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THE CREW ESCAPE MODULE was introduced into Air Force aircraft for two basic reasons. First, the conventional open ejection seat was an unsuitable system for escape at velocities above 600 knots equivalent airspeed (KEAS) or altitudes above 50,000 ft. Several modern aircraft are capable of sustained flight above these speeds and altitudes and require special escape systems. The second reason is related to the mission types that these high performance aircraft fly. A typical mission can last for 8, 10, 12, or more hours. Providing a comfortable environment during these long periods is not only desirable but essential if crew efficiency is to be maintained. This reasoning led to the development of the "shirtsleeve" environment. That is, it was felt that the crew member should not be crowded into his cockpit and should not have to continuously wear an oxygen mask and pressure suit. Thus, the escape capsule or module was developed and a new technology field opened.

As with many new technology fields, problems were quick to show up. In escape capsules, a major problem turned out to be landing the crew module on the ground under parachutes. With open ejection seats, the crew member under the parachute was able to, to a large extent, control how and where he landed. In addition, he had an excellent energy absorption system in his legs and was able to withstand quite severe landings with proper training. But in the crew module, the crewman descended inside a capsule in a seated position with no control over how or where he landed. Parachutes control vertical descent rate only. There is no way (in current systems anyway) to sense or control the drift rate of the capsule.

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ABSTRACT

Designers of emergency escape capsules cannot meet current Air Force biodynamic limits describing tolerable impacts encountered during the escape sequence. A major reason for this is the lack of an efficient lateral body support system. The objective of this program was to demonstrate the feasibility of using an inflatable restraint system in crew escape modules for lateral impact protection. Tests were conducted on both dummy and human subjects. Human impact tests using the restraint inflated to 8 psi were conducted up to 15.6 *g* without reaching a subjective tolerance endpoint. The conclusion was reached that the prototype system would improve lateral impact protection and that it was compatible with the crew escape module recovery sequence.

This means that the capsule system, with the man aboard, can have significant horizontal velocity at impact in addition to the vertical descent rate. This horizontal velocity can be as high as 43 ft/s in a 20 knot wind. This is close to a 30 mph crash. To make matters worse, there is no way to predict how the capsule will be oriented at impact. The crewman may be forced into the harness, the seat back, or the capsule side.

The characteristics of the acceleration environment were recently investigated by Peterson and Roberts (1)*. The study utilized an F-111 crew module. This system employs an airbag system outside and under the module for attenuation of the vertical component of acceleration. The module was impacted with and without the external attenuation system and at various attitudes and velocities. The results indicated that the landing environment was indeed a very severe one, characterized by high *g*, multidirectional accelerations. In addition, in certain attitudes the capsule had a tendency to bounce, roll off the vertical airbag system, and produce multiple impacts; all of this on flat, well prepared terrain.

The question had to be answered, was this environment tolerable? The Air Force evaluates multidirectional impacts with the use of an ellipsoidal tolerance envelope (2). This is essentially a way of taking individual tolerance limits in the primary body axes and weighing them in a multidirectional environment. Simply, it means that if the vertical acceleration is at the tolerance limit, no fore and aft or lateral acceleration can be present. As the vertical acceleration is decreased, other axis accelerations can be tolerated in an increasing manner. Without expanding on this any further (details can be found in Ref. 2), the critical impact direction, that is, the one with the lowest allowable *g* level, is the lateral direction. This is set at a maximum of 15 *g* with decreasing level as the acceleration time period is increased beyond 0.030 s.

These low limits in the lateral axis are greatly influenced by the amount and type of lateral body support provided. The 15 *g* limit assumes a standard 1-1/2 in lap belt with dual shoulder harness. Several studies have been conducted which show that this limit can be increased by providing other kinds of support designed specifically for the lateral direction (3, 4). The only problem has been that it has been infeasible to provide the complex system configuration in an environment where freedom of movement must be maintained. The objective of this study then was to provide and demonstrate a feasible lateral body support system which would increase the tolerable lateral *g* level into the 20-25 *g* range.

The approach selected was to draw upon the emerging technology in the inflatable restraint area. A restraint system of this type which is only active when needed is extremely attractive. For this application it is even more so since, in a sense, it is known that an impact will occur and no crash sensor is required. A prototype lateral body support system was developed which would augment, but not replace, the conventional restraint systems in use. The results of the tests conducted on this system follow.

*Numbers in parentheses designate References at end of paper.

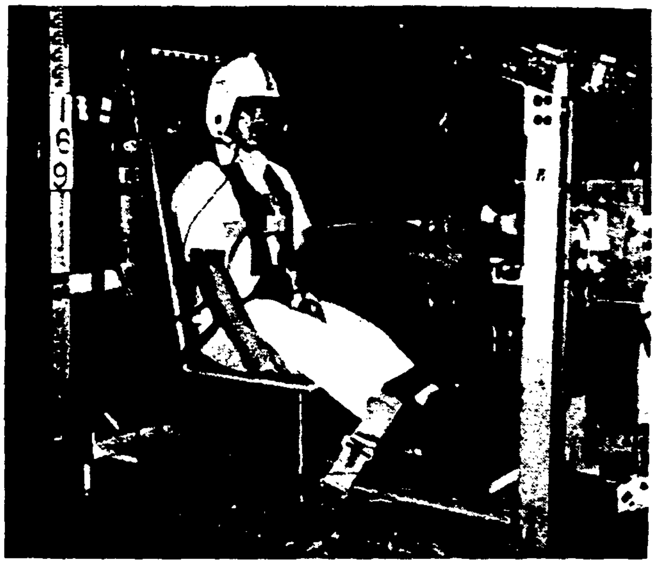

Fig. 1 - Test configuration: bag stored

TEST CONFIGURATION

Tests of the prototype lateral body support system were carried out on the Aerospace Medical Research Laboratory's Impulse Accelerator. This horizontal test facility is a 24 in HYGE Shock Tester, manufactured by Bendix Corp. The test fixture mounted on the impact sled was a simulation of a single crew member station within the F-111 escape capsule. The canopy contour was simulated by two intersecting plane surfaces. This was done to avoid having to mold the rather complex curvatures which exist in the actual canopy. The plane surfaces were so designed that they did not deviate from the actual curvature by more than 1/4 in at the head location. Acrylic 1/2 in thick was used to form the planes and to allow light to enter the interior for photographic purposes. The seat used in the capsule mock-up was a simulation of a crew member seat in the F-111. Seat back angle, width, and shape were identical to an F-111 seat, but vertical or horizontal adjustment capability was not provided. The design details of the structure are described more completely in Ref. 5.

Fig. 1 shows the seat and capsule structure and also the prototype lateral body support system in a pretest configuration. The harness used was the British Institute of Aviation Medicine version of the F-111 harness. It is a single point release harness consisting of two lap straps, two shoulder straps, and a negative *g* strap. It is in general use on the F-111. This harness has been demonstrated to have fair lateral support capability by itself (6, 7). This is thought to be primarily due to the unique upper shoulder strap attachment system (Fig. 2). The attachment straps which loop through the roller on the stole allow restraint to be applied much more laterally than on other aircraft restraint harnesses.

An inflatable bag system was used to supplement the harness restraint. The purpose of the bag was to provide better upper torso and head restraint during ground landing impacts. This bag is not of the automotive type which inflates explosively on

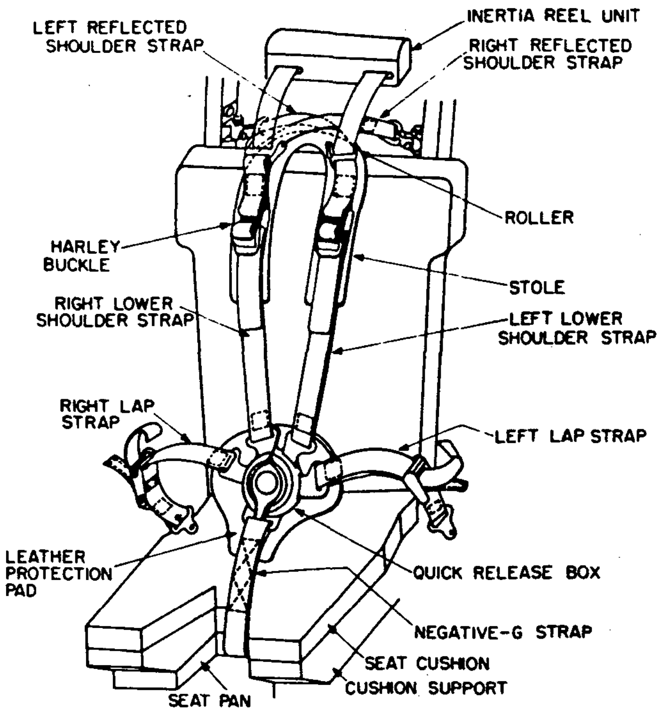

Fig. 2 - F-111 seat with British I.A.M. harness (2)

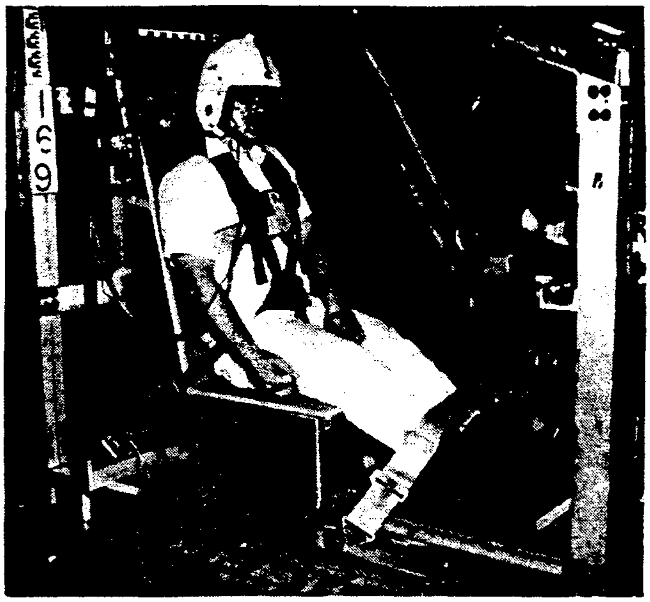

Fig. 3 - Test configuration: directly inflated bag

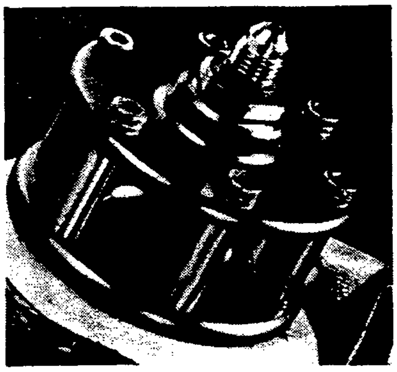

Fig. 4 - Aspirating nozzle

impact and then quickly deflates, but requires several seconds to inflate and remains inflated long enough to provide support during multiple impacts. The bag was designed for this evaluation to operate in two differing modes. In the first of these, the direct mode, the bag is deployed from its storage location along the longeron sill between the test subject and canopy structure by dumping gas (N_2) stored in a bottle under pressure into the bag. Final bag pressure is determined by the volume and initial pressure in the bottle. The bag is shown inflated in this mode in Fig. 3.

The second operating mode is what was termed the aspirated mode. In this mode the bag inlet is replaced by an aspirating nozzle (Fig. 4). During the initial inflation the aspirator entrains surrounding air into the cushion until a stall condition is reached at the design operating pressure. Bag pressure and operating time are controlled by the volume and pressure of stored gas and by the aspirator nozzle size. In this mode the aspirator was envisioned as acting as a relief valve for bag overpressures during impact and reducing large rebound accelerations which were feared with the direct mode. Further design details are given in Ref. 5 also.

Two series of tests were conducted with the inflatable restraint system, one with dummies and one with volunteer subjects. Test instrumentation was similar in both series. Bottle and bag pressures were monitored with CEC Type 4-326 pressure transducers. Sled acceleration was measured with a Statham A-52 accelerometer. Seven strap loads were measured with Strainsert universal load cells at the attachment points. Other instrumentation was unique to either the dummy or human series and will be described in those sections. All data were recorded on magnetic tape from where it was either displayed on oscillograph records or digitized for computer processing via an A/D converter.

DUMMY TESTS

A series of dummy tests were conducted on the harness and bag systems in order to select particular configurations for use in human testing. This series was conducted using both the direct and aspirated bag systems at operating pressures up to 8 psi. Shoulder strap loads were selected as the measurement for comparing one system configuration with another. Reduction of strap forces directly relates to the amount of load reacted through the bag. Strap loads after impact indicate rebound. A 95th percentile Alderson dummy was utilized for the comparison study. A head triaxial accelerometer pack and a chest triaxial accelerometer pack were added inside the dummy for the tests.

Table 1 summarizes the tests conducted on the direct bag systems. In general, the strap loads and accelerations decreased as the preimpact bag pressure increased. Significantly,

Table 1 - Lateral Body Support System–Direct Bag Dummy Tests

G Level	7.5				15			
Test	103	109	108	107	113	112	111	110
Bag pressure, psi	No bag	1	4	8	No bag	1	4	8
Head G_X	3.9	4.9	6.7	4.6	8	7.8	7.9	10.4
Head G_Y	28.3	29.5	26.8	21.8	50	50	48	43.8
Head G_Z	4.3	3.8	3.8	2.9	10	6.8	5.3	6
Chest G_X	3.2	3.8	4.7	3.4	6.9	5.6	6	5.5
Chest G_Y	22.3	27	22	8	60	50.5	47	14.3
Chest G_Z	1.5	2.3	1.4	1	7.3	5.8	4.2	5.4
Lap belt R, lb	542	670	440	235	1975	1725	1540	1610
Lap belt L, lb	32(90)	20(125)	25(105)	25(50)	62(322)	70(270)	58(208)	38(245)
Shoulder R, lb	0(100)	25(125)	14(77.5)	0(125)	0(310)	0(265)	0(222)	20(225)
Shoulder L, lb	670	720	550	290	1550	1325	1245	1040
Reflected R, lb	0(127)	25(180)	28(120)	32(162)	0(408)	0(385)	0(432)	25(332)
Reflected L, lb	750	738	552	288	1662	1422	1374	1122
Negative G, lb	750	900	825	450	1838	1748	1635	1448

NOTE: Numbers in parentheses are rebound loads.

Table 2 - Lateral Body Support System–Aspirated Bag Dummy Tests

G Level	7.5				15			
Test	103	116	115	114	113	120	119	117
Bag Pressure, psi	No bag	1	4	8	No bag	1	4	8
Head G_X	3.9	5	5.1	4.3	8	9	7.8	9.9
Head G_Y	28.3	24.5	22.5	15.9	50	43.3	42.5	42.5
Head G_Z	4.3	3.9	4.6	3.1	10	7.3	6	7.2
Chest G_X	3.2	3	3.9	4	6.9	6.6	6.1	6.9
Chest G_Y	22.3	23	21.3	16.3	60	58.8	46.3	45.8
Chest G_Z	1.5	2.4	2.6	1.2	7.3	6.1	5.3	5.8
Lap belt R, lb	542	900	525	475	1975	1838	1702	1312
Lap belt, L, lb	32(90)	25(122)	0(65)	55(295)	62(322)	52(292)	50(325)	25(300)
Shoulder R, lb	0(100)	0(112)	0(135)	0(75)	0(310)	0(325)	0(250)	32(375)
Shoulder L, lb	670	625	500	305	1550	1275	1145	925
Reflected R, lb	0(127)	0(170)	0(205)	0(118)	0(408)	0(420)	0(345)	40(590)
Reflected L, lb	750	720	540	300	1662	1446	1290	996
Negative G, lb	750	862	450	475	1838	1695	1650	1462

NOTE: Numbers in parentheses are rebound loads.

however, the rebound loads measured in the right shoulder straps did not increase. This was true for both the 7.5 and 15 *g* level tests. Large rebound loads, as had been feared, did not occur. The conclusion then is, based upon the criteria which had been selected, that for the direct bag system a preimpact bag pressure of 8 psi should be used.

Table 2 summarizes the tests conducted on the aspirated bag system. These data are very similar to those of the direct bag system. Increased preimpact bag pressure led to decreased loads and accelerations with little or no increase in rebound loads. The conclusion to be reached on the aspirated system is also that the 8 psi preimpact bag pressure should be used.

It would seem then that the two bag systems to pursue in further testing would be the 8 psi aspirated and 8 psi direct bags. Closer inspection reveals that there is very little difference between the data on the aspirated and direct systems.

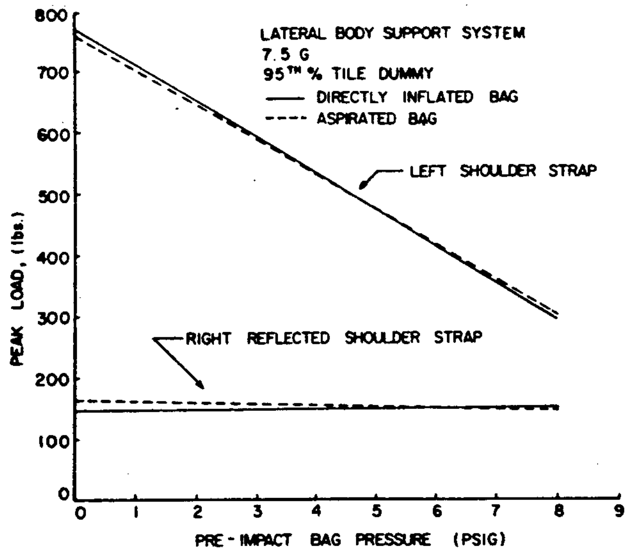

Fig. 5 - Shoulder strap loads: 7.5 *g*

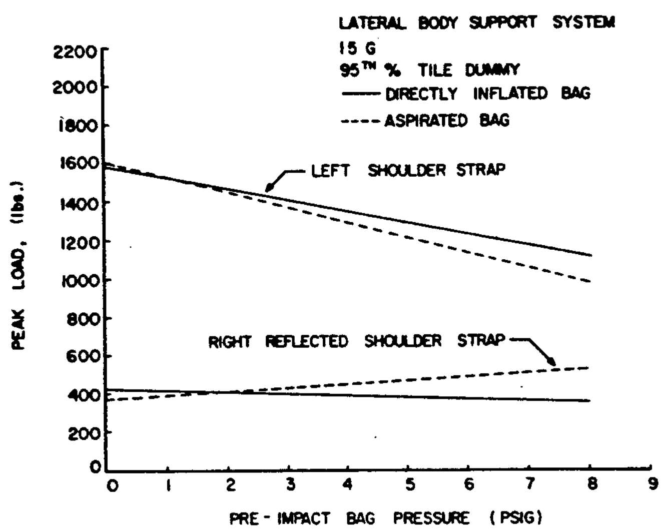

Fig. 6 - Shoulder strap loads: 15 *g*

Figs. 5 and 6 show the left and right reflected shoulder strap loads on the direct and aspirated systems for 7.5 and 15 *g*. There is no significant difference between the two systems. This would indicate that the aspirator is not functioning as a pressure relief valve during the short impacts. The question of which bag to use becomes one of convenience. That is, which is most readily applied to the escape capsule recovery sequence. Problems are present in applying either of the systems. Some of these will be discussed later in the paper. The aspirated system, however, possesses some problems that the direct system does not. These are:

1. Much shorter operating time (10-15 s versus hours for the direct).
2. Toxicity of inflation gas (vents into cabin).
3. More complex control function with increased size and weight.

Therefore, as there is no apparent difference in the functioning of the two systems, the simpler direct system operating at 8 psi was the only one selected for evaluation with human subjects.

Table 3 - Subject Anthropometry

Subject	Age, Years	Weight, lb	Shoulder Height in	Shoulder Height Percentile (8)	Height, in
RL	34	205	24-1/2	87	72
JP	36	180	23-1/2	58	68
MB	27	180	22-1/4	18	70
DF	21	169	21-3/4	10	66
CN	36	175	26-3/4	99+	73
MF	19	130	24	75	69
DK	26	152	24	75	70

HUMAN TESTS

Twenty-two impact tests were conducted with volunteers to evaluate the restraint system. Twenty tests were conducted with the 8 psi directly inflated bag at *g* levels ranging from 5.0 to 15.6 *g*. Two tests were conducted at 5 *g* without the bag for comparative purposes.

Seven test subjects were used in the program. All were male volunteer members of the Aerospace Medical Research Laboratory Hazardous Duty Panel. Each subject had successfully passed an extensive physical examination before testing. This included a Class III flying physical, Double Masters ECG, complete spinal radiograph series, and EEG. Table 3 lists pertinent anthropometric measurements for each subject.

Each subject was fitted with a triaxial accelerometer package on his chest and a small Statham A-52 accelerometer over the zygomatic arch on his face. This accelerometer was fitted to the curvature in this area by mounting it on a half-dollar sized piece of dental acrylic which had been formed in place. The number of strap load measurements was reduced from 7 to 5. This change was made in the upper shoulder straps. Only the loads in the reflected straps were measured. This was done to avoid some interference which occurred in the attachment area on smaller subjects. Dummy tests had shown that the loads measured at each end of a particular attachment strap were nearly identical so that no data would be lost by removing one of the attachment point measurements.

During all human tests, the subject's heart rate and rhythm were continuously monitored by the attending physician. The ECG signal was transmitted via telemetry directly to a recorder at the medical monitoring station. No significant ECG changes were noted during or after the impacts.

Fig. 7 is a reproduction part of the data collected on test No. 197. The peak *g* level on this test was 15.5 with an associated velocity change of 40.8 ft/s. The test utilized the 8 psi bag. Head severity index (S.I.) was calculated to be 361 from the face accelerometer. Peak values of the measurements on

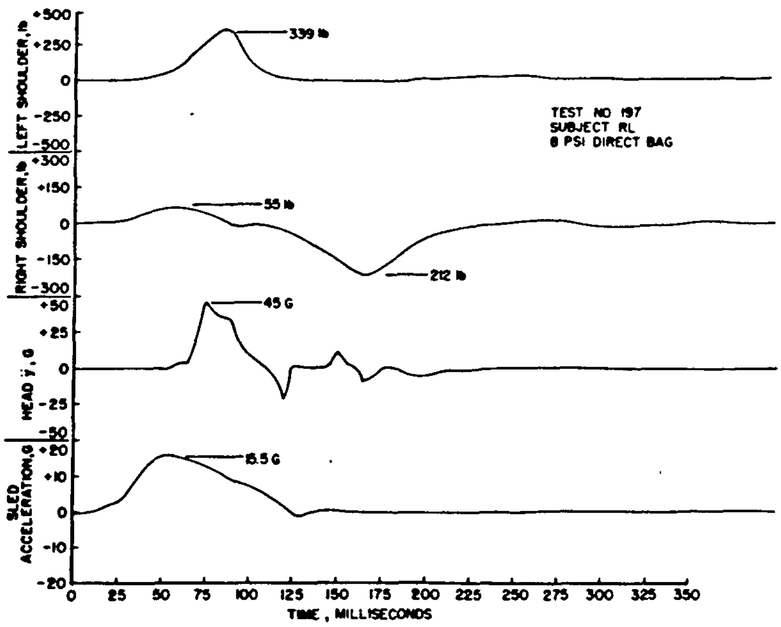

Fig. 7 - Sample data–test No. 197

Table 4 - Lateral Body Support System–8 psi Direct Bag Human Tests

Test No.	148	150	151	153	155	156	158	164	168	169
Subject	RL	JP	MB	DF	CN	MF	RL	JP	CN	DF
G level	5	5	5	5	5	5	7.5	7.5	9.4	9.5
Velocity change, ft/s	24.4	20.6	20.6	23.1	22.0	22.4	27.0	24.4	34.1	31.0
Head Ÿ, g	N.D.*	15	17.5	11.5	14.5	19.5	19.5	22.5	22.5	35
S. I.	N.D.	13	23	38	24	23	55	66	59	64
Chest Ẍ, g	5.8	3.2	2.5	3.6	2.4	2.4	8.3	4	5.1	9
Chest Ÿ, g	12.3	9.5	8.8	9.8	10	9.5	17	17	20.5	22.5
Chest Z̈, g	2.8	1.2	1.5	1.9	1.5	1.3	2.9	1.4	1.2	3
Left lap belt, lb	31.9(56)	61(89)	34(22)	48(24)	38(102)	36(44)	44(185)	N.D.	N.D.	N.D.
Right lap belt, lb	285	262	202	278	334	206	641	506	720	795
Right shoulder strap, lb	11(19.5)	22(34)	30(15)	N.D.	28(12)	24(8)	36(89)	48(50)	38(60)	30(84)
Left shoulder strap, lb	36	50	27	28	35	28	99	131	140	140
Negative G strap, lb	62.5	88.8	85	68	138	94	165	265	311	250

Test No.	171	178	179	180	188	190	192	193	197	198
Subject	DK	MF	MB	RL	CN	DK	MB	MF	RL	JP
G level	5	7.8	7.8	7.8	8.3	10.3	12.3	12.3	15.5	15.6
Velocity change, ft/s	19.6	23.6	28.2	27.2	28.8	34.3	31.9	31.6	40.8	42.2
Head Ÿ, g	15	22.5	15	25	19.5	20.5	26	18.5	45	46
S. I.	18	36	32	75	33	67	49	55	361	218
Chest Ẍ, g	3	6	10.8	8.9	4.8	3.3	15.9	8.7	15.7	14.9
Chest Ÿ, g	8.8	15.3	19.5	17.5	16.3	26.3	25.3	22.5	35	37.5
Chest Z̈, g	0.9	4.6	1.2	2.5	1.5	2.4	5.1	4.7	0.2	0.4
Left lap belt, lb	51(36)	N.D.	N.D.	N.D.	N.D.	32(20)	N.D.	N.D.	125(352)	N.D.
Right lap belt, lb	281	382	488	634	611	536	832	716	1380	1200
Right shoulder strap, lb	18(0)	32(22)	31(25)	50(0)	38(0)	50(40)	39(60)	38(86)	55(212)	N.D.
Left shoulder strap, lb	39	60	93	120	110	190	145	165	339	309
Negative G strap, lb	44	376	500	300	125	388	285	425	528	575

NOTE: Numbers in parentheses are rebound loads.
*No data.

all of the bag tests are given in Table 4. The general trends of these data are what is expected; increasing accelerations and harness loads with increasing g level. S. I. were computed for the single face accelerometer. In general, these were quite low, ranging from 13 during test 150 to 361 during test 197.

Two subjects, MB and MF, were exposed to 5 g impacts without the bag in place. These data, along with data from the tests with bags, are presented in Table 5. Substantial increases in several of the harness strap loads are seen with the bag removed. In addition, small decreases in rebound loads

Table 5 - Lateral Body Support System Human Test

Subject	MB		MF	
Condition	No bag	8 psi bag	No bag	8 psi bag
Test No.	160	151	162	156
G level	5	5	5	5
Velocity change, ft/s	18.7	20.6	22.5	22.4
Head Y, g	25	17.5	19	19.5
Chest X, g	14.9	2.5	3.7	2.4
Chest Y, g	25	8.8	10.3	9.5
Chest Z, g	1.7	1.5	1.8	1.3
Left lap belt, lb	25(77)	34(22)	18(62)	36(44)
Right lap belt, lb	525	202	420	206
Right shoulder strap, lb	24(36)	30(15)	18(25)	24(8)
Left shoulder strap, lb	150	27	161	28
Negative G strap, lb	226	85	398	94

NOTE: Numbers in parentheses are rebound loads.

Fig. 8 - Subject MF impacting airbag at 5 g

Fig. 9 - Subject MF impacting at 5 g without airbag

are noted with the bag in place. This would indicate that, at least at these low levels, the rebound from the harness alone is more severe than with the bag. Figs. 8 and 9 show subject MF at the same point in his 5 g test with and without the bag system in place. The amount of head restraint provided by the bag is apparent. Also, it appears that, on the bag test, the shoulders, neck, and head are held in good position with respect to one another. There is no shearing motion at the neck which was reported in Ref. 4 due to differing amounts of shoulder and head restraint.

SUMMARY AND CONCLUSIONS

During this test program a series of dummy and human tests were carried out on a prototype lateral body support system at levels up to 15.6 *g*. The prototype system utilized an inflatable airbag for torso and head support. The purpose of the test program was to demonstrate the feasibility of using this approach in protecting against the severe accelerations encountered during the ground landing phase of escape from high-performance aircraft with escape capsules. The program has definitely demonstrated this feasibility. Tests were conducted with human subjects beyond the current specified tolerance limits in the lateral axis (1). Even at 15.6 *g* the subjects experienced no symptoms which would indicate an approaching endpoint. It would seem reasonable to postulate that accelerations in the 20-25 *g* range could be tolerated with this system.

The inflatable lateral body support system tested here has some attractive advantages for retrofitting into an emergency escape capsule system. It requires no elaborate changes to current seat geometries or crew harnesses. No contours need be built into the head/neck area and the bag provides good support for both small and large subjects. The direct deployment mode selected works easily into automatic escape sequencing. The bag can be inflated after separation from the aircraft and held in position until ground contact. Deployment is slow enough so that there is no problem with bag slap or the noise which accompanies rapid deployment. Subjects during the tests indicated that they felt tightly restrained and slightly uncomfortable with the bag prior to impact, but felt they would have no problem maintaining the position for long periods.

The question of where to store the inflatable prior to use is a consideration which must be studied for each configuration. For the F-111 aircraft a primary location is along the longeron sill at the side of the capsule, similar to the location used in this test program. The system would add little weight to the capsule (3 lb for the bag used here) and take up little space.

One problem which is yet to be considered is that of a gas source for the system. Bottled gas was used here, but this is not an acceptable method for use in a crew compartment, where pressurized vessels are avoided. A cold gas generator appears to be the logical choice for an inflation gas source. It is small in size and weight and can produce a clean, nontoxic gas. Irregardless of the inflation system used, some sort of relief valve will have to be provided on the system to provide correct operating pressures under temperature extremes (−65 to +160°F).

In conclusion, then, it has been demonstrated that an inflatable lateral body support system can provide significant improvement in lateral *g* tolerance. In addition, the system considered requires no elaborate deployment, configuration, or timing mechanisms and can be applied to existing aircraft.

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