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PERSONNEL PROTECTION CONCEPTS FOR ADVANCED ESCAPE SYSTEM DESIGN

by

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SUMMARY

The severe emergency escape conditions associated with low-altitude and high-speed environments are often beyond the performance capabilities of contemporary ejection seats. A new escape system design approach is needed to extend the performance envelope without increasing the stresses imposed on the ejecting crewmembers. A new approach has been developed and specific ejection-seat subsystem design technologies are being explored by the United States Air Force. The central concept of the approach is the automatic selection of the performance characteristics of the escape system based on the conditions that exist at the time of ejection, and the adaptive control of the escape-system performance throughout the escape episode. Ejection-seat subsystem design concepts being developed to implement this approach are summarized. Several crew-protection concepts are reviewed, including a method to control the risk of injury to be proportional to the life threat of specific escape conditions and a windblast protection device called the flow-stagnation fence. A means to provide real-time assessment and control of the accelerations imposed on an ejection seat's occupant is vital to the new escape system design approach. This paper presents a six-degree-of-freedom acceleration exposure-limit method currently being developed to meet this requirement.

INTRODUCTION

It has become increasingly important to fly combat missions at low altitude to avoid detection and antiaircraft weapons. Both tactical and strategic penetration missions are, therefore, flown at very high speeds and very low altitudes. Air-to-ground attack missions are flown at low altitudes with jinking maneuvers. These flight regimes present extremely difficult emergency escape conditions. The difficulty of providing safe escape under these conditions is reflected in Air Force ejection statistics. During the decade from 1973 to 1983, 20 percent of all non-combat ejections were fatal. In one year (1979) the fatality rate reached 32 percent (1). Sixty-four percent of the fatal ejections in this decade were judged by investigating boards to have been initiated beyond the performance limits of the escape system. The ejections categorized as outside the escape-system performance envelope occurred in two flight regimes—at altitudes of 150 m (500 ft) or less, and at airspeeds beyond the capability of the ejection seat, which was 550 or 600 KEAS according to the respective escape-system documentation. Ejections within the low-altitude regime have become an increasingly larger percentage of the total number of ejections for more than two decades. The least-squares straight-line fit of these statistics in Figure 1 clearly show this adverse trend. The most alarming aspect of the trend is the high fatality rate within the group of ejections occurring at 150 m or below. During the past ten years, the fatality rate for ejections in this altitude regime has averaged 49 percent, ranging from 22 to 77 percent. This unacceptable situation exists despite the fact that ejection off-the-runway capability has been achieved, and the time from ejection initiation to parachute deployment has been greatly reduced.

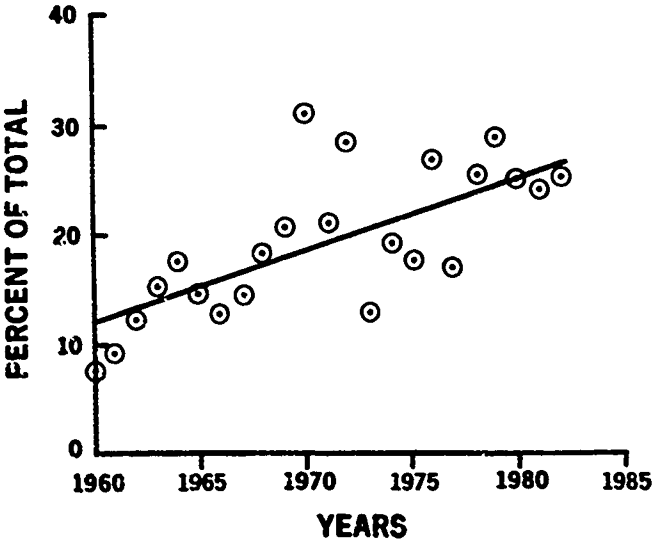

Figure 1. Percentage of USAF Non-Combat Ejections Occurring at an Altitude of 150 m or Lower as a Function of Year.

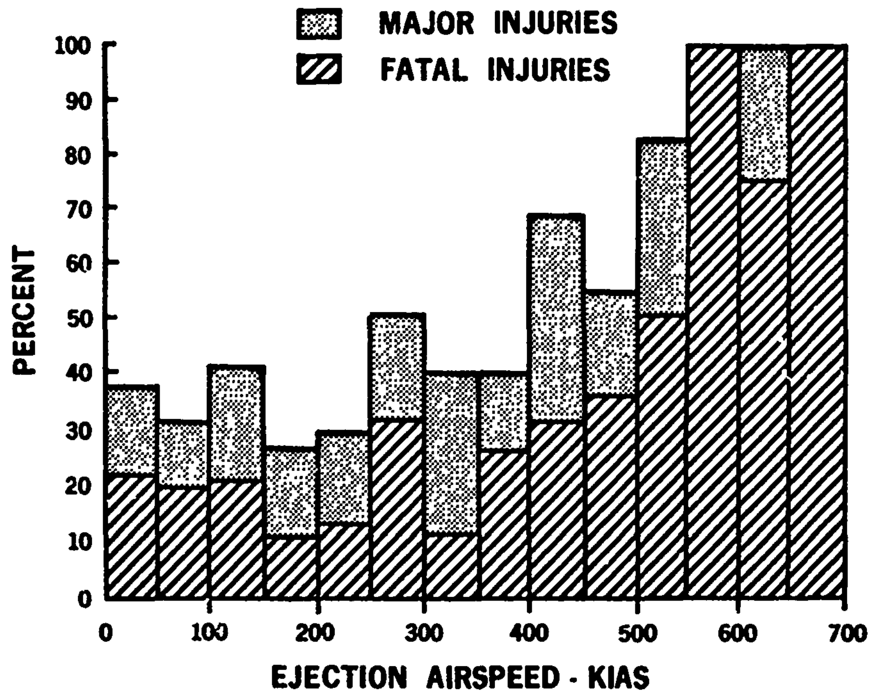

Figure 2. Percentage of Major and Fatal Injuries Resulting from USAF Non-Combat Ejections as a Function of Ejection Airspeed.

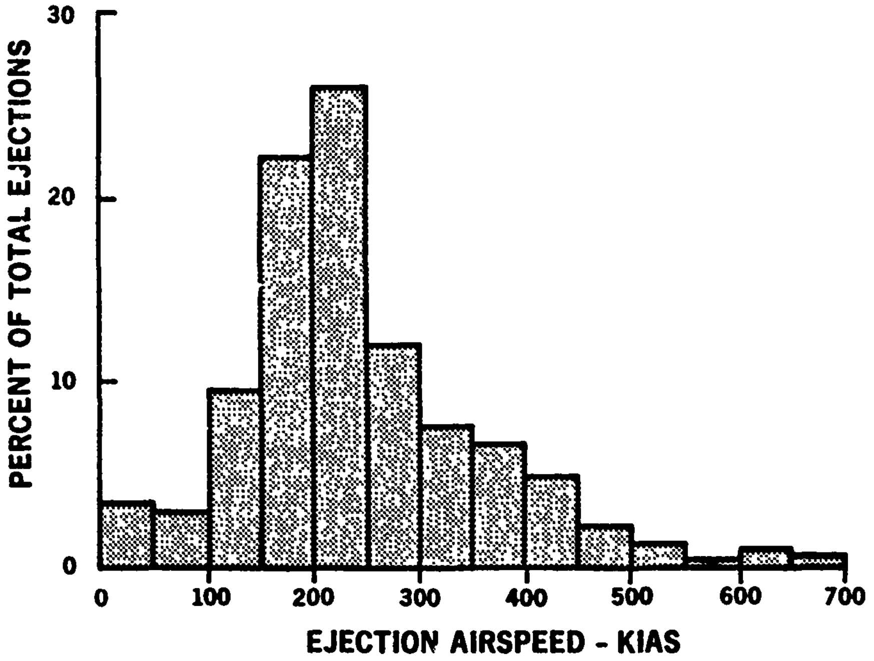

Figure 3. Distribution of USAF Non-Co[illegible]ctions as a Function of Ejection Airspeed.

Aircrews have become more aware of the limitations of their escape systems when flying low altitude missions, and this awareness has reached a point of interference with pilot effectiveness. A recent study (2) by a committee on automation in combat aircraft, conducted under the auspices of the Air Force Studies Board of the National Research Council, concluded that:

> "Systems for crew escape are ranked high by pilots as an area that requires serious attention. A review of available data revealed that pilots of Air Force fighters who use current escape systems are injured too often."

The disastrous effects of ejection at high airspeeds encountered during penetration dashes or during air-to-air combat training scenarios can be seen in Figure 2. This histogram shows USAF non-combat statistics for the period of January 1973 through December 1982 and the frequencies of fatalities and major injuries that occurred as a function of ejection airspeed. The remarkable increase in fatal and major injuries above 350 knots is largely attributable to injuries resulting from the high aerodynamic forces acting on the ejecting crewmembers' extremities and the unstable flight of the ejection seats (3, 4, 5). In view of the high fatality rates that have been experienced above 450 KEAS, it is clear that the normally published envelope limits (550 or 600 KEAS) for the ejection seats used during this period are a misstatement of system capability.

Fortunately, as shown in Figure 3, most non-combat ejections do not occur in the high fatality boundary areas of the escape system performance envelope. About one half of these ejections occur at airspeeds below 250 knots and altitudes above 150 m. Nevertheless, it would be foolish to design ejection seats for non-combat conditions only. USAF and USN experience during the Vietnam War showed that the distribution of ejection conditions shifts dramatically during combat (6). For example, the mean ejection airspeed increased more than 100 knots, and 44 percent of the survivors ejected above 450 knots. In all likelihood, these statistics underestimate the true situation since many of the crewmembers who ejected at higher airspeeds were probably fatally injured as would be predicted from the data shown in Figure 2.

The high-performance capabilities of aircraft such as the F-15 and F-16 as well as future advanced aircraft present further challenges to the escape system. These include a higher likelihood of escape during supersonic flight and a higher probability of escape during violent aircraft motions after loss of flight control since these aircraft have reduced stability margins. Furthermore, the use of multiple ejection seats in aircraft such as the B-1B requires trajectory steering to permit more rapid egress of the entire crew without collisions and entanglements among the crewmembers, seats, parachutes, and hatches.

Unfortunately, the design of ejection seats has reached an impasse because of the limitations of the single-point, fixed performance design approach that has been traditionally used. Contemporary escape systems are designed to meet some anticipated set of extreme escape conditions. For example, an ejection catapult is designed to provide an escape trajectory adequate to clear the aircraft tail structure at the highest dynamic pressure when the pre-ignition temperature of the catapult is -53 degrees C., and the seat occupant's weight is 102 kg. Under more probable moderate airspeed, catapult temperature, and ejected mass conditions, a crewmember will be exposed to higher acceleration with a higher probability of spinal injury since acceleration increases with higher pre-ignition temperatures and lower mass. The selection of the personnel recovery parachute and the velocity at which it is to be deployed is a second example of this single-point design principle. Rapid deployment of the parachute canopy is required at very low altitudes to assure the survival of the ejecting crewmember. Contemporary escape systems have been designed to deploy the parachute as rapidly as possible at the highest airspeed allowed by human tolerance to opening shock. However, a penalty is paid at higher altitudes since the opening shock increases as the air density decreases. The resulting high opening-shock loads have caused severe injuries. The traditional design approach has been to prevent parachute deployment until 4300 m (14,000 ft) above sea level and until the escape system has decelerated to a safe deployment velocity.

More recently, an improved strategy has been used. The personnel recovery parachute used on the ACES II ejection seat is deployed when measured aerodynamic pressure is lower than a predetermined value. At high airspeeds, the parachute canopy is reefed for a time to reduce its drag area and, therefore, prevent excessive opening shock that could injure the escaping crewmember. Nevertheless, parachute deployment cannot be initiated above this pre-established airspeed and altitude above sea level regardless of a life-threatening situation that might demand other action.

The ejection-seat subsystems cited as examples are primary subsystems that determine an ejection seat's fundamental performance capabilities. Although considerable effort is typically expended to select performance characteristics, once chosen, those characteristics are fixed. Unfortunately, the performance is usually fixed for performance-envelope boundary conditions. If the performance envelope must be extended, higher stresses must be imposed to assure crew survival in the extended regions. However, the higher stresses take their toll in injuries. Although the higher injury rate may be justifiable in these life-threatening regions, the single-point, fixed-performance design approach forces the toll to be paid equally over the entire performance envelope. Unless this principle of design is abandoned, no significant improvement in performance capabilities can be expected without an increase in the resulting injury rate.

A revolutionary change in ejection-seat design is taking place to provide crew safety during the catastrophic emergencies that may occur in high-risk flight regimes. This change includes a new design strategy, innovative systems concepts, and the application of emerging technologies in the areas of propulsion, digital flight control, environmental sensors, and biodynamics. It also includes recognition that higher risks of injury may be inherent if crew survival is to be achieved beyond current escape-system performance-envelope limits. However, the advancement of these limits must not be made at the expense of crewmembers who initiate escape under less demanding flight conditions.

The feasibility of this promising new approach will be demonstrated as part of an advanced development program titled Crew Escape System Technologies (CREST) which is under the direction of the Aerospace

Medical Division of the Air Force Systems Command (7). This new approach allows for the adjustment of the performance characteristics of the escape system to meet the wide range of environmental conditions that may be encountered during emergency egress from contemporary and future high-performance aircraft. Escape system performance characteristics are selected at the time of ejection on the basis of existing flight conditions and then regulated during the escape episode. Thus, emergency conditions (such as airspeed, altitude, and attitude) confronting the escape system and its occupant can be used to adapt and control the operating characteristics of propulsion, stabilization and trajectory steering, crew protection, and recovery subsystems (8, 9).

Application of this approach also provides the means to regulate the stresses imposed on the ejecting crewmember so that the injury potential is proportional to the threat to the crewmember's life (1, 10). For example, if the ejection altitude is above 3000 m and airspeed about 150 knots, the ejection catapult and rocket-thrust levels would be regulated at minimal values to reduce the chance of spinal injuries. However, if the escape conditions were worse (e.g., altitude below 100 m, airspeed about 550 knots, and high rate of descent), the thrust levels would be regulated at higher values and deployment sequence timing of the recovery system could be minimized since a higher risk of injury would be acceptable to assure survival of the crewmember under these life-threatening conditions.

CRITICAL SUBSYSTEM TECHNOLOGIES

The principal design concepts being explored to implement the new escape system design approach have been selected from exploratory development programs within the research laboratories of the United States Air Force and United States Navy and their contractors. The concepts cover a broad range of technologies including sensors, microprocessors, digital flight control, biodynamics, pyrotechnic propulsion, crew restraint, and windblast protection.

The key element of the conditionally determined performance approach is the use of an electronic control system to perform the functions of data analysis, life-threat assessment, selection of performance options, and subsystem control. The recent development of low-cost, highly reliable microprocessors, data memory units, and rapidly activated power supplies makes a relatively complex multifunction control system feasible. This technology also provides the means to improve total system reliability by permitting built-in test features that can assess the readiness of the entire escape system, and automatically manage system faults by selection of alternate redundant, functional systems (8, 13).

Means of acquiring data to determine the escape conditions are a crucial prerequisite to assessing the life threat and controlling the escape system. For example, altitude above the earth's surface is probably vital data although there is little need for fine resolution in this measurement. The attitude of the escape system with respect to the earth is also required if safe escape is to be provided from adverse initial aircraft attitudes when terrain clearance is poor. The application of advanced low-cost, lightweight radiometric systems may provide these data (11, 12). Other required environmental data that can now be measured using relatively inexpensive sensors include seat velocity, accelerations, and angular rates. Since the life-threat assessment must be made in the initial portion of the escape sequence, the data used for the assessment may be available from the aircraft. However, these data could be lost during an aircraft emergency. Therefore, a data-gathering system dedicated to the escape system is required. Such a system may be as straightforward as an array of seat-mounted sensors and could also include a processor to estimate the conditions at the instant of ejection based on last observed aircraft data.

The control laws that can be used within a seat-mounted flight control system are currently under development. One promising approach applies a multivariable, nonlinear synthesis technique that uses prestored optimal reference trajectory solutions, acceleration control, and an on-board predictive seat/man response model (14). A set of acceleration and control reference trajectories would be computed for the range of anticipated escape conditions. These computations would be accomplished using off-line computer facilities and then prestored in the escape system controller. During the escape episode the controller would manage the propulsion thrust level and thrust vector direction to steer the seat along the trajectory selected on the basis of measured conditions. The method features acceleration control because the acceleration environment is directly related to the injury potential.

Propulsion-system concepts currently being explored include ejection catapults with selectable thrust features and rocket motors that provide thrust-vector control and thrust-level management capabilities (15, 16). The ejection catapult will be capable of providing a thrust level that is appropriate for a wide range of escape conditions, including adverse aircraft attitude, acceleration, seat-occupant weight, and capatult pre-ignition temperature. Design configurations being studied include multiple propellant charges, fired separately or in combination, and catapult mechanisms which can vent energy that is excessive for the escape conditions. These same approaches are being explored to provide adjustable rocket thrust-time histories, and mechanisms such as gimballed rocket nozzles or reaction jets will be used to provide the three-axis thrust-vector control that is necessary for trajectory steering, regulation of escape-system attitude, and control of the deceleration levels after ejection at high airspeeds.

Use of an electronic control system also establishes the capability to control the operation of existing escape subsystems. For example, the controller will be used to initiate the deployment of drogue devices and the recovery parachute, control operation of the parachute-canopy reefing devices, and possibly activate the parachute four-line release mechanism. Furthermore, the controller will include fault detection and failsafe features that will allow its performance to degrade to simpler functions such as subsystem sequencing and, in the event of complete control-system failure, the escape-system operation will revert to basic pre-established capabilities similar to contemporary escape systems.

The CREST advanced development program is addressing crew-restraint problems which include the inadequacies of current in-flight restraint systems as well as crew protection during emergency escape. Technical approaches that are being investigated include the use of pilot-actuated, power-assisted body positioning and restraint that can be repetitively operated to provide improved seat and occupant coupling during combat flight maneuvers and aircraft recovery after departure from controlled flight.

This same powered body-positioning system will be used to reduce the pre-ejection sequence time, eliminate extremity-cockpit strikes during ejection, and provide improved body posture to withstand ejection, windblast, and aerodynamic deceleration stresses (17).

Extending the high-speed performance limits of ejection seats to 700 KEAS is a major challenge. Achievement of this goal would represent a great advancement in view of the poor survival rates currently experienced in ejections above 450 KEAS. The traditional approach to crew protection for emergency escape at high airspeeds has been encapsulation of the ejection seat (as in the B-58 and B-70 escape systems) or use of a separable cockpit as an escape vehicle (as in the F/FB-111 aircraft). However, the encapsulated seats have considerable weight, cost, and low-altitude performance penalties. Therefore, new windblast-protection approaches are being considered to reduce the risk of windblast injuries in open ejection seats. These include the use of both active restraint, requiring the seat occupant to take action to don the system, and passive devices that provide protection by reducing the aerodynamic flow impinging on all or a portion of the seat-occupant's body (18, 19, 20).

The most innovative approach to extending the capabilties of ejection seats to the goal of 700 KEAS is the flow-stagnation fence concept proposed by Cummings (21). The principle of the concept is to trap a volume of air in front of and around the seat occupant. The stagnated air then diverts the high-velocity airflow around the seat occupant. One of the design configurations currently being studied uses a fabric fence erected around the seat-occupant's head, torso, and upper legs prior to ejection.

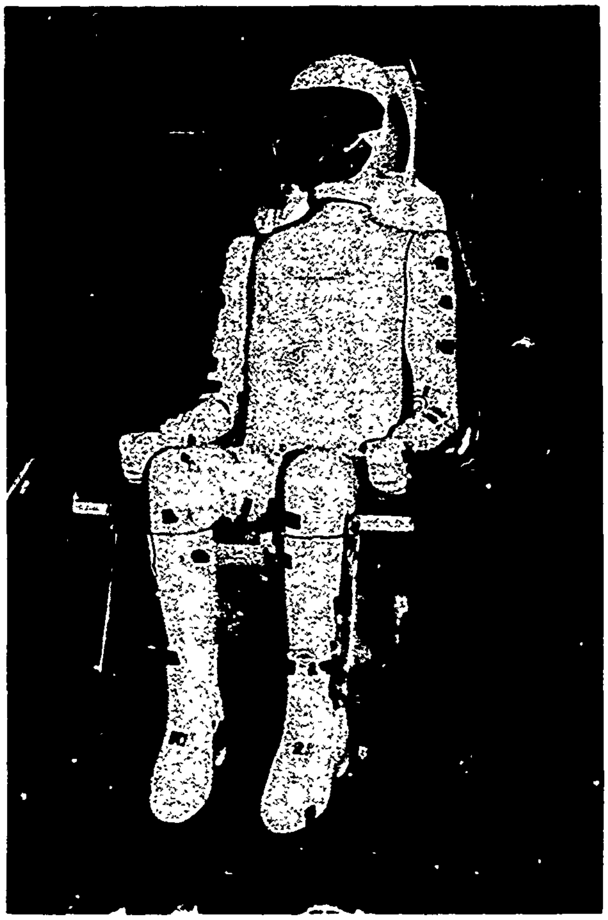

Figure 4. Photograph of One-Half Scale Model of Ejection Seat Equipped with Flow-Stagnation Fence.

The effectiveness of the flow-stagnation concept has been evaluated by wind-tunnel tests (20, 22) using the one-half-scale model of a crewmember and ejection seat shown in Figure 4. The size of the stagnation fence was varied from an estimated maximum feasible size to 25 percent of those dimensions. The maximum-size fence configuration protruded 32 cm forward above the occupant's helmeted head, 23 cm forward at mid-helmet level, 23 cm forward at upper-arm level, and 17 cm upward from the seat sides in the lower-arm (full-scale dimensions).

The data collected during the wind-tunnel tests indicated that the flow-stagnation fence is very effective. Pressure measured at various points within the cavity bordered by the fence showed the degree of stagnation ranged from 80 to 100 percent when the maximum fence was used, and one half the values when the fence dimensions were reduced by one half. The pressure measured on the seat-occupant's helmet visor and chest was raised only slightly since these areas are normally regions of stagnated flow. The loads measured by the force-measuring units within the seat-occupant model showed major reductions when the flow-stagnation fence was used. For example, the vertical forces acting on the head were lowered to nearly zero over the range of pitch angles tested. The axial forces acting on the head were reduced to near zero when the fence size was 50 percent and were negative with the maximum-dimension fence. The sideward forces acting on the head and arms were also reduced. The stagnation fences reduced the vertical force on the lower arms in the same manner as they affected the vertical forces on the head.

Force and moment measurements made to evaluate the influence of the fence on the aerodynamic properties of the model revealed several significant changes in the stability characteristics. First, the pitching-moment coefficient was reduced. This is a beneficial effect since the model without the fence has a significant negative pitching moment. Second, the addition of the fence had practically no influence on the yaw moment. Third, the drag coefficient of the model nearly doubled when the maximum-size fence was used and increased by 75 percent when the fence size was reduced by one half. Fourth, the force coefficient acting perpendicular to the wind vector increased from -0.11 to -0.58 when the full-size fence was added. Reduction of the fence size by one half did not produce a major change in this effect.

Since the windblast injury protection capabilities of the flow-stagnation fence concept appear to be excellent, additional research is currently exploring the potential of the concept in more detail. Tests have recently been completed to evaluate the efficacy of the approach at Mach numbers up to 1.2. Preparations are now being made to explore new fence configurations that may provide the benefits of flow stagnation without the drag and vertical force penalties that have been observed.

ADVANCEMENTS IN DESIGN CRITERIA - ACCELERATION EXPOSURE LIMITS

Providing an adequate technical foundation for the CREST advanced development program is a joint undertaking by the scientists and engineers of the Air Force Aerospace Medical Research Laboratory (AFAMRL) and the Air Force Wright Aeronautical Laboratories at Wright-Patterson Air Force Base. The task requires coordinated efforts because advancements in one technical area are dependent upon advancements in another. For example, the control laws of the flight-control system must be defined using knowledge of the ejection seat equations of motion, the aerodynamic properties of the seat and its occupant, and the acceleration exposure tolerance of the human body (23). Control of gimballed rockets or reaction jets to stabilize and steer an ejection seat along a desired trajectory requires an understanding of the dynamic inertial response characteristics of the human body as well as the center of mass and mass distribution of the seat and occupant.

These interdependencies also extend into such diverse areas as environmental sensor development and injury risk estimating. The problem-solving sequence that will be used by the control system to accomplish the life-threat assessment will operate on hierarchically ordered data from advanced sensor arrays. For example, although airspeed (KEAS) provides sufficient data to define a severe life threat if it is above a critical value, airspeed alone is insufficient to determine that less than a severe threat exists. Additional facts such as ground proximity, ground closure rate, and earth-referenced attitude are required to make this determination. Specific threat-assessment rules must be based on knowledge of the escape system's capability to recover its occupant under any set of environmental conditions and the injury tolerance of the occupant. Once the degree of threat is determined, a proportional injury risk may be selected and initial escape subsystem performance levels established.

One of the most challenging biotechnical problems is the definition of acceleration exposure levels. The control-system design requires that the acceleration exposure-limiting method be suitable for automation within an onboard flight controller. Moreover, exposure limits must be provided for six degrees of freedom, i.e., the three translational and three angular degrees of freedom of the escape system. The methods that have been used for escape system development do not address all six degrees of freedom and, with the exception of the dynamic response index (DRI) model (24, 25, 26), are not suitable for automation. During the development of the ACES II ejection seat (initiated in 1967 and completed in 1973), the DRI model was used by the system designers to estimate the probability of spinal injury associated with translational acceleration in a single axis. The estimate was made by computing the response of a single-degree-of-freedom dynamic model to the ejection seat acceleration acting upward and parallel to the seat-occupant's spine. The maximum response of the model, expressed in terms of a dynamic response index value, was then related to a probability of spinal injury that had been estimated by comparisons with operationally experienced ejection spinal-injury rates (26). A similar model that had been proposed to evaluate the response of the human body to acceleration acting in the fore-aft axis (24) had not been adequately correlated to human test data and models had not been developed for the other axes. Therefore, acceleration tolerance graphs and tables have been used to evaluate the acceptability of translational accelerations acting in the fore-aft, sideward, and downward directions; neither angular accelerations nor angular rates have been specified (27). This approach is unacceptable for the CREST program. The CREST technologies demonstration escape system will be able to generate accelerations along any axis and produce significan angular accelerations during trajectory control and steering maneuvers. Thus, a more comprehensive acceleration exposure-limit method must be developed.

The data available to develop better exposure-limit criteria are not extensive. Existing data from tests with volunteers at injurious as well as non-injurious levels are limited in terms of the ranges of acceleration vector directions and acceleration-time histories that have been explored. There is little information available on the effects of angular acceleration and combined angular and translational acceleration. Nevertheless, the point has been reached where a further step must be taken to provide a more comprehensive method to describe human acceleration tolerance so that the feasibility of new escape system concepts can be demonstrated. This step is currently being taken based on the available data in combination with the results of operational escape experience, judgments founded on observations of responses of volunteers to noninjurious acceleration conditions, and insights gained from computational simulations of human responses.

The approach being used (28) consists of the following major steps:

a. Development of dynamic response models for each orthogonal axis based on available data.

b. Assignment of three injury risk levels for each axis.

c. Interpolation between the orthogonal axes using the constraints of an ellipsoidal envelope.

d. Evaluation of the ellipsoidal assumption using existing data from tests with acceleration vectors off the orthogonal axes, ejection seat test data, and studies with mathematical models.

e. Assessment of angular accelerations by evaluation of the effects of their translational acceleration components.

The dynamic response models that have been developed are similar to the DRI model used successfully in the design of the ACES II ejection seat. Such models allow one to compare the injury risk associated with escape system acceleration. It is an idealized concept, but as described below, the assumptions underlying the injury risk criteria are believed to be conservative. Simply, the dynamic response is the response of a hypothetical mass, spring, and damper system attached to the seat. The virtue of this concept is that, with properly selected coefficients, the peak acceleration of the mass is monotonically proportional to the probability of injury, hereafter called injury risk. A different dynamic model is used for each orthogonal axis; and to be complete, one might expect that different restraint systems would each have their own associated dynamic model.

The equations that describe the dynamic response along each major axis are given below.

$$\ddot{\delta} + 2\zeta\omega_n \dot{\delta} + \omega_n^2 \delta = \ddot{s} \qquad \text{(Eq. 6-1)}$$

and

$$DR(t) = \frac{\omega_n^2\delta(t)}{g} \qquad \text{(Eq. 6-2)}$$

where:

$\ddot{\delta}$ is the acceleration of the dynamic response model mass relative to the acceleration input point.
$\dot{\delta}$ is the relative velocity between the input point and the model mass.
δ is the compression of the model spring.
ζ is the damping coefficient ratio.
DR is the dynamic response of the model.
ω_n is the undamped natural frequency of the model.
$\ddot{s}$ is the seat acceleration component along the pertinent axis.
g is the acceleration due to gravity.
(t) indicates that the parameter is determined as a function of time.

A left-handed coordinate system is used to designate the direction of the acceleration vector. A +Z acceleration acts from foot to head and a +X acceleration acts from back to front.

Each of the dynamic response models other than for the +Z axis have been developed by the same procedure. First, the experimental acceleration-time histories from tests with volunteer subjects were approximated with a half-sine pulse where feasible. The test data, which were measured on the test fixtures that transmitted the acceleration to the subjects in whole-body impact tests, were obtained from numerous reports published by U.S. Air Force and Navy investigators and Department of Defense contractors. The approximations were established by fitting the peak acceleration and the time to the acceleration peak (rise time) with a half-sine pulse. This procedure yielded relatively good fits for the majority of the data. However, the fit was not good where the experimental acceleration pulse shape was actually more trapezoidal, as in some of Stapp's early tests (29, 30), or where the acceleration-time history was irregular. In such instances, the procedure was used to fit only the initial portion of the pulse; this approach provided a conservative estimate since the energy of the fitted half-sine pulse was always less than that contained in the actual data. Second, a model response curve was calculated which was descriptive of the higher acceleration data points where in many cases subjective tolerance limits or injuries had been identified by the original investigators. An example is shown in Figure 5. The curve was derived by computing the peak response of a single-degree-of-freedom model to half-sine acceleration pulses of varying durations. To select the natural frequency and the damping coefficient ratio for each axis, the natural frequency and the damping coefficient ratio are adjusted until the shape of the peak response to half sine wave acceleration forcing functions with varying widths matches available human tolerance data. The results of noninjurious acceleration exposures of volunteer subjects were also considered to verify the frequency response and damping characteristics of the model. Verification was accomplished by study of the relationships between the acceleration input conditions and the measured responses of the test subjects, e.g., acceleration of body segments, displacement of body segments, restraint harness loads, and forces measured between the seat structure and the test subjects.

Figure 5 shows the model response curve initially fitted to data collected from experiments conducted with the acceleration vector directed primarily in the +X axis. The curve was derived from the responses of a mathematical model with a natural frequency of 62.8 rad/sec and a damping coefficient ratio of 0.2. Each of the models that have been developed presumes a specific restraint system consisting of a lap belt, crotch strap, and double shoulder strap configuration.

Figure 6 illustrates the curve derived for the -X axis. The points plotted on Figure 6 show that there are no data from -X axis impact tests to support the contention that the human body can tolerate increasingly high acceleration levels as the duration of the pulse decreases. However, this appeared to be a reasonable approximation on the basis of tests with animal subjects and preliminary analysis of acceleration transfer functions computed from physical responses of volunteer test subjects (28). The model coefficients are the same as those for the +X axis. They are nearly identical to the coefficients estimated by Stech and Payne (24) although their method to derive the coefficients was different and their predicted acceleration tolerance level was higher.

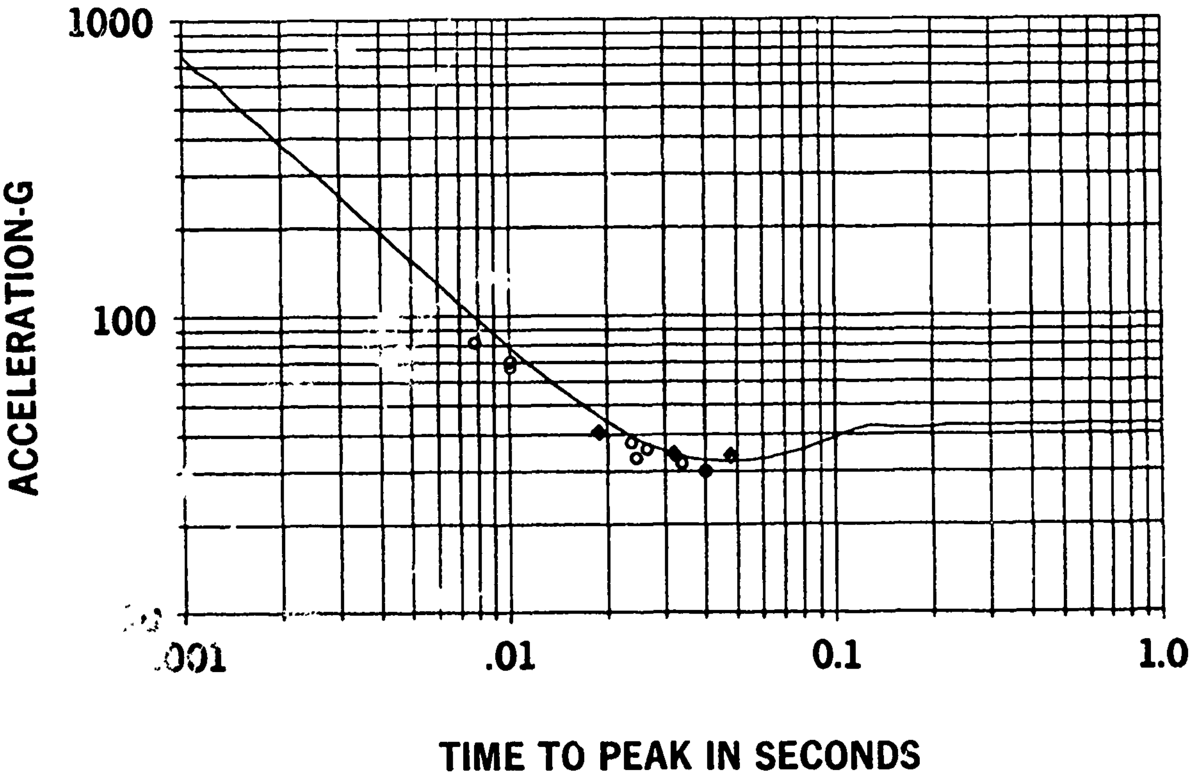

Figure 5. Acceleration Response Curve Developed for +X Axis. Data points derived from impact tests with volunteer subjects are plotted as functions of the peak acceleration and time to peak acceleration. Tests where there was evidence of injury or potentially serious sequelae are designated by black diamond-shaped symbols. The curve was plotted from the computed responses of a single-degree-of-freedom model with a natural frequency of 6[illegible].8 rad/sec and a damping coefficient ratio of 0.2.

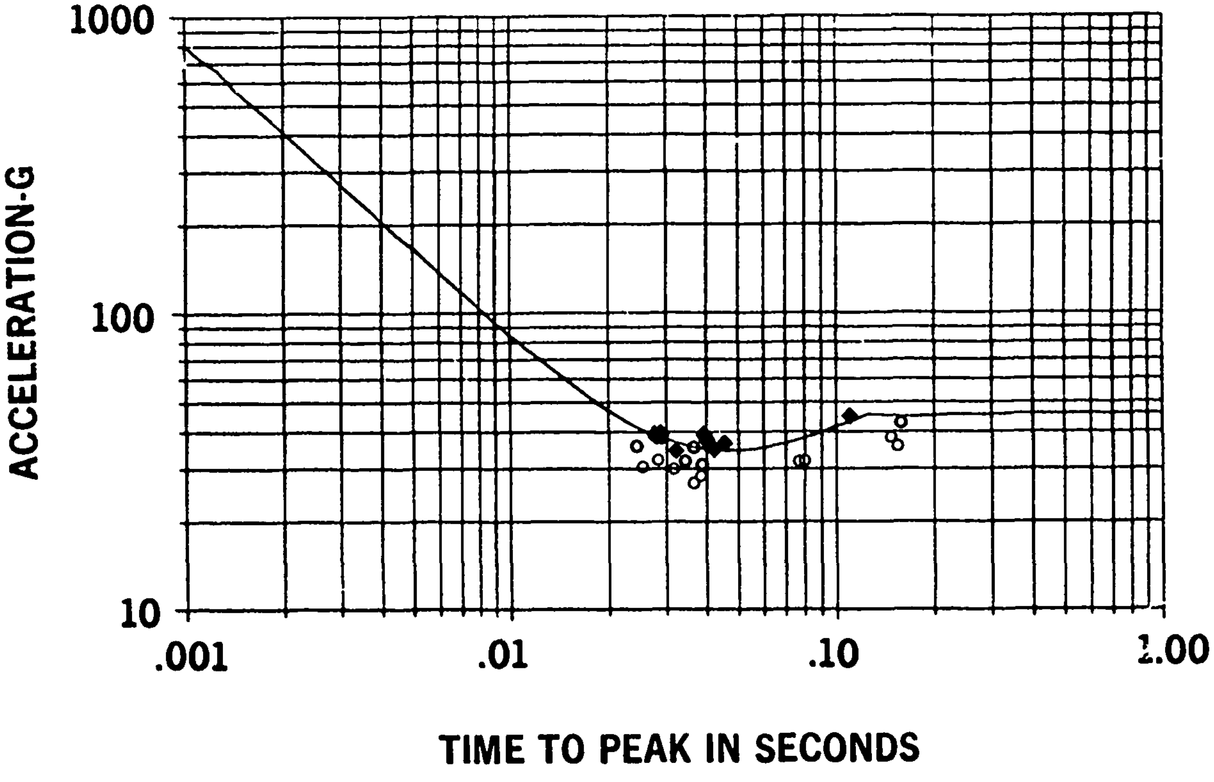

Figure 6. Acceleration Response Curve Developed for the -X Axis. Data points are from impact experiments with volunteer subjects. Tests where there was evidence of injury or potentially serious sequelae are designated by black diamond-shaped points.

The injury risk acceleration levels for the +Z axis were assigned by determining the 50, 5, and 0.5-percent probability of spinal injury from the injury probability distribution for the DRI reported in reference 26. These injury risk levels are characterized as high, moderate, and low as shown in Figure 7. A 50-percent probability of injury was selected as the highest spinal injury rate acceptable in the system design for two reasons. First, it is the highest spinal injury rate that has been observed for any USAF ejection seat, and there was no damage to the spinal cord associated with any of these injuries. Second, this level was judged to be the maximum allowable considering that multiple exposures would be likely subsequent to the catapult acceleration, i.e., rocket acceleration, parachute-opening shock, and ground landing impact. The moderate injury risk level corresponds to the level used in current USAF ejection-seat design (27) and is at a mid-point between the high and low levels. The low injury risk level corresponds to acceleration conditions used routinely without incident in tests with volunteers conducted at the AFAMRL.

The three injury risk levels for the ±X, ±Y, and -Z axes were assigned without the benefit of a statistically based method such as that used for the +Z axis. The high risk levels were determined by calculating the peak response of the mathematical model to the acceleration conditions known to cause major injuries or potentially serious sequelae. The low risk levels were estimated on the basis of the calculated model responses to acceleration conditions that have been used for numerous, noninjurious tests with human subjects in research laboratories. The moderate injury levels were assigned to a mid-point between the high and low levels. In order to interpolate between these injury risk levels, a Gaussian distribution has been presumed. Figure 8 illustrates the acceleration exposure injury risk levels assigned for the -X axis.

The methodology used to establish the acceleration exposure risk levels produced higher statistical confidence in its application to the ±X and +Z axes than in its application to the ±Y and -Z axes since more data are available to define the higher injury risk levels. The data used to define the injury risk levels for the ±Y axis did not permit the assignment of high risk levels with an adequate degree of confidence since clear evidence of injury has not been observed under laboratory conditions. Furthermore, the frequency response and damping characteristics of a descriptive model could not be determined with adequate confidence. In view of this situation, the ±Y axis model was assigned the same dynamic coefficients as the X axis model. But the injury risk levels were lowered to correspond to the levels judged reasonable on the basis of available human test data.

A similar situation exists for the data available for the -Z axis; however, the acceleration-time histories that have been used in noninjurious tests with volunteer subjects span a relatively large range of time durations. The low risk level was assigned on the basis of injury-free laboratory tests with volunteer subjects. The moderate level was selected on the basis of previous downward ejection-seat catapult acceleration limits, and the upper bounds of the available human test data were used to establish the high risk limits since injuries had not been observed under laboratory conditions. The available data were not sufficient to do more than provide a rough approximation of the frequency response range of a model that would be descriptive of human dynamic response to -Z axis acceleration inputs. Since the +Z axis model was in that range, the natural frequency and damping coefficient for the +Z axis model were selected for the -Z axis acceleration limit model.

A method was required to evaluate acceleration vectors with components in several axes since the aforementioned acceleration limit criteria models are for the orthogonal axes. The method selected presumes that the acceleration exposure limits in three dimensions are defined by an ellipsoidal envelope that is restricted in each axis by the dynamic response limits of the injury model of the orthogonal axis. The boundary of the ellipsoidal envelope is defined mathematically. Thus the accelerations measured on an ejection seat up to the instant the occupant is separated from the seat by the recovery-parachute opening loads will be limited using the following equation:

$$\left[\left(\frac{DRX(t)}{DRX_L}\right)^2 + \left(\frac{DRY(t)}{DRY_L}\right)^2 + \left(\frac{DRZ(t)}{DRZ_L}\right)^2\right]^{\frac{1}{2}} \leqq 1.0 \qquad \text{(Eq. 6-3)}$$

where:

The suffix L denotes the limiting value for the assigned risk value.
DRX is the dynamic response computed from the X axis acceleration component.
DRY is the dynamic response computed from the Y axis acceleration component.
DRZ is the dynamic response computed from the Z axis acceleration component.

The task of providing criteria for the control of angular acceleration of an ejection seat and its occupant has been a problem that has required an assessment from first principles since no precedent exists. There is very little data available on human tolerance to angular acceleration and velocity. Translational accelerations and angular rates have been measured in only one test where a volunteer was exposed to the combined translational and high-level angular accelerations that may be associated with the operation of the CREST demonstration ejection seat (31). The approach selected to limit the angular acceleration is based on the hypothesis that the injuries associated with angular acceleration are directly related to the translational components of the angular acceleration. This hypothesis has some suport based on the experimental findings of Tardov (32) and Weiss et al (33). Thus, the tangential and, to a greater degree, the centripetal acceleration must be considered. Payne has recommended that assessment of the effects of angular acceleration be accomplished by applying to the injury models acceleration-time functions that contain the translational acceleration plus the translational components of the angular acceleration acting along the relevant body axis (34).

CONCLUSION

The performance limits of contemporary ejection seats must be expanded to meet the emergency conditions imposed by combat mission scenarios and the unique characteristics of advanced performance aircraft. Escape systems must be designed to successfully operate under a wide spectrum of severe

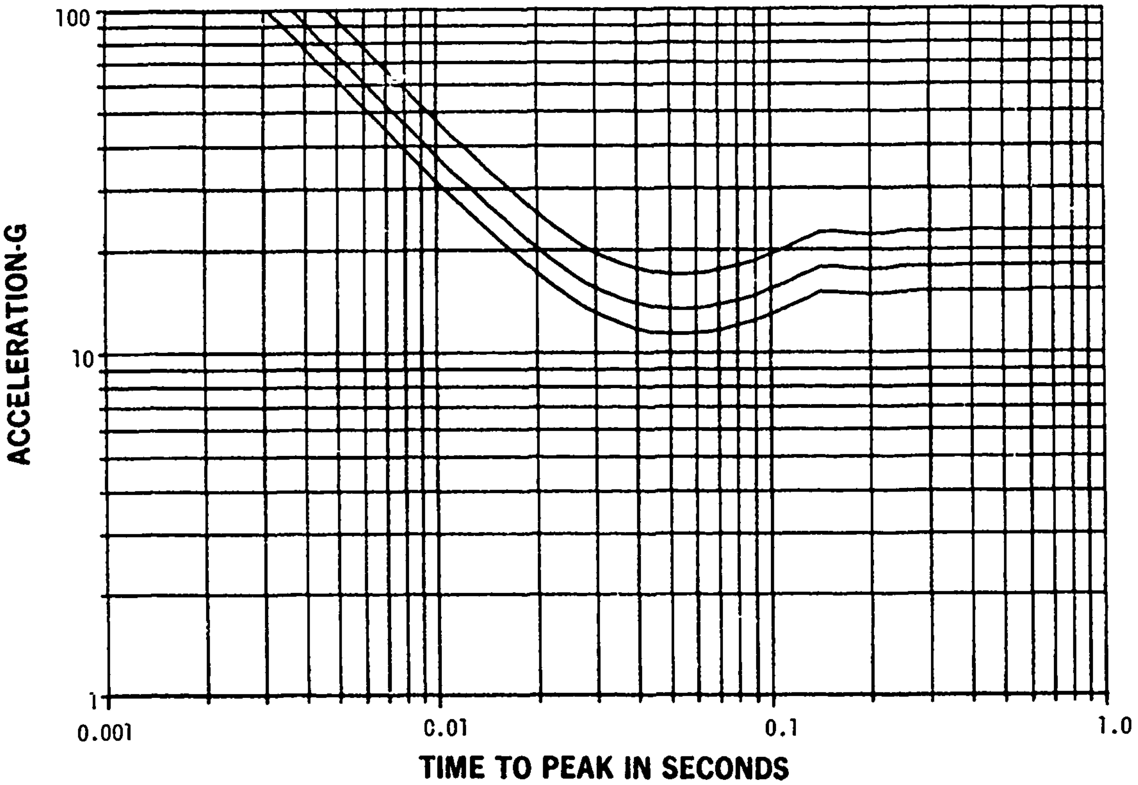

Figure 7. Acceleration Exposure Injury Risk Levels for the +Z Axis. Level A is the high-risk level, Level B is the moderate-risk level, and Level C is the low-risk level. The curves that are shown are calculated for peak half-sine acceleration pulses that will yield a constant model response. The natural frequency of the +Z axis dynamic model is 52.9 rad/sec and the damping coefficient ratio is 0.224.

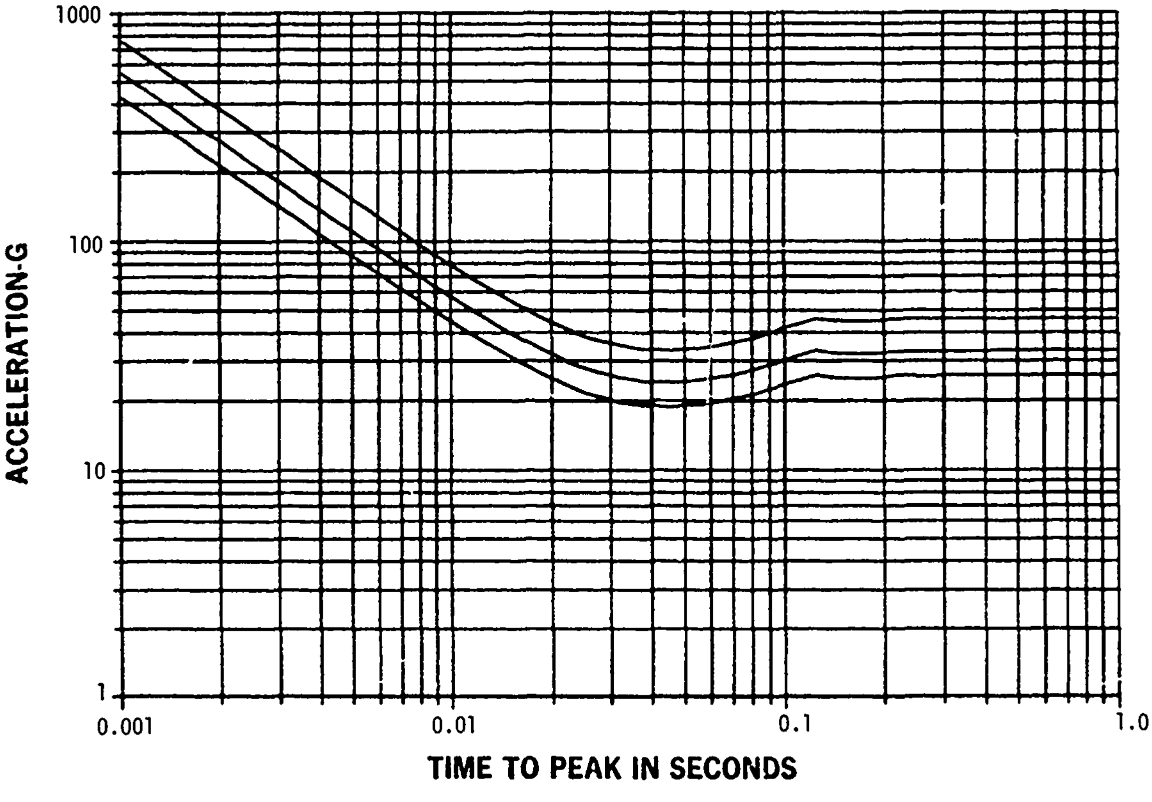

Figure 8. Acceleration Exposure Injury Risk Levels for the -X Axis. Level A is the high-risk level, Level B is the moderate-risk level, and Level C is the low-risk level. The injury risk levels presume that the ejection seat occupant is restrained by double shoulder straps, a lap belt, and crotch strap configuration. The exposure limits assume that aerodynamic loads exist that retard flexion of the cervical spine.

conditions beyond the capabilities of existing systems. These conditions include airspeeds up to 700 KEAS, low altitude with adverse combinations of aircraft attitude and sink rate, and unfavorable aircraft accelerations and angular rates associated with escape after departure from stable flight. These challenges cannot be met by modifications of existing escape systems. A fundamentally different approach based on new and emerging technologies is required.

A general concept for an escape system whose performance is conditionally determined and adaptively controlled has been formulated to expand escape-system performance boundaries beyond those of current systems. Design approaches and subsystem concepts have been described that can be used to implement the general system concept. The CREST advanced development program has been initiated to explore the feasibility of the continuous adaptive control concept. The performance capabilities of the CREST system concept will be demonstrated by design, development, test, and analysis. This approach provides a unique opportunity to investigate the practicality of achieving the performance objectives without the high costs associated with a program committed to full-scale development and production. Furthermore, the influences of the real-world constraints such as aircraft cockpit configuration, system reliability, life-cycle cost, and maintainability can be more factually evaluated.

The six-degree-of-freedom, real-time acceleration exposure limit method reported in this paper represents a significant departure from earlier methods for specifying human tolerance levels for escape system design. The dynamic response models used in this method are descriptive of available empirical data, but they do not attempt to predict the location, severity, or (except for the +Z axis model) the mode of injury. The new method permits a continuous estimate of the injury risk from an arbitrary acceleration environment, and it can be mechanized as part of an adaptive control system for any manned six-degree-of-freedom vehicle. The method can and should be verified or amended on the basis of additional experimental observations. As such, the method establishes the foundation for further research even while serving its primary purpose of supporting the advanced development of new escape sytem technologies. The CREST advanced development program provides the unique opportunity to examine the applications and limitations of the dynamic response acceleration exposure limit method before a commitment is made to develop an escape system for operational use.

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