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ENGINEERING ANALYSIS OF CRASH INJURY IN ARMY CH-47 AIRCRAFT

Directorate for Investigation, Research & Analysis
U.S. Army Agency for Aviation Safety
Fort Rucker, Alabama 36362

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NOTICES

The findings of this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

The information contained in this report is intended for accident prevention purposes only and specifically prohibited for use for punitive purposes or for matters of liability, litigation, or competition.

The analysis reported herein was performed by a study group formed by representatives of several Army agencies and commands. The US Army Agency for Aviation Safety provided technical direction and management of the team. Participating agencies were the Army Applied Technology Laboratory of the US Army Research & Technology Laboratories, Aviation Research and Development Command, Aeromedical Research Laboratory and the Armed Forces Institute of Pathology.

This report has been approved by the Commander, US Army Agency for Aviation Safety.

ABSTRACT

An analysis of crashworthiness deficiencies in the CH-47 aircraft system is discussed. Basic data for this study is taken from Army CH-47 aircraft accidents occurring during CY 71 through 76. Injury and impact data are extracted from accident reports using a specially-developed coding system. The costs of personnel injuries are determined in accordance with Department of Defense policy regarding the effects of accidental injuries on Army operational readiness. The underlying engineering causes of crash injury are determined considering presently documented biological limitations of the human body. Crash hazards are identified and ranked according to the magnitude and probability of their effect. Recommendations are made as to the most urgent crashworthiness research/development/acquisition efforts for consideration by aircraft systems managers and aviation research laboratories.

CONTENTS

SUMMARY

This report contains the results of an analysis of crash injury causes in CH-47 aircraft accidents. The analysis was performed to provide systematic direction to Army crash safety research.

The baseline for the analysis was all major aircraft accidents which occurred to Army CH-47 series aircraft during CY 71-76. The accidents were analyzed in detail by a study group formed by representatives of several Army agencies. This group determined the extent and underlying causes of crash injuries based on medical and engineering data contained in accident reports and related files. Crash hazards which resulted in the largest personnel losses were identified and prioritized to determine pressing crashworthiness research and development programs. The impact conditions under which these crash hazards resulted in preventable injuries were summarized to aid in future determination of crashworthiness design criteria.

The study identified 16 separate crash hazards in CH-47 aircraft. It was determined that the research, development and acquisition efforts which would result in the greatest benefits in reducing these hazards for current aircraft were (1) seats for enlisted crewmembers which permit their use during critical portions of flight, (2) passenger seats with improved structural integrity, and (3) transmission oil containment with improved post-crash fire protection.

This study also suggests that an improved method of estimating crash impact conditions is necessary for accurate determination of future crashworthiness design criteria.

INTRODUCTION

A systematic technique for the identification of crash injury causes in Army aircraft accidents has been developed as reported in Reference [1]. This report documents the application of this technique to the Army/Boeing-Vertol CH-47 cargo helicopter.

The goal of this analysis is the determination of the most critical crash hazards in current aircraft and the identification of the most beneficial research programs to improve its crash survivability.

Study of other major Army aircraft is planned and subsequent reports are anticipated.

OBJECTIVES

The overall objectives of this study were to (1) identify the most significant CH-47 injury causes, (2) determine the extent of losses attributable to each and (3) establish under what crash mechanisms and impact conditions each becomes a problem. Emphasis was placed on not merely documenting the types and frequency of injuries sustained but also on identifying their underlying engineering causes. The analysis of the engineering causes of crash injury was to consider the presently documented biological limitations of the human body. It was envisioned that a primary output of this effort would be an improved direction for crashworthiness research including identification of follow-on efforts to define specific hardware to reduce the hazards in current and future aircraft.

ASSUMPTIONS

The major assumptions of this analysis are as follows:

a. Past aircraft accident data provides a valid baseline for establishment of future crashworthiness design criteria.

b. The frequency and severity of crash injuries are the primary rationale and justification for research designed to reduce crashworthiness deficiencies.

c. Additional rationale and justification for crashworthiness research is the economic effects of accidental injuries on Army operational readiness (Reference [2]).

d. The aircraft fleet flying hour rate and rates of injury occurrence and cost as identified in the baseline study period will prevail for a future 20 year period.

APPROACH

Data Sources

The primary data source for this study was the case files of Army CH-47 series aircraft accidents occurring during calendar years 1971 through 1976. Accident data used was taken from the U.S. Army Agency for Aviation Safety files at Fort Rucker, Alabama. A total of 29 CH-47 aircraft accidents occurred during this period as summarized in Table I. Appendix A contains definitions of terms used in Table I and in other portions of this report.

TABLE I

US Army CH-47 Aircraft Accidents, CY 71-76

Number of Accidents	29*
Number of Accidents Analyzed in this Study	28**
Number of Aircraft Flight Hours	428,548
Accident Rate (per 100,000 flight hours)	6.76
Number of Occupants	294
Number of Occupants Killed or Injured	239

Another data source was the aviation pathology data bank maintained by Armed Forces Institute of Pathology. This source provided additional data beyond that available in the USAAAVS accident files for certain fatal injury cases.

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* There were 30 CH-47 aircraft involved in the 29 accidents.

** One aircraft accident during CY 71-76 involved other type aircraft flying into a stationary, secured and unoccupied CH-47 aircraft. This was not considered a CH-47 accident within the context of this study and is not included in the analysis and findings herein.

A final data source was a description of currently available technology in the aircraft crashworthiness and life support equipment areas. This information was derived primarily from research and development studies by US Army Applied Technology Laboratory. Representative information available in the open literature is contained in References [3] through [7].

Overall Approach

Each step in the analysis sequence is shown in Figure 1. The overall scheme is one in which analyses of individual accident case histories establishes a data base of injury causes and related impact conditions. This data base is then analyzed to identify the crash hazards resulting in the largest losses and the research necessary to reduce them.

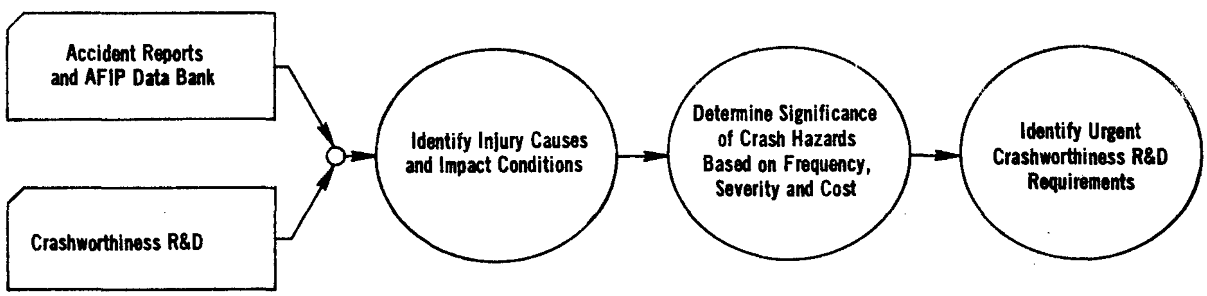

FIGURE 1.–Overall Sequence of Analysis

Additional details of the analytical technique are contained in Appendix B. A team of engineers, air safety specialists and flight surgeons representing several Army agencies performed the required accident report analysis. Appendix C lists the participants in the study group.

RESULTS

The results discussed below are intended to identify the most significant CH-47 crash hazards and the impact conditions under which they occur. Statistical injury patterns by body locations are also provided for future use in developing specific solutions to the hazards identified, whether in aircraft design or life support equipment.

Combined Velocity Components

Figure 2 depicts the longitudinal and vertical components of the change in velocity of the aircraft center of gravity during its major impact for each of the accidents studied. The resulting impact survivability is indicated. Insufficient data are available for accurate determination of statistical distributions.

The velocities at the instant of major impact were established from one or more of the following factors: (a) recorded value from the accident report as determined from witnesses or board estimates, (b) structural deformation observed in photographs, (c) comparison of crash to similar instrumented full-scale tests, and (d) type and degree of personnel internal injuries.

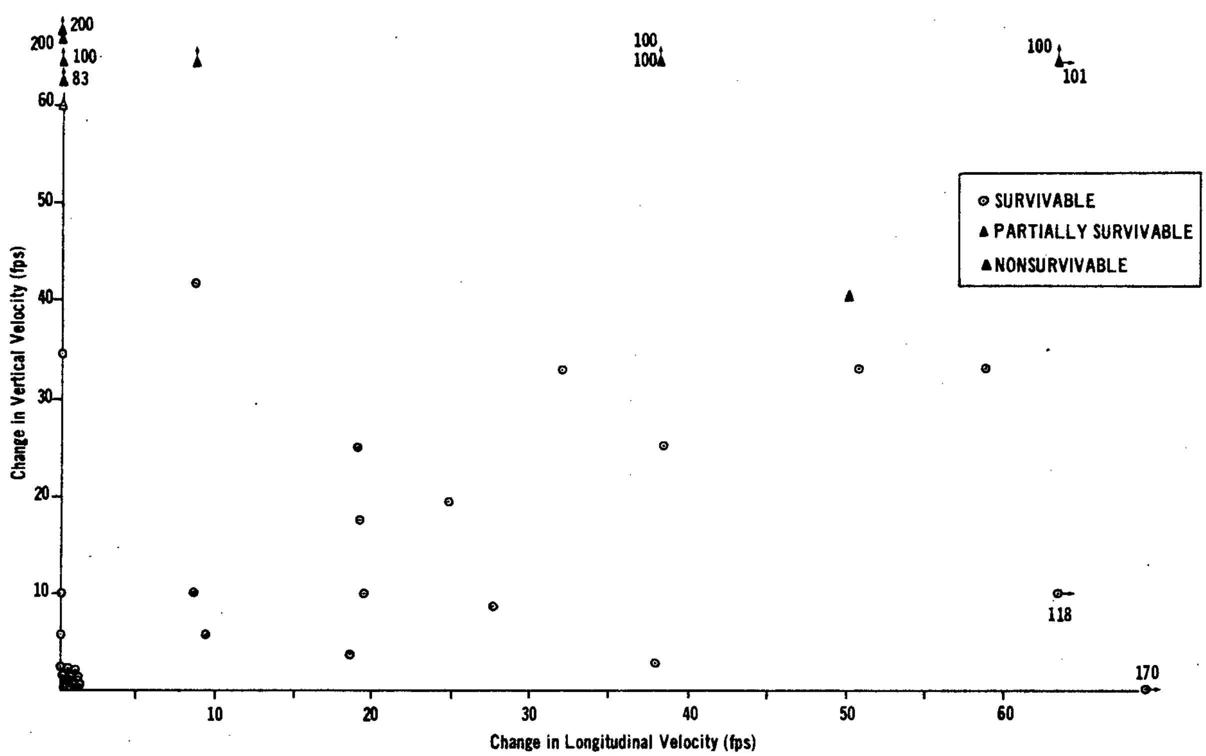

FIGURE 2.–Vertical and Horizontal Components of Impact Velocity Change (CH-47)

Combined Force Components

Figure 3 depicts the longitudinal and vertical components of the peak crash force for all accidents studied. The resulting impact survivability is indicated. Compared to the velocity change data of Figure 2, Figure 3 indicates less accuracy in the crash force data.

The force components at the instant of major impact were established by one or more of the following factors: (a) recorded value from accident report as determined by the board, (b) structural deformation observed in photographs, (c) comparison of crash to similar instrumented full scale tests, and (d) type and degree of personnel internal injuries.

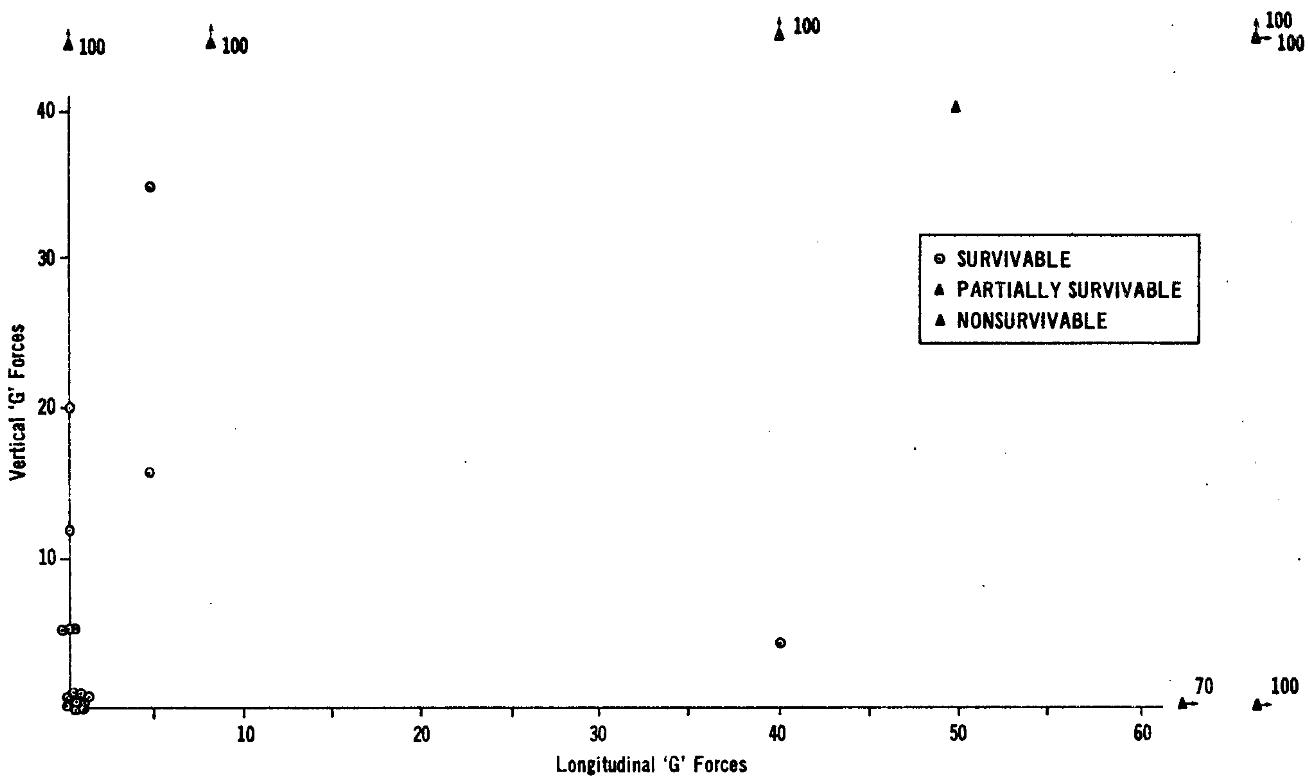

FIGURE 3.–Combined Vertical and Longitudinal Force Components (CH-47)

Impact Kinematics

The kinematics of the aircraft motion following initial ground impact influence occupant survivability by introducing additional crash hazards beyond the initial crash. The frequencies of occurrence of CH-47 impact kinematics which appeared to have the strongest influence on occupant survivability are shown in Figure 4.

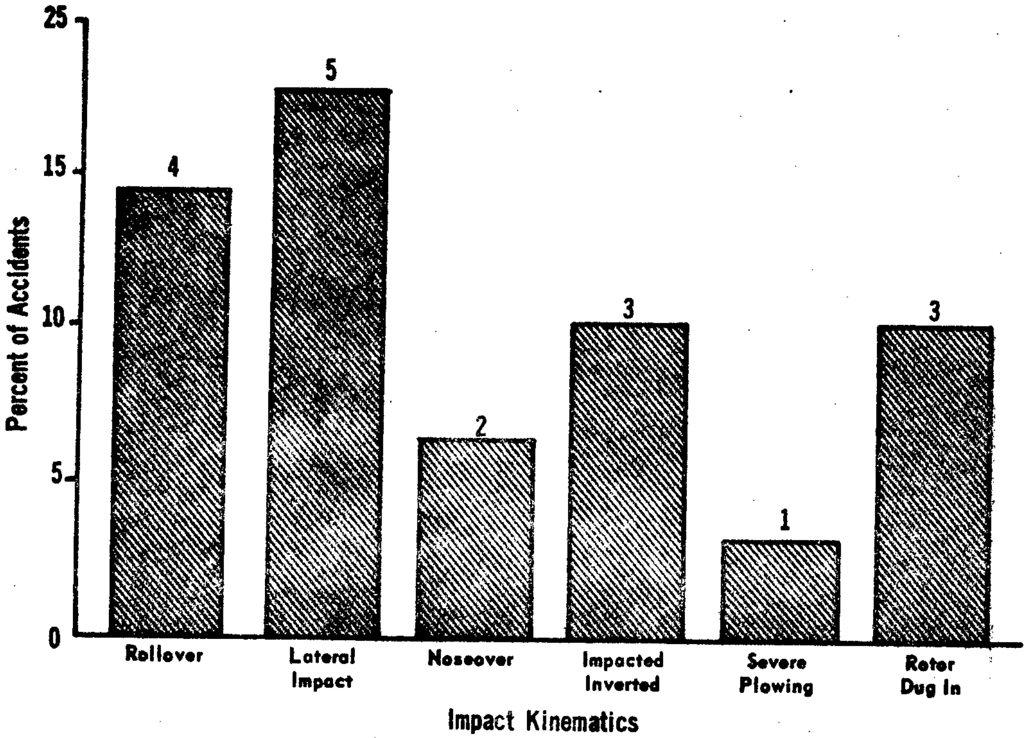

FIGURE 4.—Relative Frequency of CH-47 Impact Kinematics

Description of Terrain Struck

The type of terrain at the point of major impact affects occupant survivability through its influence on aircraft stopping distance. The relative frequency of occurrence of important terrain characteristics in the CH-47 accidents studied is shown in Figure 5.

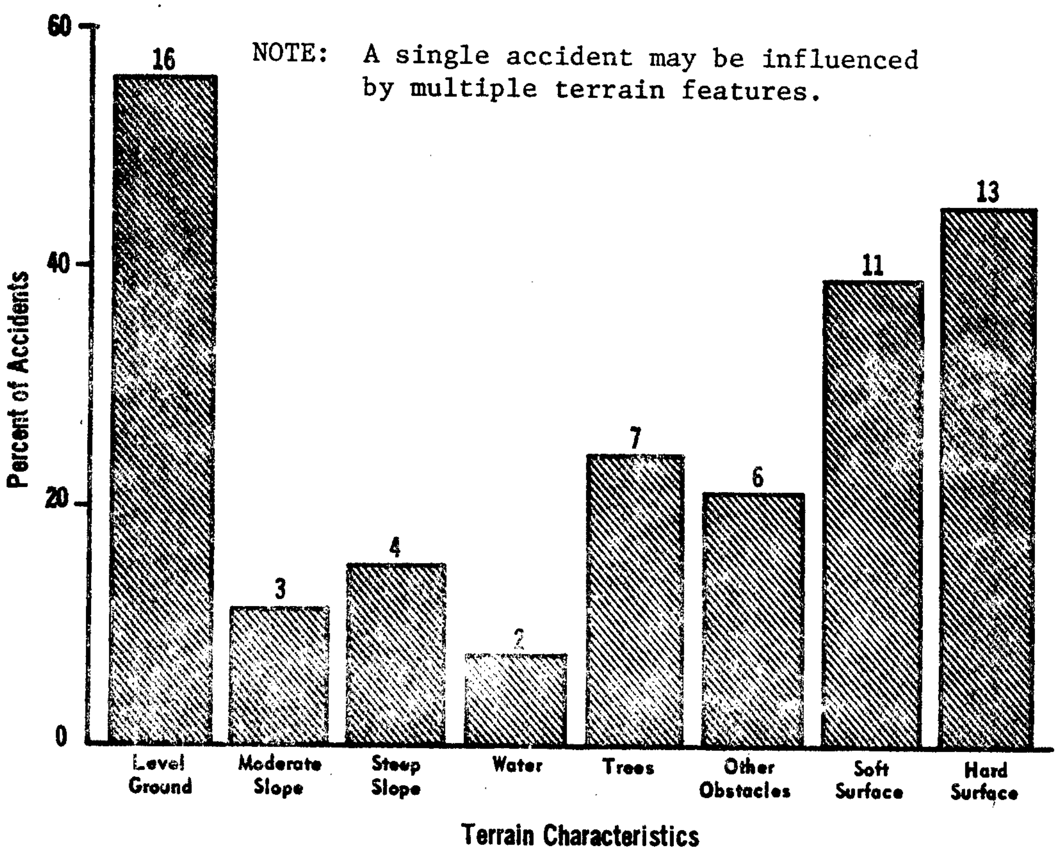

FIGURE 5.–Relative Frequency of CH-47 Accidents Involving Important Terrain Characteristics

Frequency of Injury by Severity

The frequency of injuries by severity is shown in Table II. (Multiple injuries per occupant are included in these figures.)

TABLE II

Frequency of CH-47 Injury by Severity (Casualties)

Severity	Percent of All Injuries	Percent of All Occupants
None	-	19.4
Minimal/Minor	15.0	8.2
Major	14.7	4.4
Critical	<1	<1
Fatal	55.0	52.7
Unclassified/Unknown	14.7	15.3
Total	100.0	100.0

Frequency of Injury by Location

The body locations of the above crash injuries have a strong influence on the engineering solution to the associated injury cause factors. Figures 6 through 8 indicate the relative frequency of injury to the major body locations.

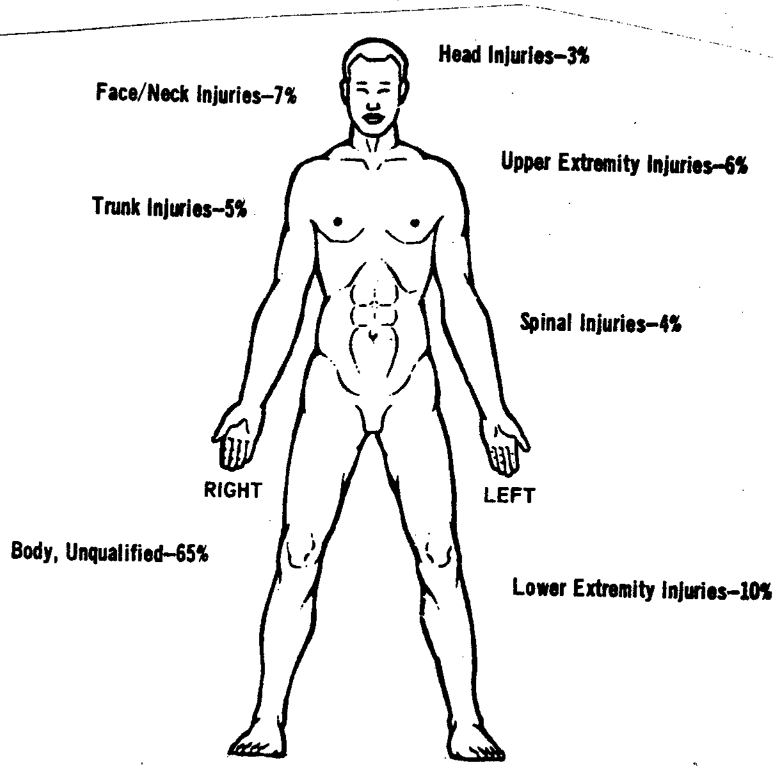

FIGURE 6.–Location of ALL Injuries

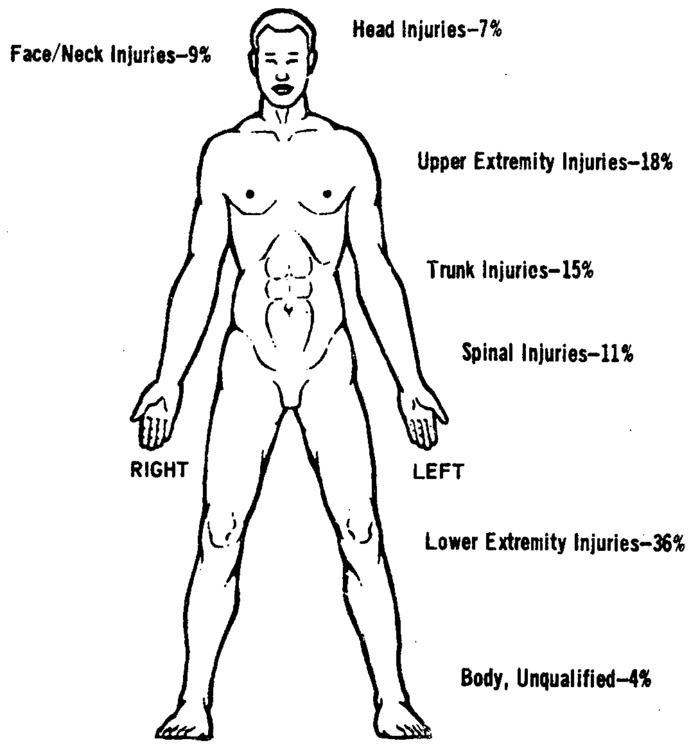

FIGURE 7.–Location of Major Injuries

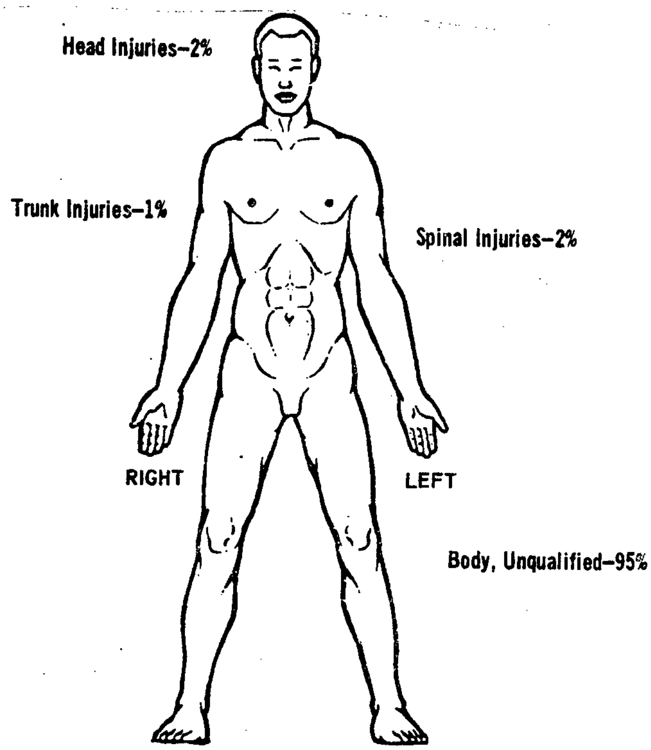

FIGURE 8.–Location of Fatal/Critical Injuries

Influence of Impact Conditions on Injury

Figure 9 depicts the relative frequency of back injuries versus impact vertical velocity change. Figure 9 indicates that significant numbers of back injuries do not occur in CH-47 impacts involving vertical velocity changes less than 25 feet per second.

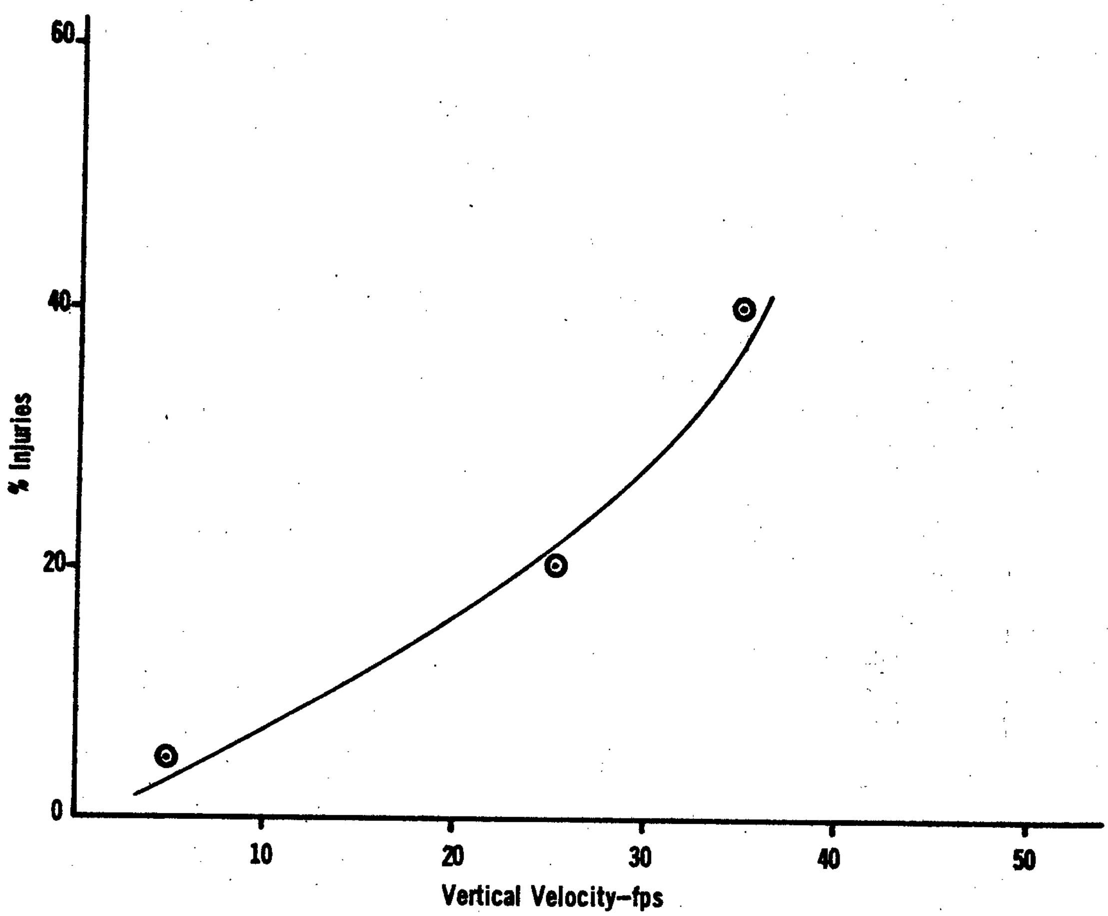

FIGURE 9.–Relative Frequency of Spinal Injuries Versus Change in Vertical Velocity (CH-47)

Frequency of Occurrence and Costs of Injury Mechanisms

Figure 10 depicts the frequency of occurrence and cost associated with the most prevalent crash injury mechanisms. All accidents regardless of survivability and all injuries regardless of severity are included in Figure 10. Figure 10 indicates that the injury mechanism which produced the largest frequency and cost of injuries was determined to be "Body struck structure." After these, the mechanisms of "Body exposed to fire" and "Body received excessive decelerative force" produced the next largest frequency and costs of injuries.

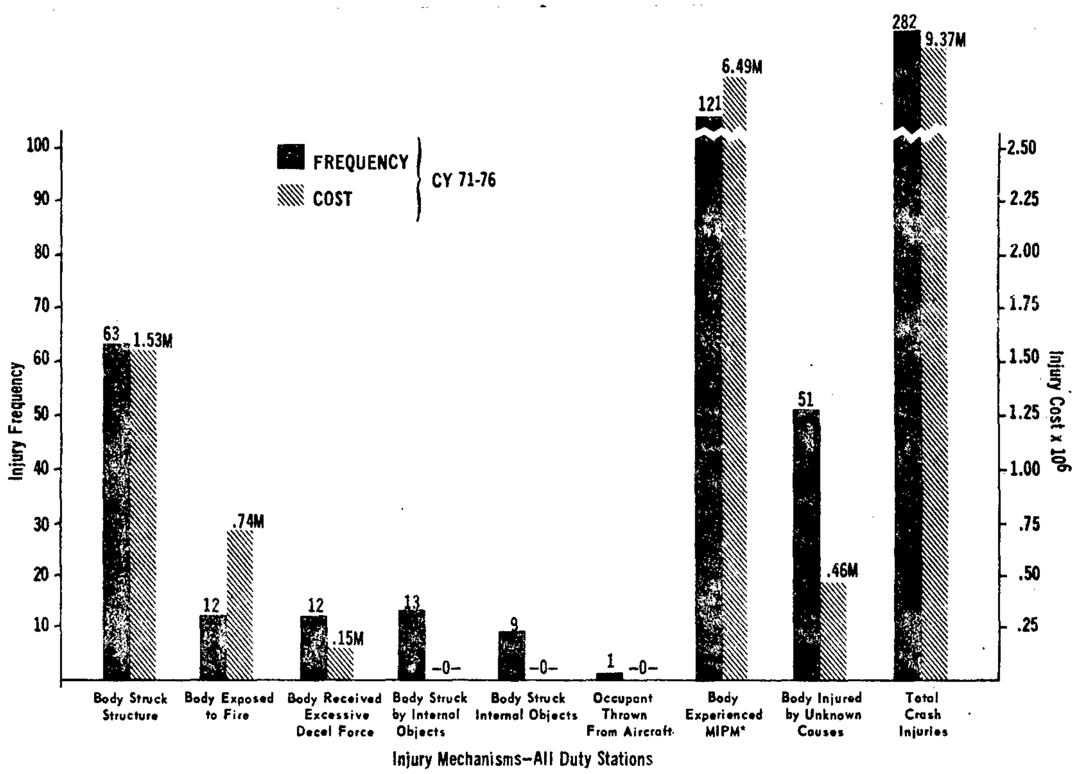

FIGURE 10.—Frequency and Costs of CH-47 Injury Mechanisms

*Multiple Injury Producing Mechanisms

Cause Factors Resulting in Injury Mechanism "Body Struck Structure"

As discussed above, the mechanism "Body struck structure" resulted in the highest frequency of injuries. The engineering factors which caused this mechanism to occur are depicted in Figure 11. Figure 11 indicates that the most frequent cause factor resulting in "Body struck structure" injuries was that a seat was not provided. This applied to 23 enlisted crewmembers (flight engineers, crew chiefs and door gunners) who were injured because their duties precluded use of the aircraft passenger seats. Figure 11 indicates that the next highest frequency cause factor resulting in "Body struck structure" was that a seat was provided but not used.

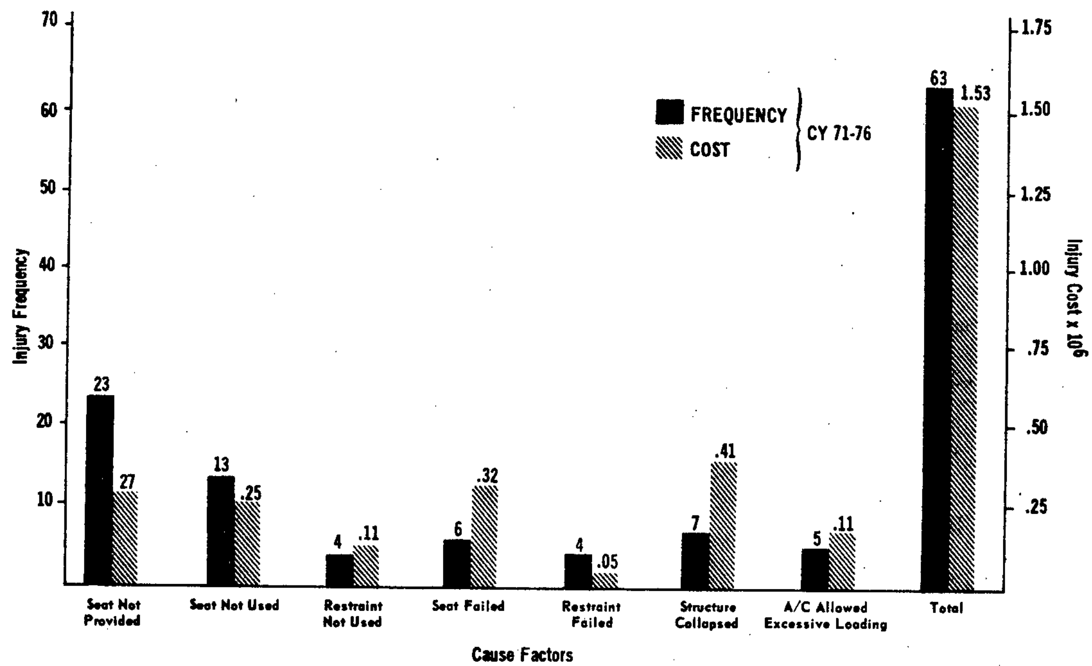

FIGURE 11.–Frequency and Costs of CH-47 Injury Cause Factors Resulting in "Body Struct Structure"

Most Significant Crash Hazards

The methodology for identification and ranking of these crash hazards is discussed in Reference [1]. That discussion has been extracted and is included as Appendix B.

The combinations of the above injury mechanisms and engineering cause factors comprise the crash hazards identified through analysis of CH-47 aircraft accident data. A total of 16 crash hazards were identified for this aircraft type. Table III lists the hazards in decreasing order of significance (based on frequency, severity and cost). The injury costs associated with each hazard were computed for a 20-year period of aircraft operation, with the rates and types of accidents assumed the same as in the base study period (CY 71-76). The fleet flying hour rate was taken to be 50,000 aircraft flight hours per annum, which is approximately the average annual rate over the most recent five year period for which complete data was available. The hazards listed in Table III are divided into two groups: those which are reasonably influenced by crashworthiness design and those which are not. This is done to focus on those hazards and injuries which are preventable. All of the hazards listed on the upper portion of Table III are potentially preventable.

It should be noted that Table III does not include costs associated with injuries which occurred in crashes in combat. Nor does it include costs due to litigation by injured personnel or their families, whether directly against the Government or indirectly against the Government's contractors. These additional cost factors could substantially increase the hazard costs shown in Table III.

TABLE III

Rank-Ordered Listing of CH-47 Crash Hazards

Hazard No.	Significance Group	Description	Frequency Index	Severity Index	Projected 20-Year Hazard Cost
Hazards reasonably influenced by crashworthiness design:					
1		FE/CE's struck structure because seat was not provided	A	I	629.9K
2		Personnel exposed to fire when fuel system failed on impact	B	I	956.3K
3		Personnel struck structure when structure collapsed	B	I	951.9K
4		Personnel exposed to fire when transmission oil ignited on impact	B	I	774.6K
5		Personnel struck structure when seat failed	B	I	738.2K
6		Personnel struck structure when aircraft allowed excessive load	B	I	384.9K
7		Personnel rec'd excessive decelerative load when seat and aircraft transmitted excessive force	B	I	219.5K
8		Personnel rec'd excessive decelerative force when seat/restraint failed	C	I	140K
9		Personnel struck structure because restraint failed/allowed excessive motion	B	II	14.7K
10		Personnel struck by internal objects due to inadequate restraint of cargo, etc.	B	III	5.8K
11		Personnel struck internal objects because restraint was not provided	B	III	.7K
12		Personnel thrown from aircraft because restraint/seats were not provided	D	II	9.1K
13		FE/CE received excessive load because seat was not provided	D	III	.2K
Hazards not reasonably influenced by crashworthiness design:					
14		Personnel experienced multiple injuries when impact exceeded design limits	A	I	15,129.5K
15		Unclassified/unknown injury causes	A	I	1,066.2K
16		PAX struck structure because seat or restraint was not used	A	I	842.2K

Crashworthiness R&D Requirements for Current Aircraft

The above rank-ordered listing of crash hazards was analyzed to identify pressing research and development requirements. Table IV summarizes the hardware deficiencies which resulted in serious but preventable hazards in current aircraft. Research, development and acquisition programs required to reduce these deficiencies are also suggested in Table IV, along with the potential 20 year savings which would accrue if all of the associated injuries were prevented.

TABLE IV
Crashworthiness RD&A Requirements for CH-47 Aircraft

Priority	Crashworthiness Deficiency	Hazards Resulting From This Deficiency	RD&A Requirement	Potential 20-Year Savings
1	Seats are not provided for enlisted crewmembers (FE, CE, gunner). Duties preclude use of existing pax seats during critical portions of flight (takeoffs, landings, and low level flight).	1, 11, 12, 13	Develop and procure enlisted crew seats which permit use during critical portions of flight. Primary crashworthiness design goal should be structural strength (±15g, 3 axes) rather than energy absorption. Personnel restraint system should be included per MIL-S-58095 to include lap belt and shoulder harness which permit the occupant to stand without releasing restraint. A design approach is contained in References 4 and 5.	639.9K
2	Pax seats fail under moderate crash loading, resulting in release of occupant restraint.	5, 8, 9	Develop and procure replacement pax seats having increased structural strength. Design goal should be 15g, 3 axes. Also, seat design should face fore and aft as much as practical, rather than laterally. Adequate lap belt and shoulder harness restraint should be included as integral part of seat. Possible design concept is contained in Reference 6.	892.9K
3	Transmission oil containers fail on crash impact. Flammable spray is released which ignites and results in postcrash oil fires.	4	Develop and procure crashworthy transmission oil containment. Design criteria should be equivalent to that contained in MIL-T-27422B for crashworthy fuel systems.	774.6K

In addition to the above requirements, preventable thermal injuries due to fuel-fed postcrash fires in accident aircraft not equipped with a crashworthy fuel system made the completion of the fuel system retrofit program a high priority requirement. This program has been completed during the study period for CH-47 aircraft, and therefore this requirement is considered fulfilled for this aircraft type. The thermal casualties which occurred in the study period, however, underscore the requirement to complete the retrofit of all aircraft types.

Additional R&D Requirements

The results of the present analysis suggest that a more accurate system of determining the impact conditions in all Army aircraft accidents is required. Presently, these conditions (velocities, angles and forces) are estimated by the accident investigation board based on witness statements and physical evidence such as aircraft and terrain damage. The inaccuracies in this method are evidenced by the fact that accurate estimates of the crash impact forces were impossible to obtain using information presently available. These data were seen to cluster around certain "typical, reasonable" values and precluded any valid estimate of their actual distribution (such as their 95th percentile values). An onboard crash data recorder is required for proper analysis of the impact conditions against which crashworthiness improvements must be designed and evaluated. Such a system is included as a portion of the Accident Information Retrieval System (AIRS) which is under development at the Army's Applied Technology Laboratory (Reference [8]).

CONCLUSIONS

Crashworthiness design deficiencies in CH-47 aircraft and the research necessary to remedy them have been identified based on a systematic analysis of aircraft accident reports.

It is concluded that the research, development and acquisition programs of highest priority in improving the crash survivability of the CH-47 series aircraft are:

(1) Enlisted crewmembers seat.

(2) Passenger seat with increased structural strength.

(3) Transmission oil containment systems with improved postcrash fire protection.

In addition, it is concluded that an onboard crash data recording system is necessary in all Army aircraft for accurate determination of future crashworthiness design criteria.

RECOMMENDATIONS

(1) Crashworthiness R&D for CH-47 aircraft address each of the three high priority research requirements identified in Table IV.

(2) Expedited development of the Accident Information Retrieval System.

(3) Application of the present study methodology to all operational Army aircraft.

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9. Headquarters, Department of Defense, *System Safety Program Requirements,* Military Standard 882A, 28 June 1977.

APPENDIX A

DEFINITIONS

Aircraft Accident - Damage which occurs to one or more aircraft while flight was intended. Damage as a direct result of hostile fire is not an accident but a combat loss.

Crash Force - The maximum value of an assumed triangular crash pulse, determined at the aircraft center of gravity, which occurs during the major impact.

Crash Hazard - A condition due to the design or configuration of an aircraft or life support equipment which may result in injuries to occupants in aircraft accidents.

Crashworthiness - The ability of a vehicle to sustain a crash impact and reduce occupant injury and hardware damage.

Hazard Frequency - The frequency of occurrence of injuries resulting from a particular crash hazard.

Hazard Severity - The severity of the worst credible injury resulting from a particular crash hazard.

Hazard Cost - The sum of the costs of all injuries resulting from a particular crash hazard.

Injury Cause Factor - The design deficiency which caused a specific injury mechanism to occur.

Injury Classification - A designation of the medical significance of all of the injuries incurred by a given casualty taken as a whole.

Injury Cost - The economic effect on the operational readiness of the Army due to accidental injuries to servicemembers, as calculated according to Reference [2].

Injury Mechanism - The mechanical process through which a specific injury was determined to have occurred, i.e., "what happened."

Injury Severity - A designation of the medical significance of a specific injury.

Major Impact - That impact of the aircraft which results in the largest decelerative forces being transmitted to the aircraft and occupants.

Survivable Accident - An accident in which the following statements are satisfied for at least one occupant aboard the aircraft:

a. The forces transmitted to the occupant through his seat and restraint system do not exceed the limits of human tolerance to abrupt accelerations.

b. The fuselage structural container maintains a livable volume around the occupant.

Non-Survivable Accident - An accident in which neither of the above statements is satisfied for all occupants aboard the aircraft.

Partially Survivable - An accident in which both survivable and non-survivable occupant positions exist.

Velocity Change - The change in velocity of the aircraft cg during the major impact.

Other terminology is as defined in Reference [3].

APPENDIX B

METHODOLOGY FOR IDENTIFICATION AND RANKING OF CRASH HAZARDS (FROM USAAAVS TECH REPORT TR 78-3)

As used herein, a crash hazard consists of the combination of an injury location, its mechanism and its associated cause factor. These hazards identified through the analysis of accident reports were rank-ordered according to their overall significance. The criteria which were used to rank the hazards were (1) the frequency of injuries resulting from the hazard, (2) the severity of these injuries and (3) their total cost. For purposes of shorthand notation, these factors are termed the "hazard frequency", "hazard severity" and "hazard cost", even though the <u>result</u> of the hazard is the factor which is being evaluated and not the hazard itself.

The procedure used to rank the hazards consisted of two steps: first, the hazards were placed into groups of significance according to their frequency and severity. Next, the hazards within each significance group were ranked according to their cost. These hazards were considered in identifying urgent crashworthiness research and development programs for both current and future helicopters.

Ranking According to Frequency

Each hazard was evaluated according to the frequency of occurrence of the resulting injuries as shown in Table B-I. The format and rationale for this frequency ranking was modeled after Reference [9].

TABLE B-I

Crash Hazard Frequency Ranking

Frequency Index	Descriptive Nomenclature	Mathematical Definition
A	Frequent	$0.5 < f$*
B	Reasonably probable	$0.1 < f \leq 0.5$
C	Occasional	$0.05 < f \leq 0.1$
D	Remote	$0.01 < f \leq 0.05$
E	Improbable	$f \leq 0.01$

*f is defined as the relative frequency of injury occurrence and is calculated as

$$f = \frac{\text{Frequency of occurrence of resulting injuries}}{\text{Number of accidents studied}}$$

Ranking According to Severity

Each crash hazard was evaluated relative to the severity of the resulting injuries as shown in Table B-II. The rationale and format for this severity ranking procedure was taken from Reference [9].

TABLE B-II

Crash Hazard Severity Ranking

Severity Index	Descriptive Nomenclature	Definition
I	Life-threatening	Results** in fatal or critical injury
II	Serious	Results in major injury
III	Marginal	Results in minor injury
IV	Negligible	Results in no more than minimal injuries

**Worst credible result

Overall Ranking of Crash Hazards

The results of evaluating each crash hazard according to its frequency and severity as described above were used together to place the hazards into overall significance groups. The frequency and severity rankings of each hazard were weighted equally in this process. Table B-III indicates how all hazards were placed into one of eight groups as determined by the combination of frequency and severity indices.

TABLE B-III

Hazard Significance Groups Based On Frequency & Severity Indices

Significance Group	Frequency Index-Severity Index
1	A.I
2	A.II, B.I
3	A.III, B.II, C.I
4	A.IV, B.III, C.II, D.I
5	B.IV, C.III, D.II, E.I
6	C.IV, D.III, E.II
7	D.IV, E.III
8	E.IV

After placing all hazards into significance groups, the crash hazards <u>within</u> each group were then rank-ordered according to the cost of the resulting injuries. The rank-ordered list which resulted comprises a "totem pole" cf the most serious crash hazards.

APPENDIX C

PARTICIPANTS IN STUDY GROUP

The analysis contained herein is the result of the efforts of a study group chaired by USAAAVS. Participants are listed below:

US Army Agency for Aviation Safety, Fort Rucker, AL

Dr. James E. Hicks, Aerospace Engineer (Chairman)
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