1
Northrop Aircraft Corp., Burbank, CA	1
Sikorsky Aircraft Corp., Stratford, CN 06602	1
Simula Inc., Tempe, AZ 85282	1
Stencel Aero Engineering Corp., Asheville, NC 28803.	1
Teledyne-Ryan, 2701 Harbor Dr., San Diego, CA 92112.	1
Vought Corp., Dallas, TX 75222	1