AMRL-TR-65-36

A SUMMARY OF HUMAN TOLERANCE TO PROLONGED ACCELERATION

ALVIN S. HYDE, MD, PhD
HAROLD W. RAAB

FEBRUARY 1965

BIOPHYSICS LABORATORY
AEROSPACE MEDICAL RESEARCH LABORATORIES
AEROSPACE MEDICAL DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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ERRATA, June 1965

The following corrections apply to Technical Report No. AMRL-TR-65-36, A Summary of Human Tolerance to Prolonged Acceleration.

Page 5

Paragraph entitled "Number of Subjects Attaining:" 3rd line change "$(n < 1)$" to read "$(n > 1)$"

Page 6

Table II, under column headed "Duration at G (Seconds)" 1st line add "660"

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FOREWORD

This effort was conducted in the Environmental Stress Branch, Multi-environment Division, Biophysics Laboratory of the Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, in support of Project No. 7222, "Biophysics of Flight." The data were selected from a comprehensive search of the literature and summarized during the period from January 1963 to January 1965.

The authors wish to acknowledge Mr. John W. Frazier and Mr. Raymond U. Whitney of the Environmental Stress Branch for their assistance in reviewing and selecting pertinent data from the AMRL Centrifuge Record Books.

This technical report has been reviewed and is approved.

J. W. HEIM, PhD
Technical Director
Biophysics Laboratory

ABSTRACT

Human subject tolerance to accelerations of greater than one second duration is summarized for the orthogonal X, Y, and Z axes. Because each investigator at each laboratory utilizes different restraint systems, body positions, ambient temperatures, etc, and most important, utilizes different criteria of "tolerance," the data are referenced and presented in tables and graphs for each major category (direction) of acceleration. The points presented in the graphs and tables are usually the highest values achieved; in each series there were subjects who could not tolerate the given direction, amplitude, and duration.

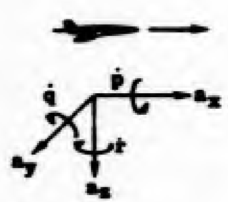
TABLE OF CONTENTS

LIST OF TABLES

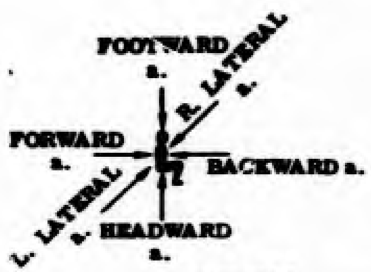
LIST OF ILLUSTRATIONS

TABLE I

BODY ACCELERATION - COMPARATIVE TABLE OF EQUIVALENTS (REF. 12)



SYSTEM 1



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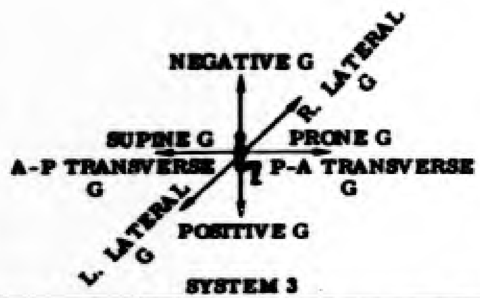
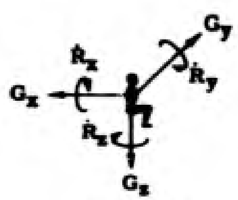


SYSTEM 3



SYSTEM 4

LINEAR MOTION	TABLE A Direction of Acceleration		TABLE B Inertial Resultant of Body Acceleration		
	Aircraft Computer Standard (Sys. 1)	Acceleration Descriptive (Sys. 2)	Physiological Descriptive (Sys. 3)	Physiological Computer Standard (Sys. 4)	Vernacular Descriptive
Forward	$+ a_x$	Forward accel.	(1,2) Transverse A-P G Supine G Chest to Back G	$+ G_x$	Eye Balls In
Backward	$-a_x$	Backward accel.	Transverse P-A G Prone G Back to Chest G	$-G_x$	Eye Balls Out
Upward	$-a_z$	Headward accel.	Positive G	$+ G_z$	Eye Balls Down
Downward	$+a_z$	Footward accel.	Negative G	$-G_z$	Eye Balls Up
To Right	$+a_y$	R. Lateral accel.	Left Lateral G	$+ G_y$	Eye Balls Left
To Left	$-a_y$	L. Lateral accel.	Right Lateral G	$-G_y$	Eye Balls Right
ANGULAR MOTION					
Roll Right	$+\dot{p}$		Roll	$-\dot{R}_x$	
Roll Left	$-\dot{p}$			$+\dot{R}_x$	
Pitch Up	$+\dot{q}$		Pitch	$-\dot{R}_y$	
Pitch Down	$-\dot{q}$			$+\dot{R}_y$	
Yaw Right	$+\dot{r}$		Yaw	$+\dot{R}_z$	
Yaw Left	$-\dot{r}$			$-\dot{R}_z$	

FOOTNOTES:

1. Large letter, G, used as unit to express inertial resultant to whole body acceleration in multiples of the magnitude of the acceleration of gravity. Acceleration of gravity, g_o, = 980.665 cm/sec^2 or 32.1739 ft/sec^2.
2. A-P, P-A refers to Anterior-Posterior, Posterior-Anterior.

SECTION I

INTRODUCTION

For vehicle design and mission analysis, any clearly expressed relationship existing between man's tolerance and the onset rate, magnitude, and duration of sustained acceleration force would be desirable. Indeed, attempts have been made by some experimenters (e.g., refs 5, 16, 19) to express these relations. Their utility, however, is limited because they are inaccurate. This has been established by comparing the attempted predictions with data obtained from reviewing the literature reporting human acceleration tolerance experiments. Such inspection demonstrates nearly random disparity between prediction and reality, with both over- and underestimation of tolerance occurring often and with random severity.

We have no quarrel with the desirability of establishing stimulus:response relationships; they are a major goal of environmental physiologists and a continuing need for design engineers. Because no predictive relationship has yet been found, this report presents a summary of data from the literature in the form of tables and graphs, using standard terminology.

SECTION II

ACCELERATION TERMINOLOGY

Table 1 summarizes the terminology in use in major laboratories throughout the world; it is derived from an Advisory Group for Aeronautical Research and Development (AGARD)—North Atlantic Treaty Organization (NATO) agreement regarding the equivalence of acceleration terminology. The terms in this report are those of table B, system 4, entitled : Physiological Computer Standard. This system is preferred by facilities with multiple degree-of-freedom devices on the basis of simplifying computer programing. This system of terminology utilizes the direction in which tissue is displaced as a result of acceleration, either angular or linear.

SECTION III

METHOD OF PRESENTATION

Most of the graphs present the magnitude of acceleration on an arithmetic ordinate axis and the duration of exposure on a logarithmic abscissa. Separate groups of graphs are included for each direction of acceleration, i.e., the X, Y, and Z (orthogonal) axes. Each group of graphs (G_x , G_y , G_z) is further divided on the basis of the presence, absence, or character of experimental variables, such as restraint and support system, aides (i.e., anti-G suit, pressure breathing, etc.) and the number of subjects involved (n=1, n > 1).

For each graphic summary of magnitude, direction, and duration, a stick-figure illustration of the subject's attitude is given (with respect to the acceleration vector) and a table is provided. Each table defines each point on each graph with respect to the following variables: vector magnitude, duration, average onset (G/second), back angle (degrees of tilt), cause of termination of experimental exposure, trauma, number of subjects involved, countermeasures used, support, restraint, and the reference from which this information was obtained.

SECTION IV

RESULTANT VECTOR MAGNITUDES AND THE RETINAL-AORTIC AXIS

The $+G_z$ (footward inertia) component of any acceleration directly influences a subject's tolerance to any acceleration. The footward redistribution of blood produced by this direction of inertial force first influences the perfusion of blood to the subject's eyes, through his brain, causing loss of vision (blackout) and loss of consciousness, respectively.

An important, but obscure, relation exists between the anatomic $+G_z$ and the physiologic $+G_z$, the latter being termed Retinal-Aortic $+G_z$. This relation results because the eyeballs are in front of (ventral to) the anatomic G_z axis. That is, a line drawn from the root of the heart to the eyes and a line extended along the G_z axis and passing through the heart will include an angle of approximately 15°. In figure 1, the effective angle causing blackout, termed the Retinal-Aortic $+G_z$, is compared to the $+G_x$ and $+G_z$ component of any given acceleration. The ordinate in figure 1 gives the percent of any acceleration vector amplitude in each of three axes ($+G_z$, $+G_x$, and Retinal-Aortic +G), all as a function of the back angle (the amount of forward angulation of the subject toward the direction of acceleration). The angle included between the subject's $+G_z$ axis and the plane normal (perpendicular) to the direction of acceleration is given as the abscissa. For example, if a subject is inclined 45° toward a 10-G acceleration, the acceleration is then termed either a +10 G_x or a +10 G_z, and the resultant in the X-axis (see figure 1) is about +7 G_x and the apparent $+G_z$ acceleration is also +7 G_z. However, the Retinal-Aortic $+G_z$ is 15° forward and the effective vector component contributing to blackout, therefore, is about +9 G_z. With regard to causing blackout, this is approximately 28% greater than is apparent from the $+G_z$ component used alone.

The reader must be sensitive to the back angles utilized in $+G_x$ acceleration. Resolving the $+G_z$ component of a $+G_x$ acceleration is not enough; the reader must also resolve the Retinal-Aortic axis component if he desires to realize the effective contributor to blackout or loss of consciousness evolving from a given $+G_x$

acceleration. The same applies to $+G_z$ accelerations; the reader must again obtain the Retinal-Aortic component to predict probable tolerance in the Z-axis.

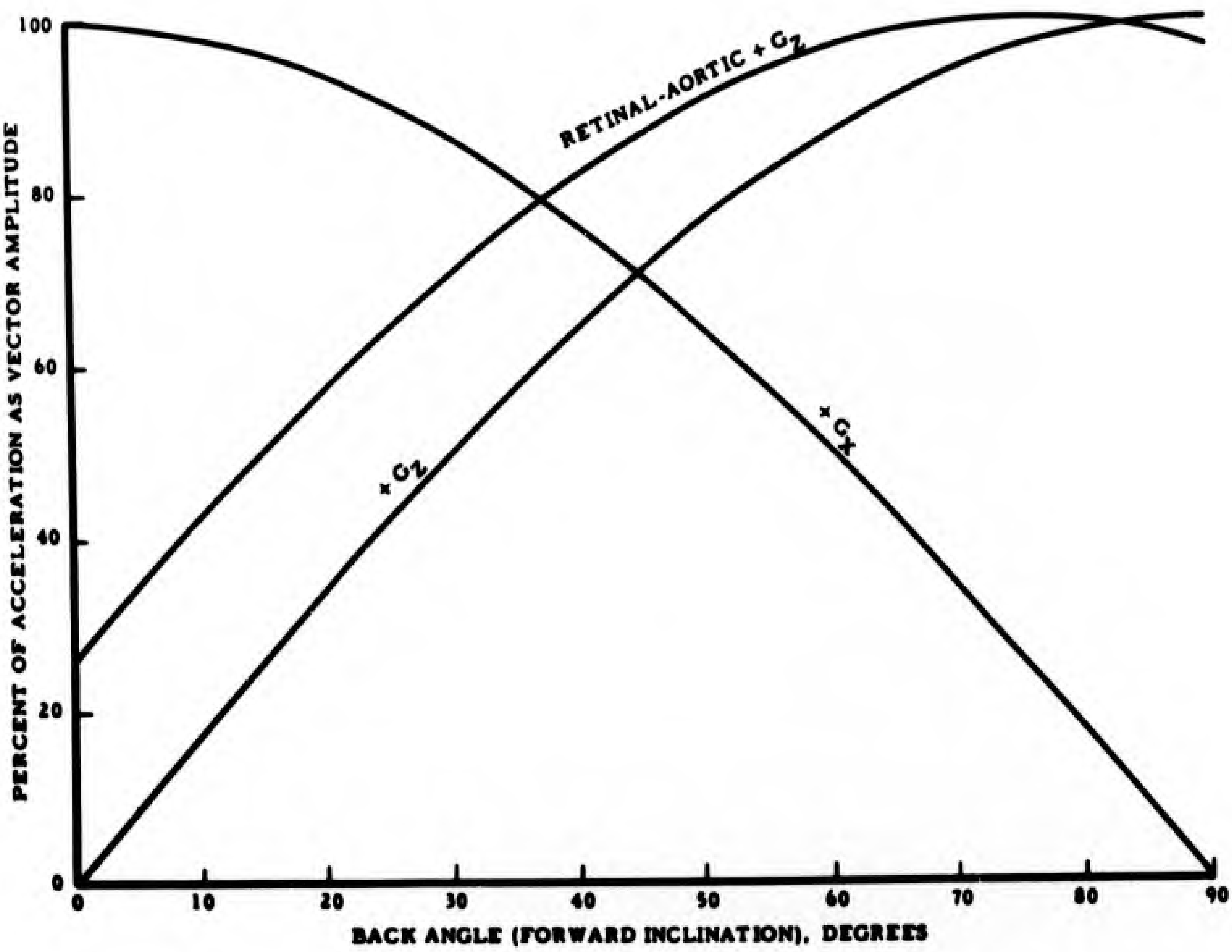


Figure 1. Resolution of Important Vectors of Any Given X-, or Z-Axis Accelerations (Ref 18)

SECTION V

TOLERANCE

The term "tolerance" means different things to different people. The flight-controls designer designates a given decrement in man-machine performance as unacceptable, and any environmental input that causes less than this given decrement is termed "tolerable." The physiologist designates certain functional decrements, say a 30% decrease in cardiac output, as "intolerable." The same may be true of other reference systems, such as visual acuity, thus, the particular tolerance that is meant must be defined.

In this report the term "tolerance" also means many different things, because the various investigations reported herein were often of different intent, therefore, different criteria were used for what was and was not tolerable. The criteria used to terminate any given experiment have been assigned to categories (in this report) as "subjective" or "arbitrary" (time limit). The reader should consult the specific report referenced for details of any given point on the graphs.

To reduce the number of points plotted on the graphs, only the highest runs (both amplitude and duration) of any series were used. Replication of magnitude points of different durations of exposure indicates that other significant variables should be considered, since large differences in tolerance were obtained with different restraint systems, countermeasures and so forth. The graphs and tables (figs. 2-14 and tables II-XIII) necessarily represent present upper limits of known, primarily subjective, tolerance, and should be recognized as upper limits; there are many subjects who, for any given time, duration, and direction of acceleration, could not tolerate the exposure.

SECTION VI

SUMMARY OF DATA

EXPLANATION OF TERMS AND COLUMN HEADINGS

G (Dimensionless): The ratio of acceleration (deceleration) resulting from a change in velocity or direction to acceleration due to the earth's gravity.

Resultant Vector Magnitude (G): The resultant inertial force (in G units acting on a subject resolved from component forces, such as tangential, centripetal, linear, and gravitational acceleration.

Component Vector (s) Magnitude (G): The orthogonal component (s) of the resultant vector.

Vector Magnitude (G):	Same as resultant vector magnitude.
Duration at G (Seconds):	The length of time a subject is at the G-level indicated. "Peak" denotes an acceleration profile with no "plateau." At the rates of onset in this report there is little error in plotting peak as equivalent to a one-second duration.
Average Rate of Onset (G/Second):	A measure of how rapidly G is applied to the subject.
Back Angle (Degrees):	The angulation of subject's trunk with respect to a plane normal (perpendicular) to the resultant acceleration axis. (See the "Subject Configuration" figures.)
Cause of Termination:	The symbol (S) is used when the subject terminates the experiment because of pain, fatigue, or dyspnea, or when he is not permitted to continue because of heart rate, ECG changes, or "blackout." The symbol (A) is used for termination of totally arbitrary nature, such as arbitrary time limits, or completion of experimental measurements.
Trauma:	Trauma listed are those reported in the references and are of a "serious" nature. The notation "none" does not exclude blackout, petechiae, fatigue, or discomfort.
Number of Subjects Attaining:	A duration attained by a single subject (n=1) in a group of subjects (e.g., 1 of 4) is the longest of the group. Durations attained by more than one subject (n<1) in a group of subjects (e.g., 3 of 4) are the longer of the group.
Countermeasures:	Countermeasures are those aids (e.g., Anti-G suit) intended to augment the physiology of the subject. The notation "none" does not exclude the use of "natural" aids, such as straining (M-1 maneuver) and abdominal breathing.
Support:	A structure, such as an aircraft seat, that supports a subject's body and determines the presentation of the subject to the inertial vector.
Restraint:	Restraints are those accessories (e.g., harness) that restrain the subject from forces that the support does not.

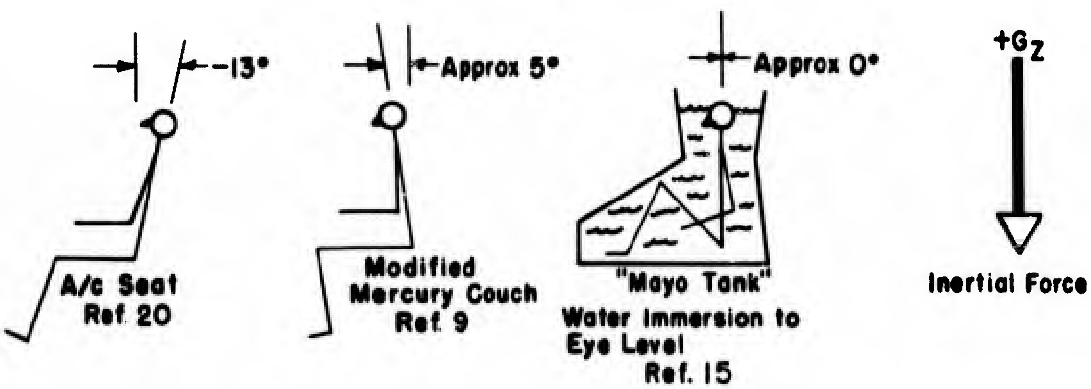
TABLE II*

+Gz n = 1

Vector Magnitude (G)	Duration at G (Seconds)	Average Onset (G/Second)	Back Angle (Degrees)	Cause of Termination	Trauma	Number of Subjects Attaining	Countermeasures	Support	Restraint	Reference
Unaided n = 1										
4.5		0.07	13°	A	None	1 of 8	Subjects Instructed to Relax: None	Aircraft Seat	Integrated Harness	20
4.0	1260	0.07	13°	A	None	1 of 8	None	" "	" "	20
3.5	3600	0.07	13°	A	None	1 of 8	None	" "	" "	20
Aided n = 1										
16.0	Peak	12.5 Sec. to Peak Sinusoidally	Approx. 0°	S	Irritation of Glottis and Pharynx	1	Hydrostatic Counter-pressure to Eye Level	"Mayo Tank"	Bungee Cords	15
6.0	390	?	Approx. 5°	S	None	1	Anti-G Suit	Modified Mercury Couch	Helmet and Webbing	9
6.0	120	0.07	13°	A	None	1 of 8	" " "	Aircraft Seat	Integrated Harness	20
5.0	300	0.07	13°	A	None	1 of 8	" " "	" "	" "	20
4.0	1200	0.07	13°	A	None	1 of 2	" " "	" "	" "	20
3.5	3600	0.07	13°	A	None	1 of 4	" " "	" "	" "	20

*See also figure 15 for tolerance levels using the criterion of vision.

Subject Configuration



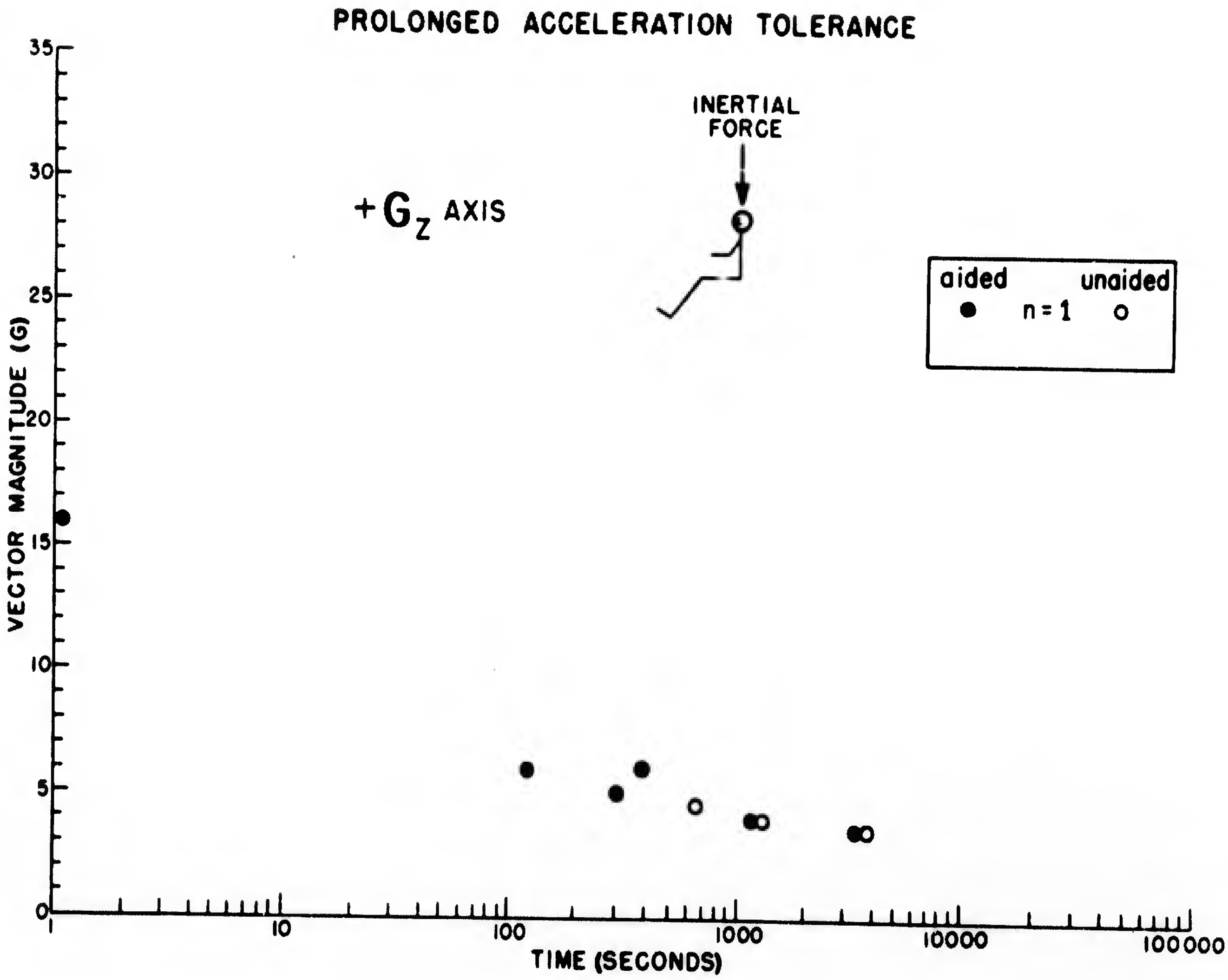


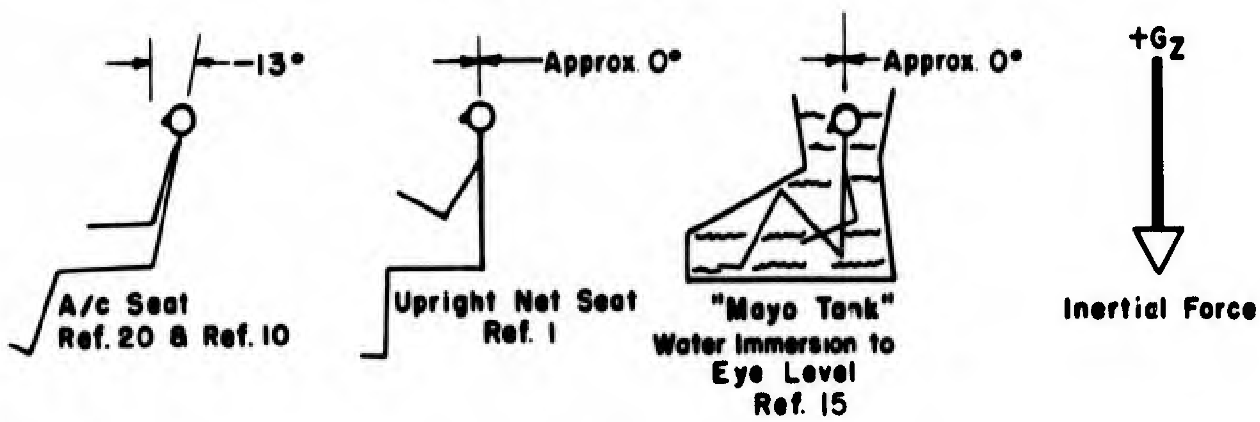
Figure 2. $+G_z$, n = 1

TABLE III

+Gz n>1

Vector Magnitude (G)	Duration at G (Seconds)	Average Onset (G/Second)	Back Angle (Degrees)	Cause of Termination	Trauma	Number of Subjects Attaining	Countermeasures	Support	Restraint	Reference
Unaided n>1										
9.0	Peak	0.07	0°	A	None	2 of 31	None (M-1 Maneuvers)	Upright Net Seat	None	1
7.0	15-30	0.56	Approx. −10°	A	None	3 of 33	Subjects Instructed to Relax: None	Aircraft Seat	? Integrated Harness	10
5.0	240	0.07	−13°	A	None	3 of 8	None	" "		20
4.5	≥540	0.07	−13°	S	None	3 of 8	None	" "	" "	20
4.0	≥1200	0.07	−13°	A	None	3 of 8	None	" "	" "	20
3.5	>2700	0.07	−13°	S	None	3 of 8	None	" "	" "	20
3.0	3600	0.07	−13°	A	None	7 of 8	None	" "	" "	20
Aided n>1										
10.5	Peak	12.5 Sec. to Peak Sinusoidally	Approx. 0°	A	None	2	Hydrostatic Counter-pressure to Eye Level	"Mayo Tank"	Bungee Cords	15
10.0	Peak	12.5 Sec. to Peak Sinusoidally	Approx. 0°	A	None	3 of 3	" " " "	" "	" "	15
7.0	15-30	0.56	Approx. −10°	A	None	13 of 30	Anti-G Suit	Aircraft Seat	? Integrated Harness	10
6.0	≥60	0.07	−13°	S	None	4 of 8	" " "	" "		20
5.0	≥240	0.07	−13°	A	None	6 of 8	" " "	" "	" "	20
4.5	600	0.07	−13°	A	None	4 of 8	" " "	" "	" "	20
4.0	≥720	0.07	−13°	S	None	2 of 2	" " "	" "	" "	20
3.5	≥1340	0.07	−13°	S	None	4 of 4	" " "	" "	" "	20
3.0	3600	0.07	−13°	A	None	2 of 3	" " "	" "	" "	20

Subject Configuration



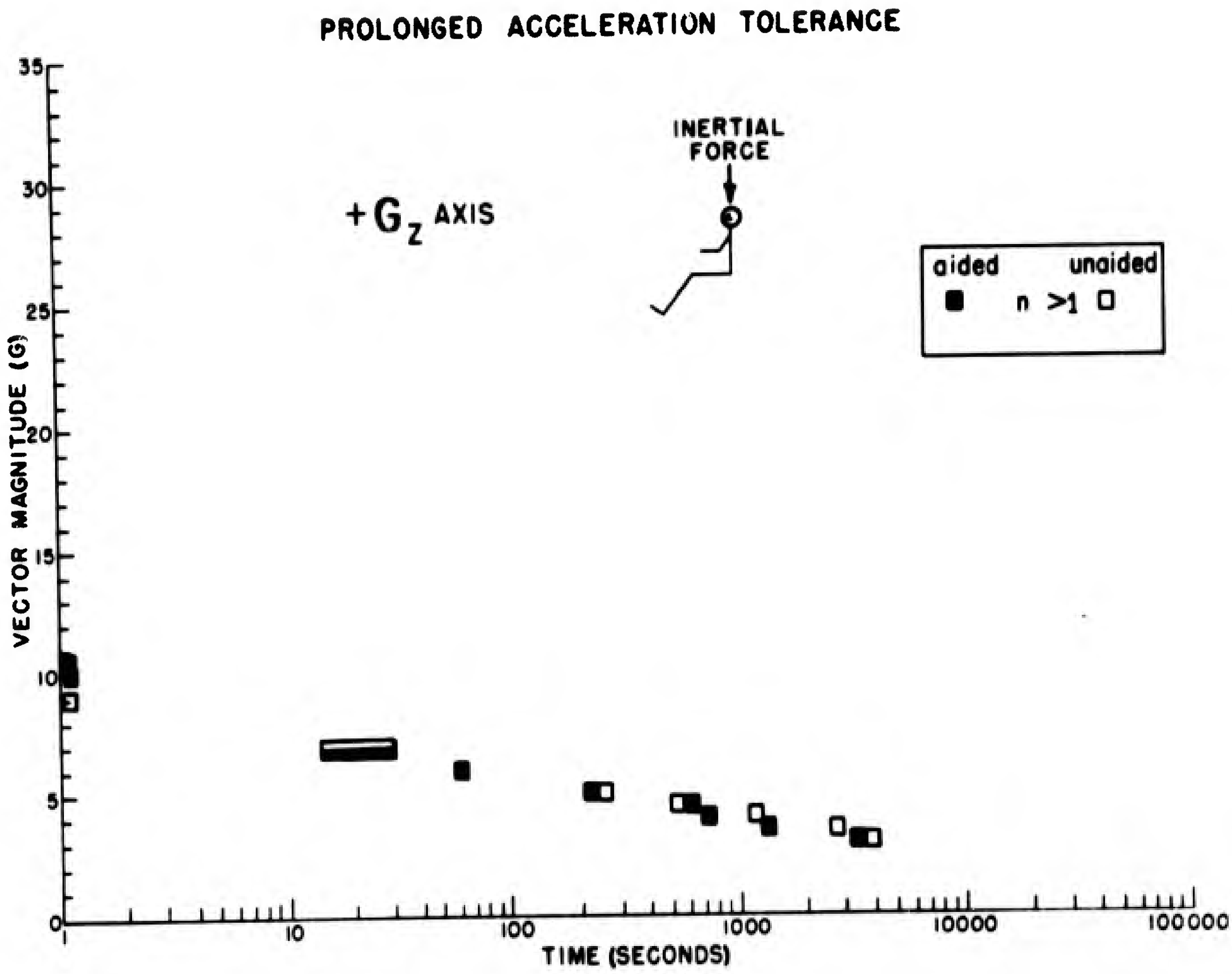


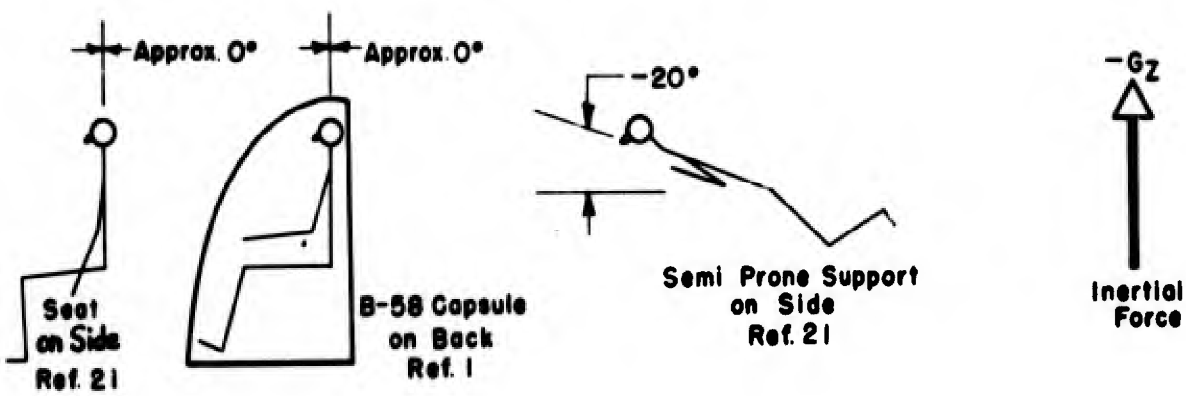
Figure 3. $+G_z$, n> 1

TABLE IV

Gz

Vector Magnitude (G)	Duration at G (Seconds)	Average Onset (G/Second)	Back Angle (Degrees)	Cause of Termination	Trauma	Number of Subjects Attaining	Countermeasures	Support	Restraint	Reference
Unaided n = 1										
4.5	5	? Aircraft Maneuvers	?	S?	None	1	None	Aircraft Seat	Lap Belt	26
2.5	56		Approx. 0°?	S?	None	1	None	Aircraft Seat	Harness	1
2.5	30		Approx. 0°	A	None	1	None	B-58 Capsule on Back	Harness	1
2.0	60		?	A	None	1	None	Turntable	Harness	1
1.5	68		?	A?	None	1	None	Turntable	Harness	1
Unaided n>1										
3.0	10	Usually > than 0.2	Approx. 0°	A	None	5 of 19	None	Seat	Harness	21
2.5	10		Approx. 0°	A	None	19 of 21	None	Seat	Harness	21
Aided n>1										
5.0	10		Approx. 0°	A	None	15 of 15	Pressure Helmet 25 mm Hg/G	Seat	Harness	21
4.0	10		Approx. 0°	A	None	15 of 15	" " " "	Seat	Harness	21
4.0	10		−20°	A	None	14 of 14	Body Position with Respect to Vector	Semiprone Support	Padded Wood Form	21
3.0	10		Approx. 0°	A	None	29 of 29	Pressure Helmet 25 mm Hg/G	Seat	Harness	21

Subject Configuration



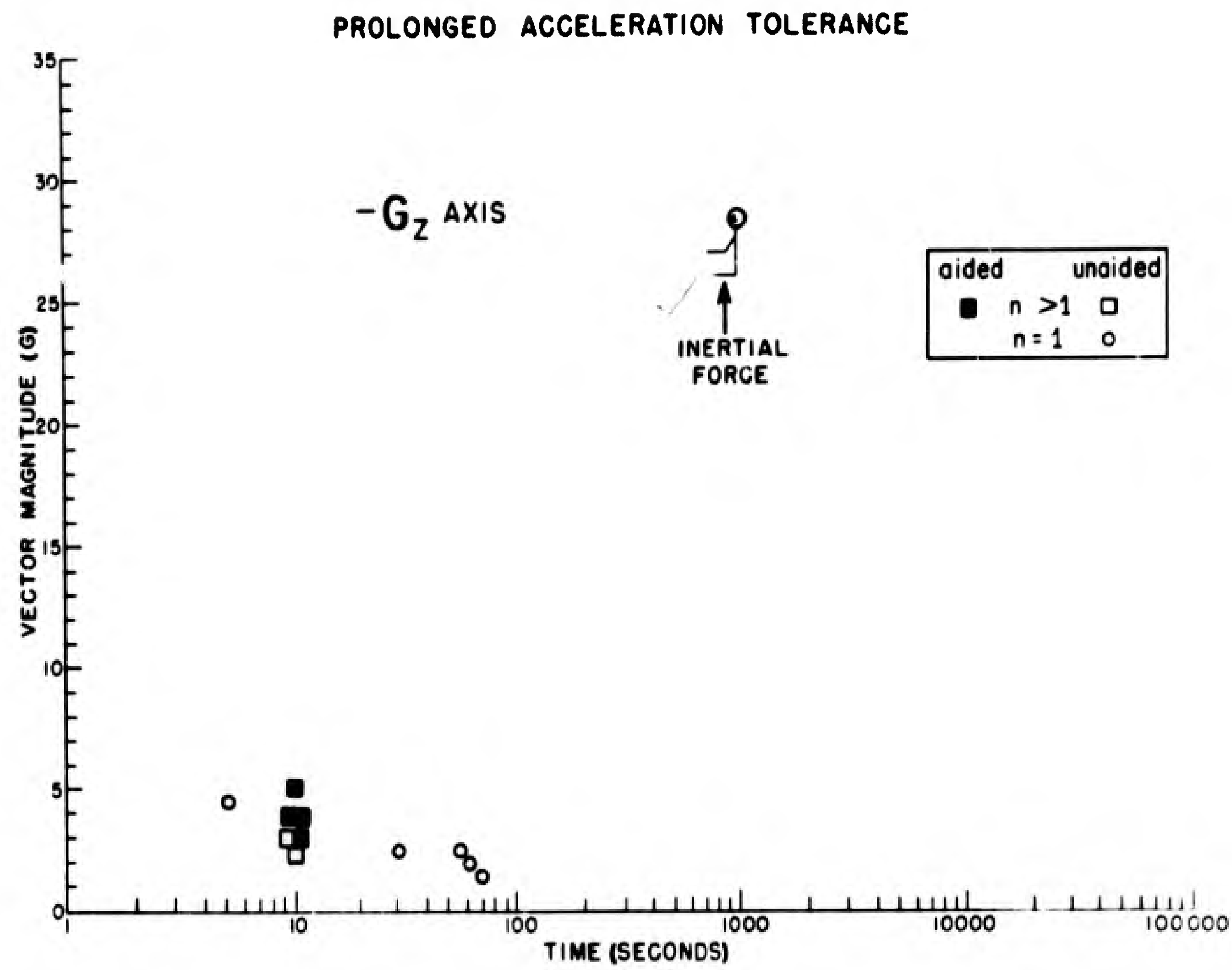

PROLONGED ACCELERATION TOLERANCE
$-G_Z$ AXIS
INERTIAL FORCE
aided
unaided
n >1
n = 1
VECTOR MAGNITUDE (G)
TIME (SECONDS)
35
30
25
20
15
10
5
0
1
10
100
1000
10000
100000

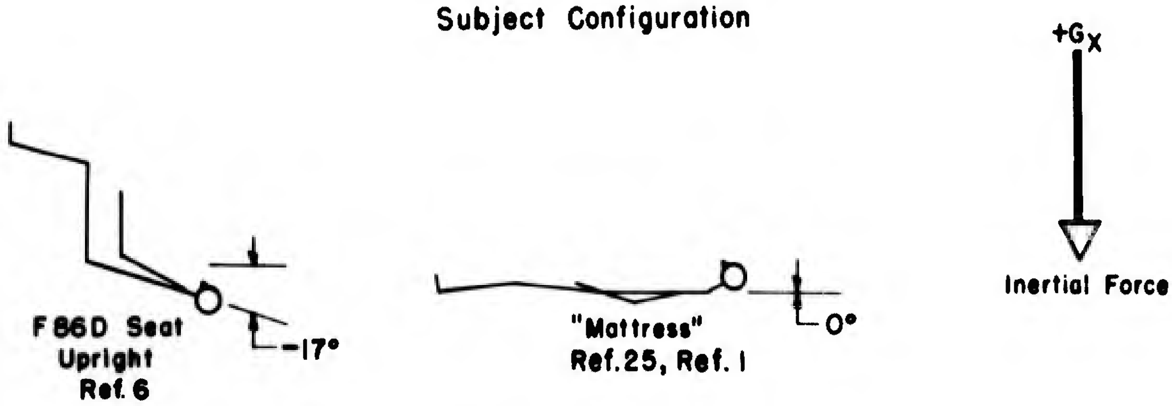
Figure 4. $-G_z$

TABLE V

+Gx 17° to 0° Back Angle n = 1

Vector Magnitude (G)	Duration at G (Seconds)	Average Onset (G/Second)	Back Angle (Degrees)	Cause of Termination	Trauma	Number of Subjects Attaining	Countermeasures	Support	Restraint	Reference
Unaided n = 1										
12.0	Peak	0.2	0°	S?	None	1	None	Mattress	None	1
10.0	150	?	0°	S	None	1	100% O_2	Foam Matt.	None	25
8.0	Peak	0.5	17°	S	None	1	None	F-86D Seat	Helmet and Lap Belt	6
8.0	195	?	0°	A	None	1	None	Mattress	None	1
8.0	13	0.5	17°	S	None	1	None	F-86D Seat	Helmet and Lap Belt	6
6.0	390	"Gradual"	0°	A	None	1	None	Mattress	None	1
4.0	600	"Gradual"	0°	A	None	1	None	Mattress	None	1
3.0	610	"Gradual"	0°	A	None	1	None	Mattress	None	1
Aided n = 1										
10.0	328	0.1 to 0.2	0°	S	None	1	19 mm Hg 100% O_2 Positive Pressure Breathing	Foam Matt.	MA-2 Helmet	25
10.0	252	0.1 to 0.2	0°	S	6 Hour Hemoptysis	1	29 mm Hg 100% O_2 Positive Pressure Breathing	Foam Matt	MA-2 Helmet	25

Subject Configuration



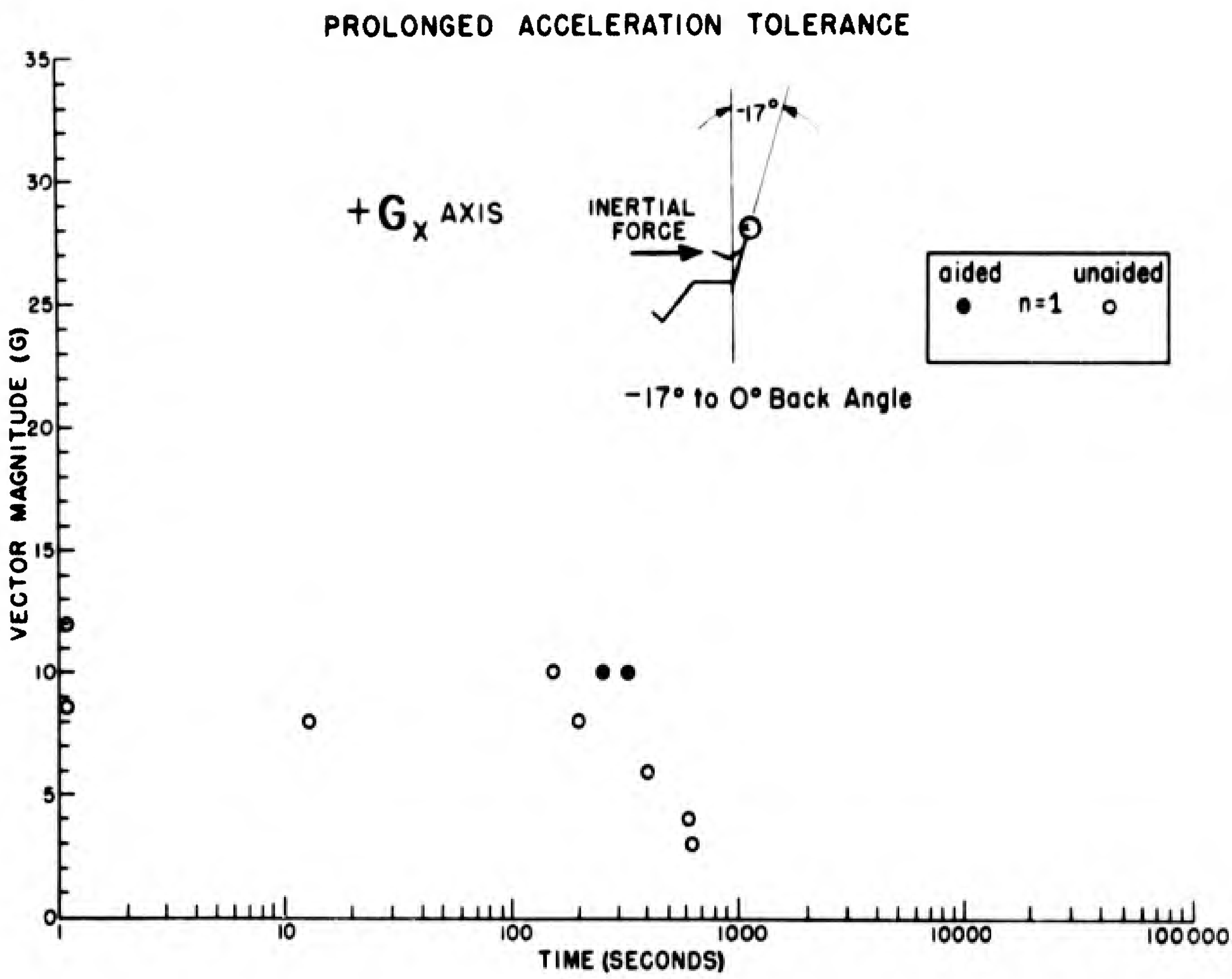
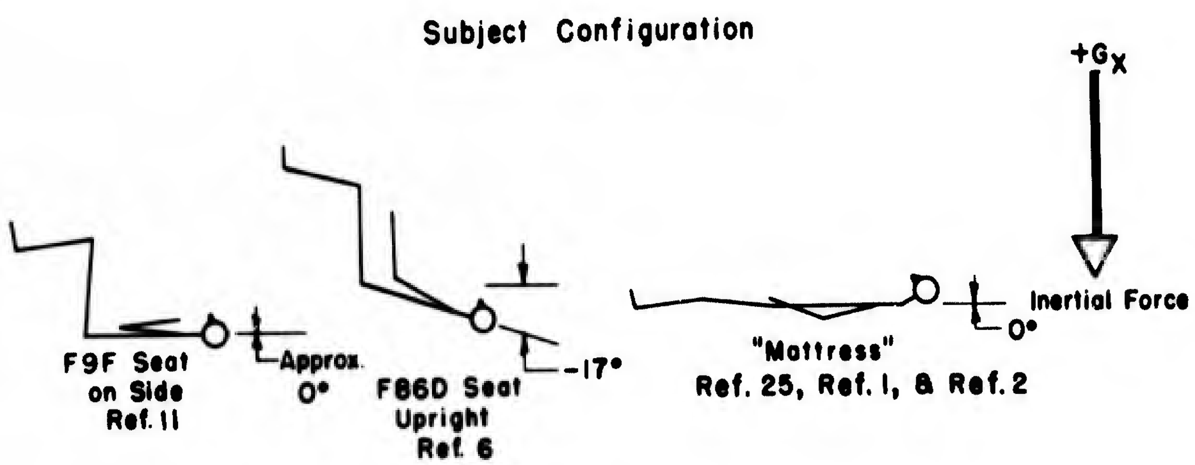


Figure 5. $+G_x$, -17° to 0° Back Angle n = 1

TABLE VI

+Gx 17° to 0° Back Angle n>1

Vector Magnitude (G)	Duration at G (Seconds)	Average Onset (G/Second)	Back Angle (Degrees)	Cause of Termination	Trauma	Number of Subjects Attaining	Countermeasures	Support	Restraint	Reference
Unaided[1] n>1										
15.0	5	8-10	Approx. 0°	Considered as Voluntary Limit	None	5 of 5	None	F-9F Seat on Side	Harness	11
10.0	>130	?	0°	S	None	3 of 9	100% O_2	Foam Matt.	None	25
8.0	>180	0.2	0°	A	None	7	None	Mattress	None	1
8.0	Peak	0.5	17°	S	None	4	None	F-86D Seat	Helmet and Lap Belt	6
7.0	210	?	0°	A	None	7 of 8	None	Cotton Matt.	None	2
6.0	>360	0.2	0°	A	None	7	None	Mattress	None	1
6.0	270	?	0°	A	None	7 of 8	None	Cotton Matt.	None	2
5.0	330	?	0°	A	None	9 of 9	None	Cotton Matt.	None	2
5.0	>180	0.2	0°	A	None	6	None	Mattress	None	1
4.0	>600	"Gradual"	0°	A	None	7	None	Mattress	None	1
4.0	480	?	0°	A	None	9 of 9	None	Cotton Matt.	None	2
3.0	900	?	0°	A	None	9 of 10	None	Cotton Matt.	None	2
Aided n>1										
10.0	>200	0.1 to 0.2	0°	S	1 Subject Hemoptysis	4 of 9	19-29 mm Hg 100% O_2 Positive Pressure Breathing	Foam Matt.	None MA-2 Helmet	25



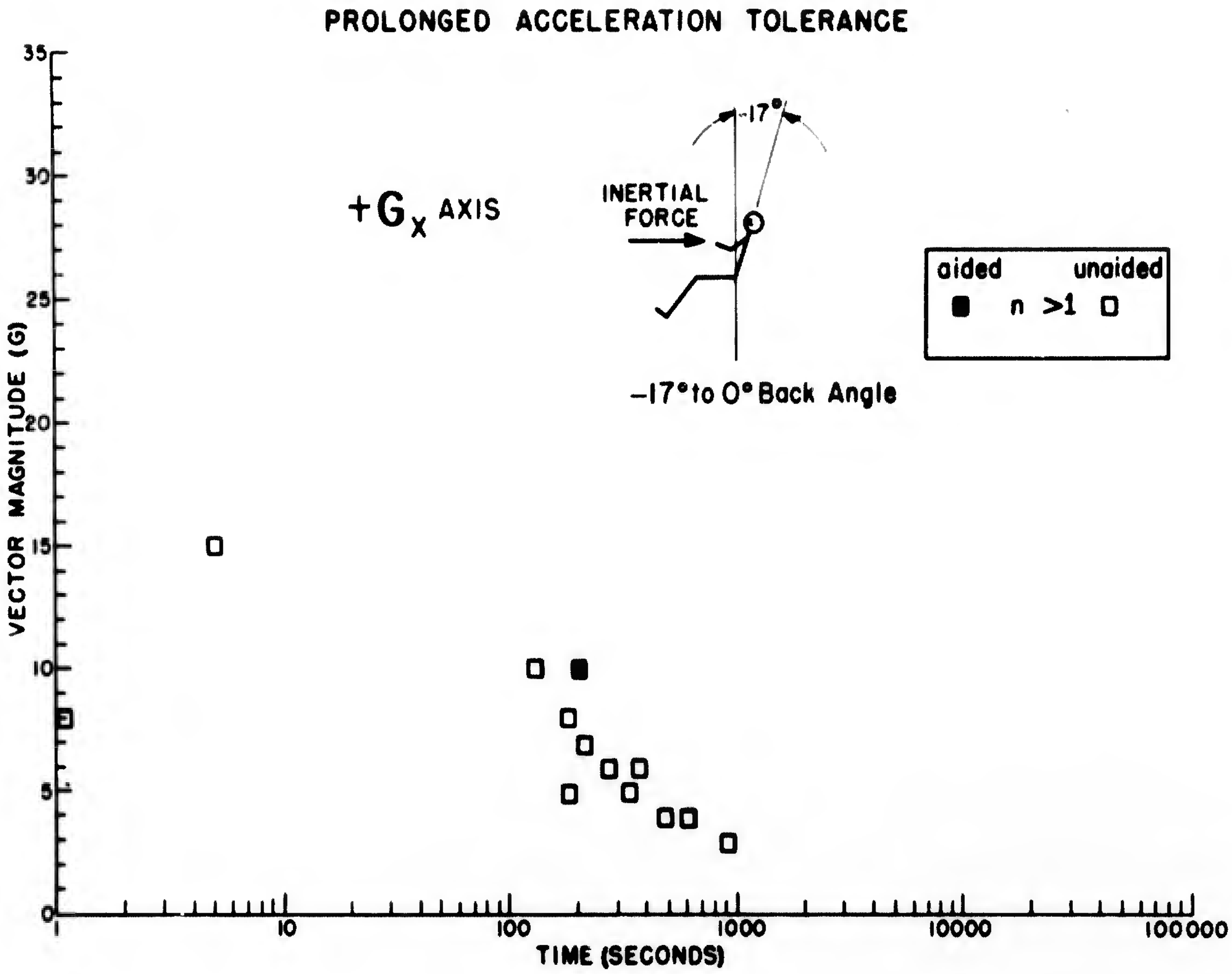


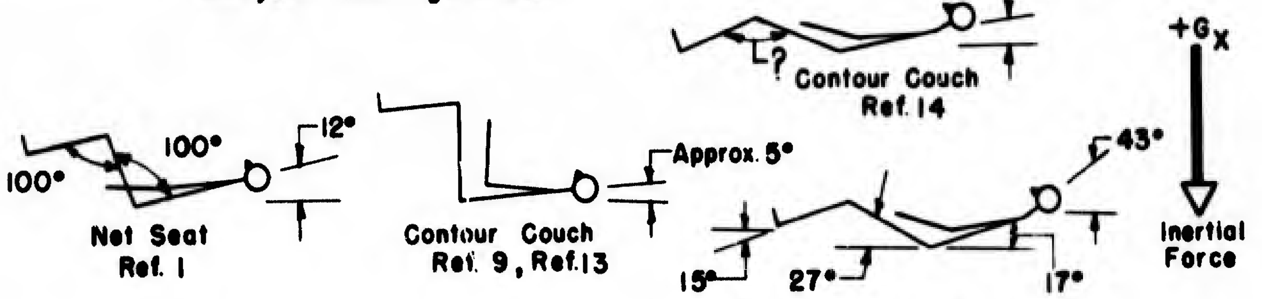
Figure 6. $+G_x$, -17° to 0° Back Angle n > 1

TABLE VII

+Gx 5° to 17° Back Angle n = 1

Vector Magnitude (G)	Duration at G (Seconds)	Average Onset (G/Second)	Back Angle (Degrees)	Cause of Termination	Trauma	Number of Subjects Attaining	Countermeasures	Support	Restraint	Reference
Unaided n = 1										
14.0	127	?	Approx. 5°	S?	None	1	None?	Contour Couch	Ref. 23	13
12.0	173	0.2	12°	S?	None	1	None	Net Seat	None	1
12.0	105	"Rapid"	12°	S?	None	1	None	" "	None	1
10.0	90	"Rapid"	12°	A	None	1	None	" "	None	1
9.0	270	0.2	12°	A	None	1	None	" "	None	1
8.0	240	?	12°	A	None	1	None	" "	None	1
6.0	540	0.1	12°	A	None	1	None	" "	None	1
6.0	500	?	12°	A?	None	1	None	" "	None	1
6.0	390	?	Approx. 5°	S?	None	1	None	Modified Mercury Couch	Helmet and Webbing	9
4.5	850	"Gradual"	12°	S?	None	1	None	Net Seat	None	1
4.0	660	?	12°	A	None	1	None	" "	None	1
3.0	1800	0.2	12°	A	None	1	None	" "	None	1
Aided n = 1										
25.0	Peak	?	Approx. 10°	S?	None	1	Anti-G Suit?	Molded Couch	?	14
23.0	Peak	?	Approx. 10°	A	Inverted T-Wave	1	Anti-G Suit?	" "	?	14
20.7	Peak	1.0	17°	A	None	1 of 2	Anti-G Suit	NACA Mod. 1 Contour Couch	Harness	8
8.0	600	"Rapid"	12°	A	None	1	100% O_2 Positive Pressure Breathing	Net Seat	A-13A Mask	1

Subject Configuration



NACA Contour Couch Mod. 1

Note: One of 2 subjects experienced B.O. at 16 G_X at this 17° back angle (Ref. 8)

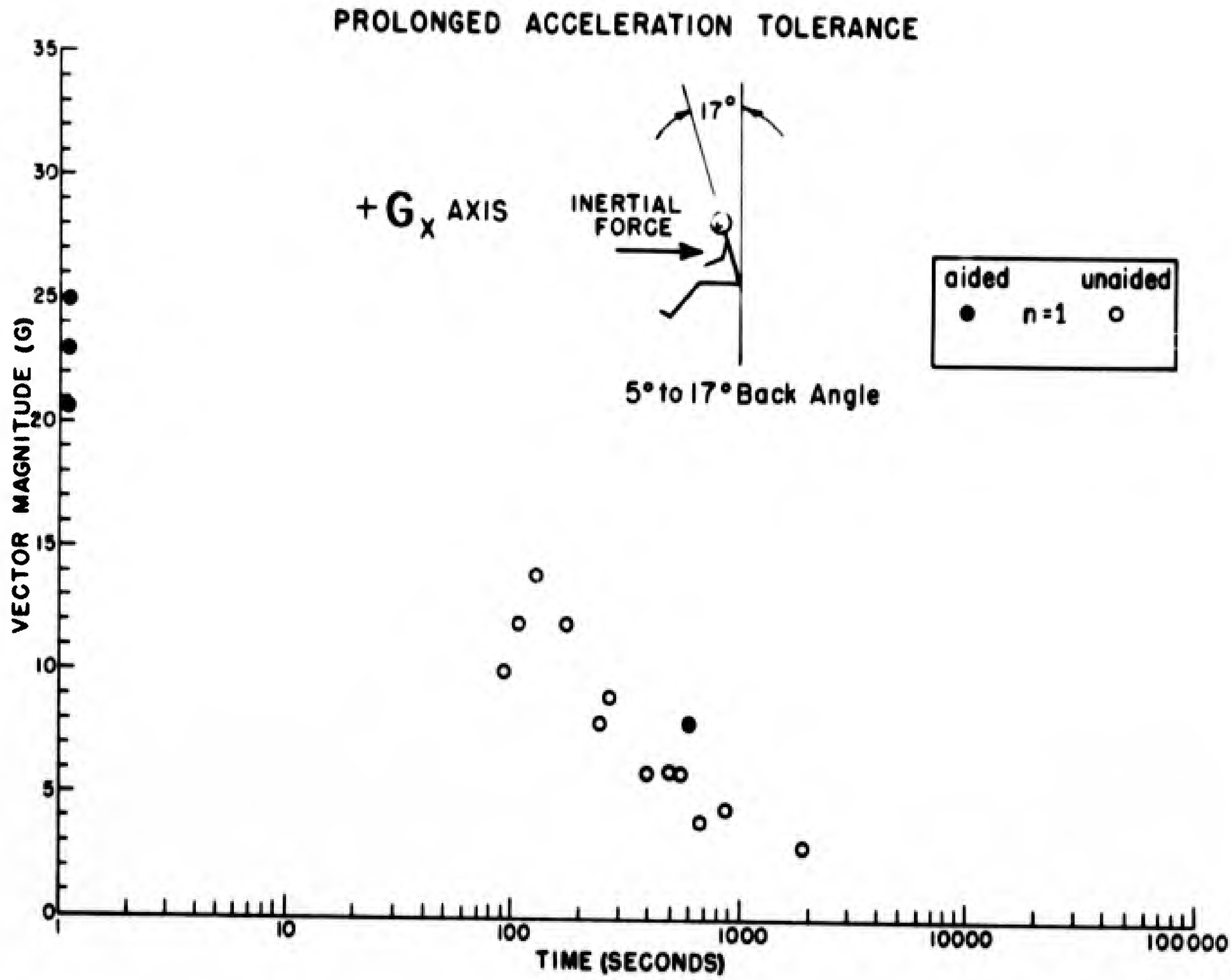


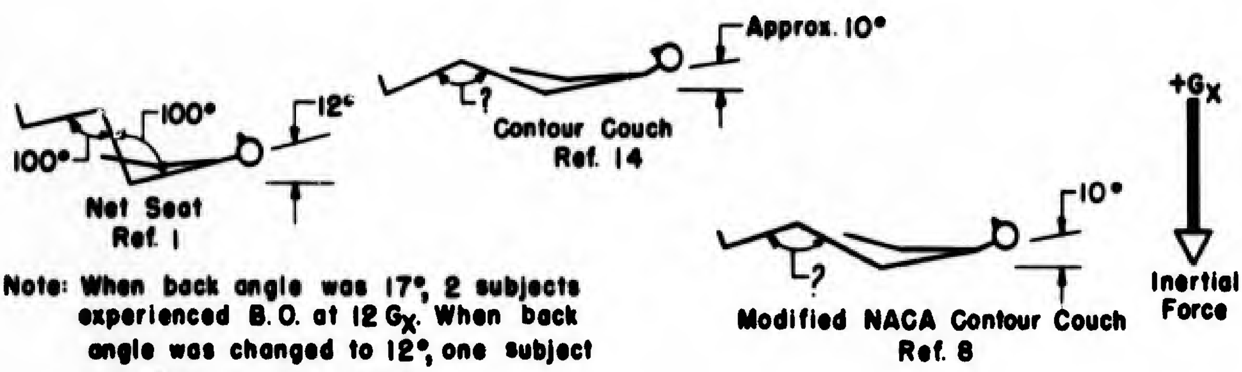
Figure 7. $+G_x$, 5° to 17° Back Angle n = 1

TABLE VIII

+Gx 5° to 17° Back Angle n>1

Vector Magnitude (G)	Duration at G (Seconds)	Average Onset (G/Second)	Back Angle (Degrees)	Cause of Termination	Trauma	Number of Subjects Attaining	Countermeasures	Support	Restraint	Reference
Unaided n>1										
16.5	Peak	0.14 to 8.5G, then 0.32 to 16.5G	12°	A	None	5 of 7	None	Net Seat	None	7
12.0	≥110	0.2	12°	S?	None	3	None	" "	None	1
12.0	≥60	"Rapid"	12°	A	None	10	None	" "	None	1
12.0	45	1.0	12°	A	None	8	None	" "	None	1
10.0	≥60	"Rapid"	12°	A	None	3	None	" "	None	1
8.0	≥240	"Rapid"	12°	A	None	2	None	" "	None	1
8.0	≥85	0.2	12°	A	None	10	None	" "	None	1
6.0	>60	0.2	12°	A	None	6	None	" "	None	1
4.0	≥600	"Gradual"	12°	A	None	8	None	" "	None	1
Aided n>1										
23.0	Peak	?	Approx. 10°	A	1 Subject Inverted T-Wave	2	Anti-G Suit?	Molded Couch	?	14
20.7	Peak	1.0	10°	A	None	2 of 2	Anti-G Suit	NACA Mod. 1 Contour Couch	Harness	8

Subject Configuration



Note: When back angle was 17°, 2 subjects experienced B.O. at 12 G_x. When back angle was changed to 12°, one subject had B.O. at 16 G_x. (Ref. 7)

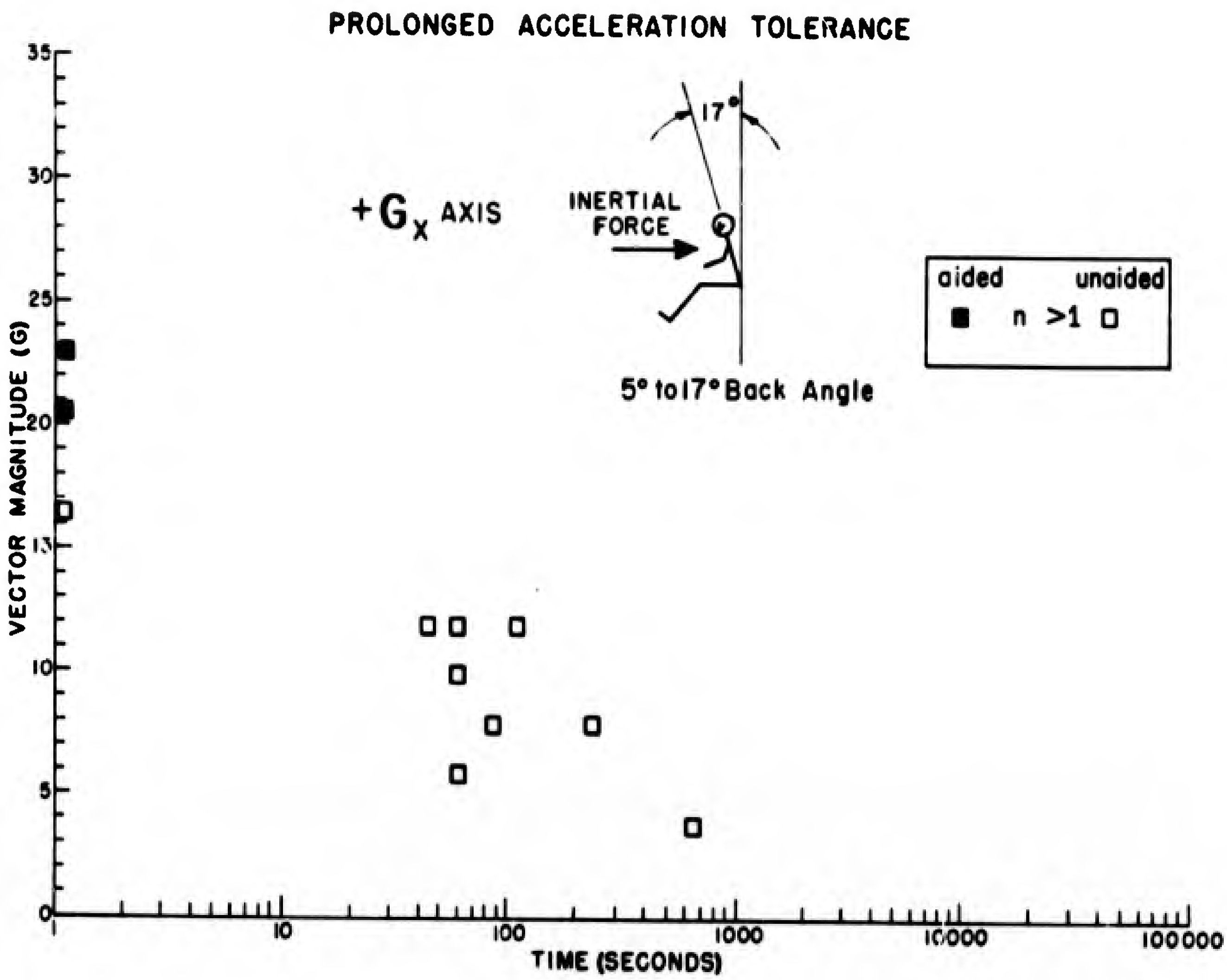


Figure 8. $+G_x$, 5° to 17° Back Angle n > 1

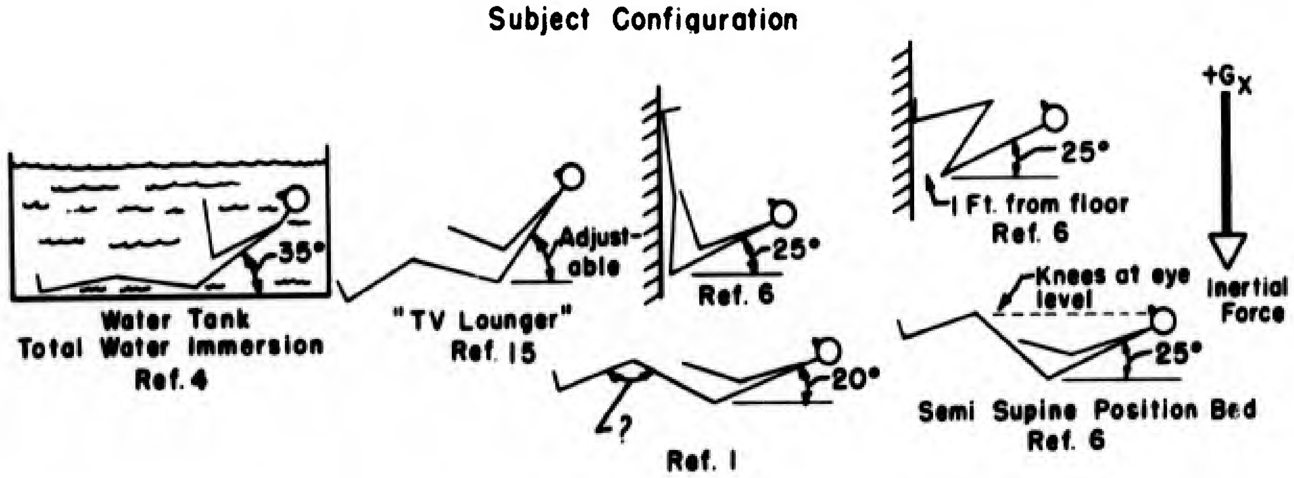
TABLE IX

+Gx 20° to 45° Back Angle n = 1

Vector Magnitude (G)	Duration at G (Seconds)	Average Onset (G/Second)	Back Angle (Degrees)	Cause of Termination	Trauma	Number of Subjects Attaining	Countermeasures	Support	Restraint	Reference
Unaided n = 1										
12.0	14	0.5	25°	S	None	1 of 6	None	Seated, Legs Flexed	Helmet and Lap Belt	6
11.0	33	0.5	25°	S	None	1 of 7	None	Semisupine-Position Bed	Helmet and Lap Belt	6
9.0	105	?	20°	A	None	1 of 3	None	Semisupine	None?	1
8.0	360*	?	Approx. 20°	A	None	1	None	Supine-Rocket	?	1
8.0	100	0.5	25°	S	None	1 of 6	None	Seated, Legs Flexed	Helmet and Lap Belt	6
6.0	395	0.5	25°	S	None	1 of 6	None	Seated, Legs Flexed	Helmet and Lap Belt	6
4.0	660	0.5	25°	S?	24 Hour Leg Pain	1	None	Seated, Legs Extended	Helmet and Lap Belt	6
2.0	Approx. 24 Hrs.	?	Approx. 45° ? Adjustable	S	Circulatory Deterioration	1	None	TV Lounger	None	15
Aided n = 1										
14.0	126	0.2	35°	S	None	1	Total Water Immersion Positive Pressure Breathing	35° Wedge	None	4
12.0	230	0.2	35°	A?	None	1 of 4	Total Water Immersion Positive Pressure Breathing	35° Wedge	None	4
6.0	810	0.2	35°	S?	None	1 of 5	Total Water Immersion Positive Pressure Breathing	35° Wedge	None	4

*Female Subject: Tolerated 2 consecutive runs of this duration.

Subject Configuration



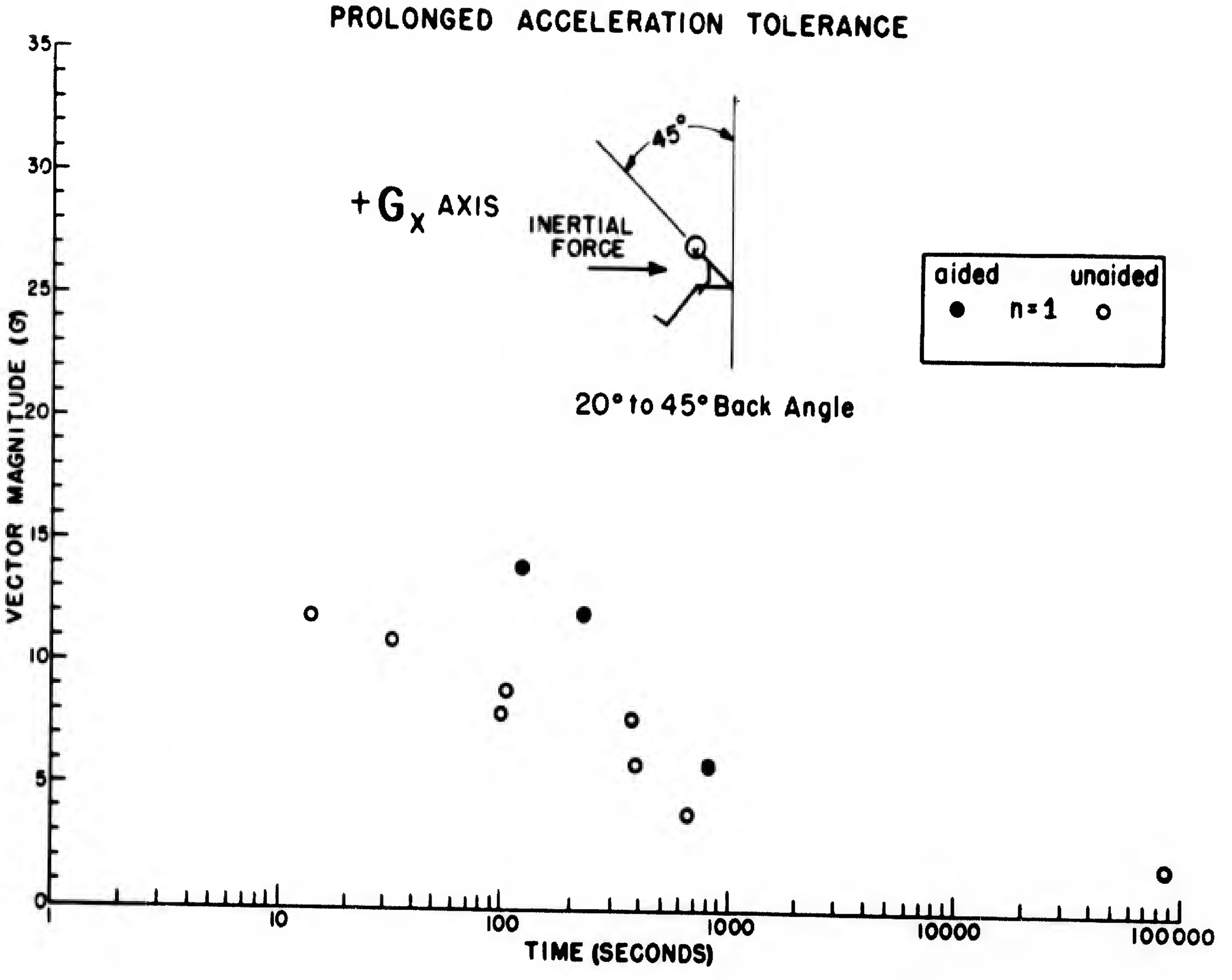


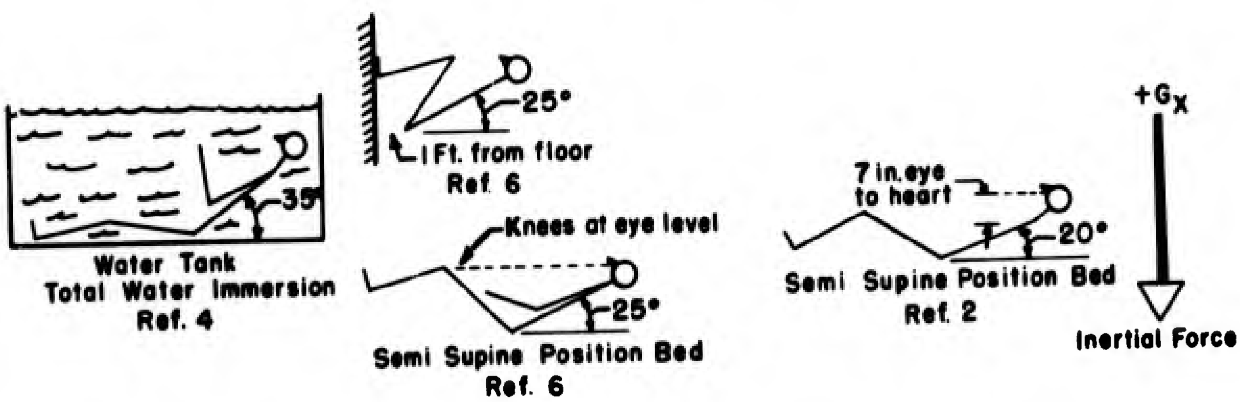
Figure 9. $+G_x$, 20° to 45° Back Angle n = 1

TABLE X

+Gx 20° to 45° Back Angle n>1

Vector Magnitude (G)	Duration at G (Seconds)	Average Onset (G/Second)	Back Angle (Degrees)	Cause of Termination	Trauma	Number of Subjects Attaining	Countermeasures	Support	Restraint	Reference
Unaided n>1										
12.0	2	0.5	25°	S	None	4	None	Seated, Legs Flexed	Helmet and Lap Belt	6
10.0	126	?	20°	S?	None	2 of 3	None	Semisupine-Position Bed	Straps	2
10.0	40	0.5	25°	S	None	2 of 6	None	Seated, Legs Flexed	Helmet and Lap Belt	6
8.7	2	0.5	25°	S	None	2	None	Semisupine-Position Bed	Helmet and Lap Belt	6
8.0	150	?	20°	A	None	3 of 3	None	Semisupine-Position Bed	Straps	2
8.0	≥40	0.5	25°	S	None	6 of 6	None	Seated, Legs Flexed	Helmet and Lap Belt	6
6.0	≥200	0.5	25°	S	None	3 of 6	None	Seated, Legs Flexed	Helmet and Lap Belt	6
4.0	900	0.5	25°	A	None	2 of 6	None	Seated, Legs Flexed	Helmet and Lap Belt	6
Aided n>1										
10.0	270	0.2	35°	A	None	5 of 6	Total Water Immersion Positive Pressure Breathing	35° Wedge	None	4
8.0	360	0.2	35°	A	None	6 of 6	Total Water Immersion Positive Pressure Breathing	35° Wedge	None	4

Subject Configuration



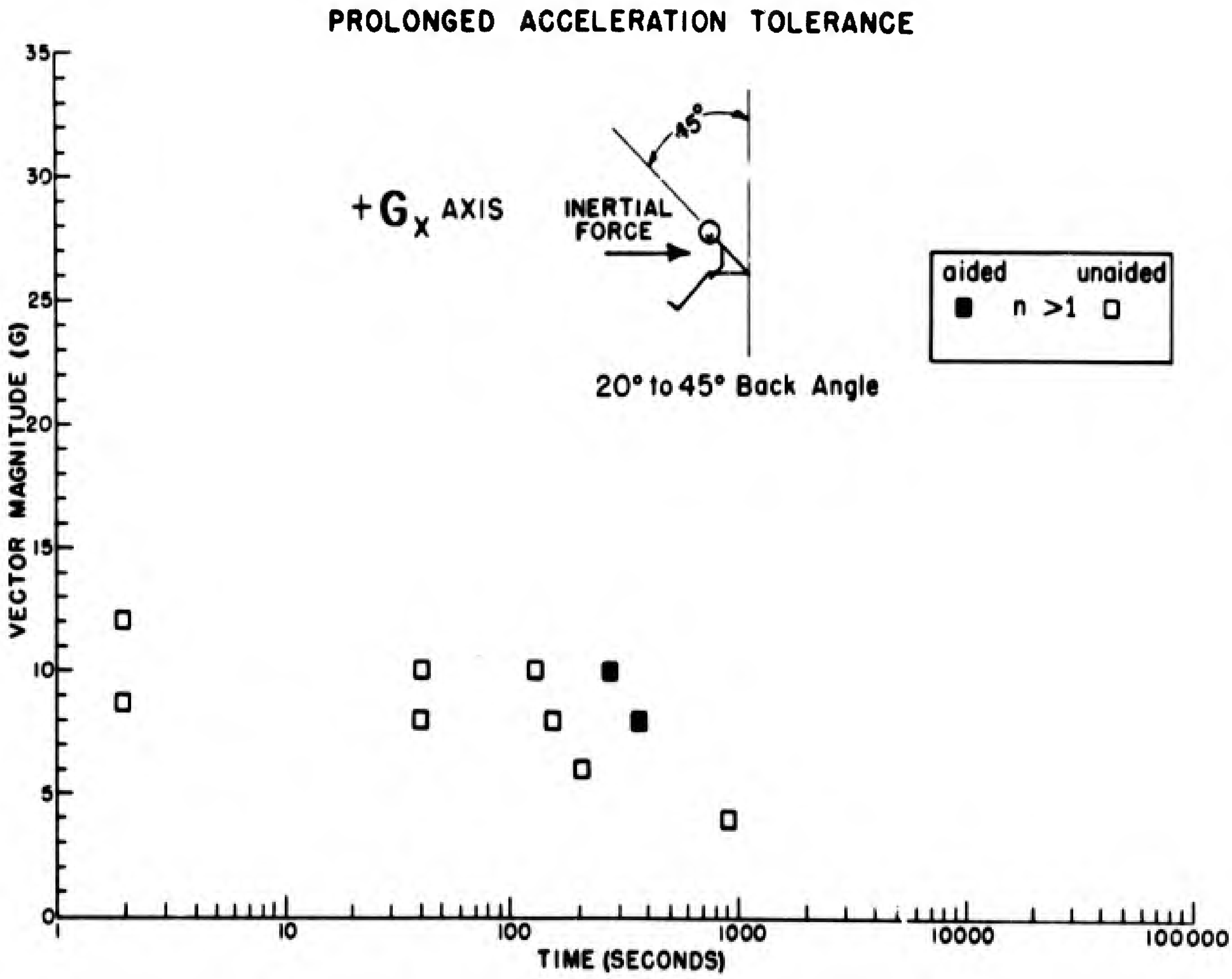
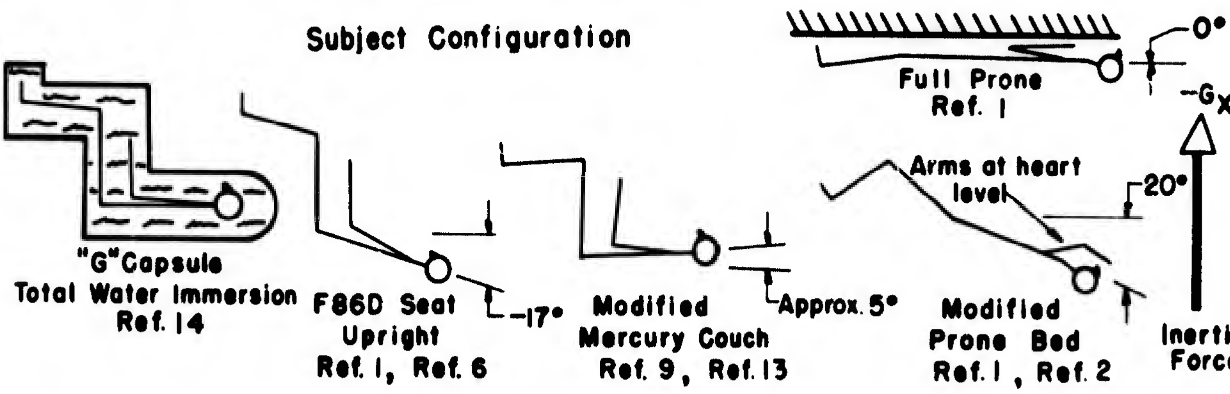


Figure 10. $+G_x$, 20° to 45° Back Angle n > 1

TABLE XI

Gx n = 1

Vector Magnitude (G)	Duration at G (Seconds)	Average Onset (G/Second)	Back Angle (Degrees)	Cause of Termination	Trauma	Number of Subjects Attaining	Countermeasures	Support	Restraint	Reference
Complete Restraint n = 1										
31.0	5	2.5	Approx. 0°	A?	Blood in Mucous	1	Total Water Immersion Positive Pressure in Lungs	G-Capsule	Water Immersion	14
28.0	Peak?	2.5	Approx. 0°	S	" " "	1	" " " " " " "	" "	Water Immersion	14
26.0	Peak?	2.5	Approx. 0°	S	" " "	1	" " " " " " "	" "	Water Immersion	14
12.0	6	0.5	17°	S	None	1	None	F-86D Seat	Bernadini Restraint	6
11.0	11	0.2	20°	S?	None	1	None	Semi Prone Bed	None?	1
10.0	90	0.2	20°	S	None	1	None	Modified Prone Bed	Head Support Helmet	2
10.0	71	?	Approx. 5°	S?	None	1	None	Contour Couch	Ref. 23	13
10.0	18	0.5	−17°	S	None	1	None	F-86D Seat	Bernadini Restraint	6
8.0	65	0.5	17°	S	None	1	None	F-86D Seat	Bernadini Restraint	6
7.0	300	?	Approx. 5°	S?	None	1	None	Modified Mercury Couch	Helmet and Webbing	9
7.0	240	?	Approx. 5°	S?	None	1	None	Modified Mercury Couch	Helmet and Webbing	9
7.0	210	?	0°	S?	None	1	None	Full Prone on Mat	None	1
6.0	140	0.5	−17°	S	None	1	None	F-86D Seat	Bernadini Restraint	6
5.0	180	0.5	−17°	A	None	1	None	F-86D Seat	Bernadini Restraint	6
4.0	300	0.5	−17°	A	None	1	None	F-86D Seat	Bernadini Restraint	6
3.0	1223	0.5	−17°	S	None	1	None	F-86D Seat	Bernadini Restraint	6
Partial Restraint n = 1										
5.0	18	0.5	−17°	S	None	1	None	F-86D Seat	Integrated Harness	6
3.0	450	0.5?	−17°	S	None	1	None	F-86D Seat?	Integrated Harness	6
2.0	3600	?	−17°	A	None	1	None	F-86D Seat?	Integrated Harness	1
2.0	1800	0.5?	−17°	A	None	1	None	F-86D Seat?	Integrated Harness	6



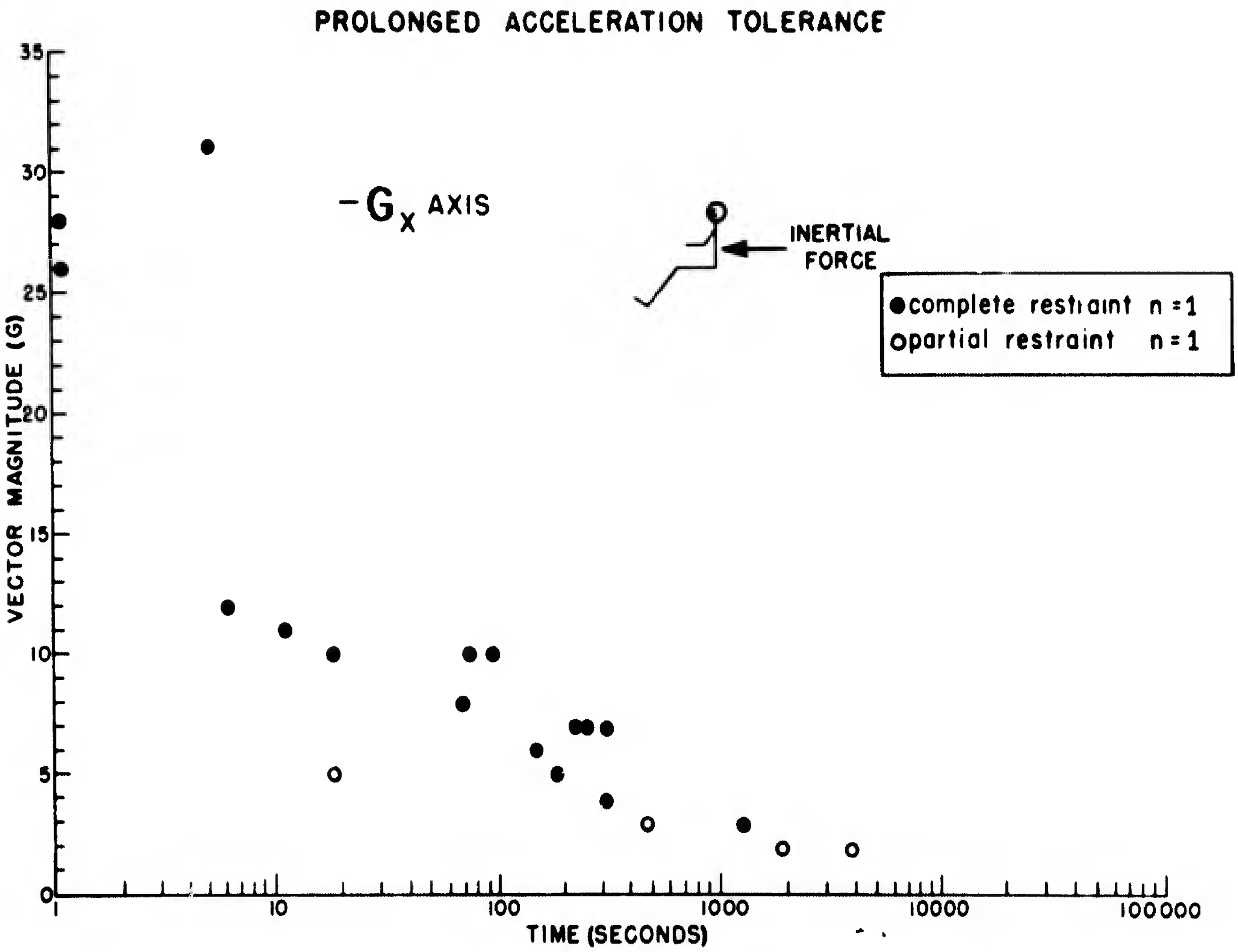
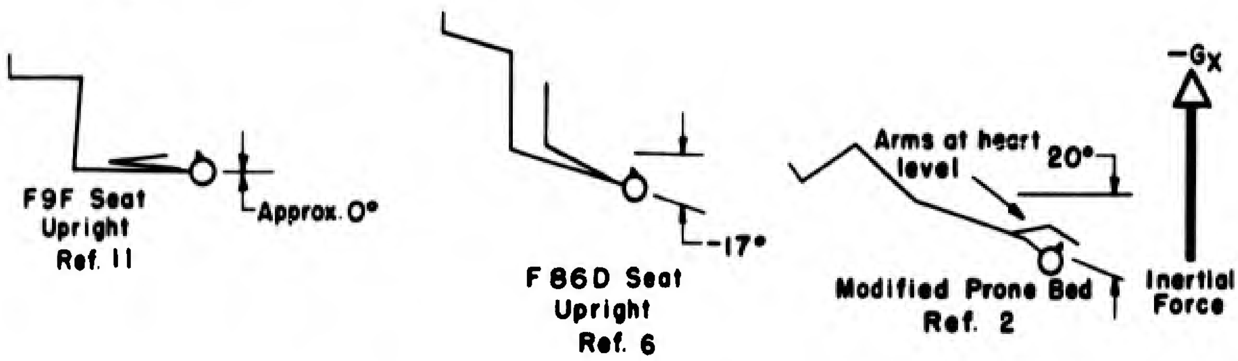


Figure 11. -G_x, n = 1

TABLE XII

Vector Magnitude (G)	Duration at G (Seconds)	Average Onset (G/Second)	Back Angle (Degrees)	Cause of Termination	Trauma	Number of Subjects Attaining	Countermeasures	Support	Restraint	Reference
Gx n>1										
Complete Restraint n>1										
15.0	5	8-10	Approx. 0°	Voluntary Limit	None	5 of 5	None	F-9F Seat Upright	Padded Barrier	11
12.0	30	0.2	20°	A	None	2 of 2	None	Modified Prone Bed	Head Support Helmet	2
12.0	≥3	0.5	17°	S	None	4 of 4	None	F-86D Seat	Bernadini Restraint	6
10.0	120	0.2	20°	A	None	4 of 9	None	Modified Prone Bed	Head Support Helmet	2
10.0	≥10	0.5	17°	S	None	3 of 4	None	F-86D Seat	Bernadini Restraint	6
8.0	120	0.2	20°	A	None	13 of 13	None	Modified Prone Bed	Head Support Helmet	2
8.0	>30	0.5	−17°	S	None	3 of 4	None	F-86D Seat	Bernadini Restraint	6
6.0	>50	0.5	−17°	S	None	4 of 4	None	F-86D Seat	Bernadini Restraint	6
5.0	≥80	0.5	17°	S	None	4 of 4	None	F-86D Seat	Bernadini Restraint	6
4.0	>240	0.5	−17°	S	None	3 of 4	None	F-86D Seat	Bernadini Restraint	6
3.0	≥1200	0.5	−17°	A	None	2 of 4	None	F-86D Seat	Bernadini Restraint	6
3.0	900	0.2	−20°	A	None	10 of 13	None	Modified Prone Bed	Head Support Helmet	2
2.0	1200	0.5	−17°	A	None	2 of 2	None	F-86D Seat	Bernadini Restraint	6
Partial Restraint n>1										
5.0	≥5	0.5	−17°	S	None	4 of 5	None	F-86D Seat	Integrated Harness	6
3.0	>300	0.5?	−17°	S	None	4 of 4	None	F-86D Seat?	Integrated Harness	6
2.0	>1000	0.5?	−17°	S	None	2 of 3	None	F-86D Seat?	Integrated Harness	6

Subject Configuration



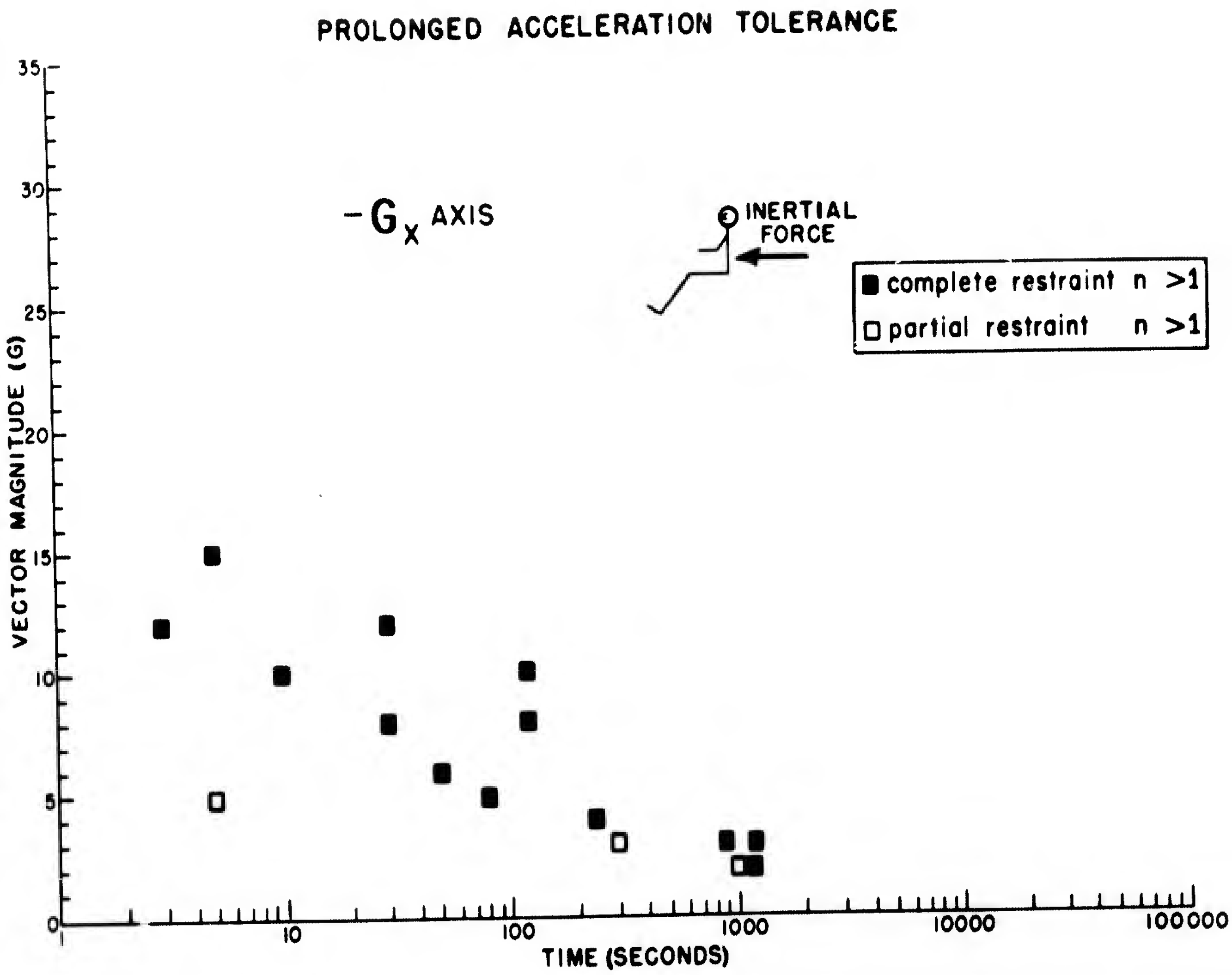


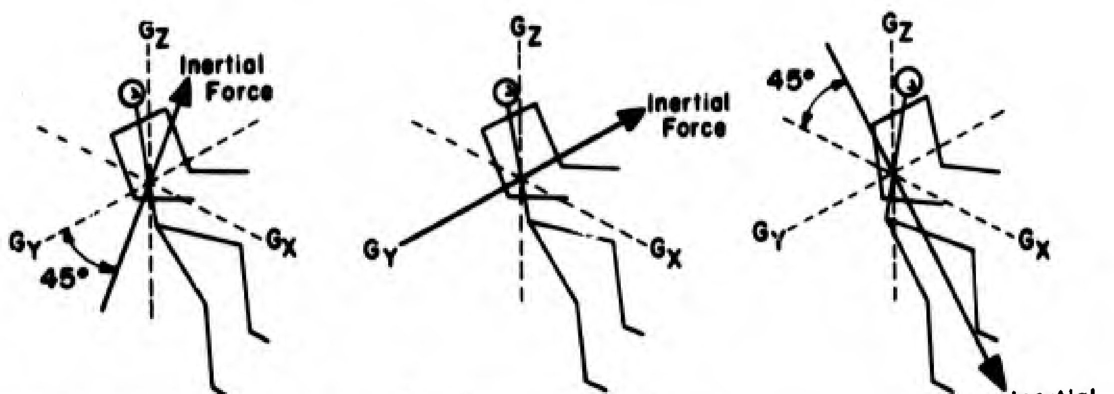
Figure 12. $-G_x$, n > 1

TABLE XIII

±Gy

Resultant Vector Magnitude (G)	Component Vector(s) Magnitude (G)	Duration at G (Seconds)	Average Onset (G/Second)	Back Angle (Degrees)	Cause of Termination	Trauma	Number of Subjects Attaining	Countermeasures	Support	Restraint	Reference
6.6	±?6.6 Gy	35	0.2	13°	A	None	1	None	Modified Aircraft Seat	Harness Suit	1
5.6	±?5.6 Gy	25	0.2	13°	A	None	1	None			1
5.4	±?5.4 Gy	40	0.2	−13°	A	None	1	None	(See Ref. 17 for		1
5.0	±?5.0 Gy	60	0.2	13°	A	None	1	None	other particulars)		1
4.5	±?4.5 Gy	30	0.2	13°	A	None	1	None			1
Combinations of Various Vectors											
10.0	+7.1 Gx ±?7.1 Gy	1	?	−13°	S?	None	1	None	Aircraft Seat Rotated 45° from Centrifuge Arm Axis	Harness Suit	1
6.0	+4.2 Gx ±?4.2 Gy	15	?	−13°	A	None	1	None			1
4.0	+2.8 Gx ±?2.8 Gy	15	?	−13°	A	None	1	None			1
8.5	+6.0 Gz −6.0 Gx	20	?	Approx. 5°	S	None	1	Anti-G Suit	Modified Mercury Couch	Helmet and Webbing	22
7.1	+5.0 Gz −5.0 Gx	162	?	Approx. 5°	S	None	1	" " "	" " "	" " "	22
5.6	+4.0 Gz −4.0 Gx	348	?	Approx. 5°	S	None	1	" " "	" " "	" " "	22

Subject Configuration



Resultant vector from equal $+G_X$ & $+G_Y$ components. −13° back angle. Ref. 1

Resultant vector from $+G_Y$. −13° back angle Ref. 1 & Ref. 17

Resultant vector from equal $-G_X$ & $+G_Z$ components. Ref. 22

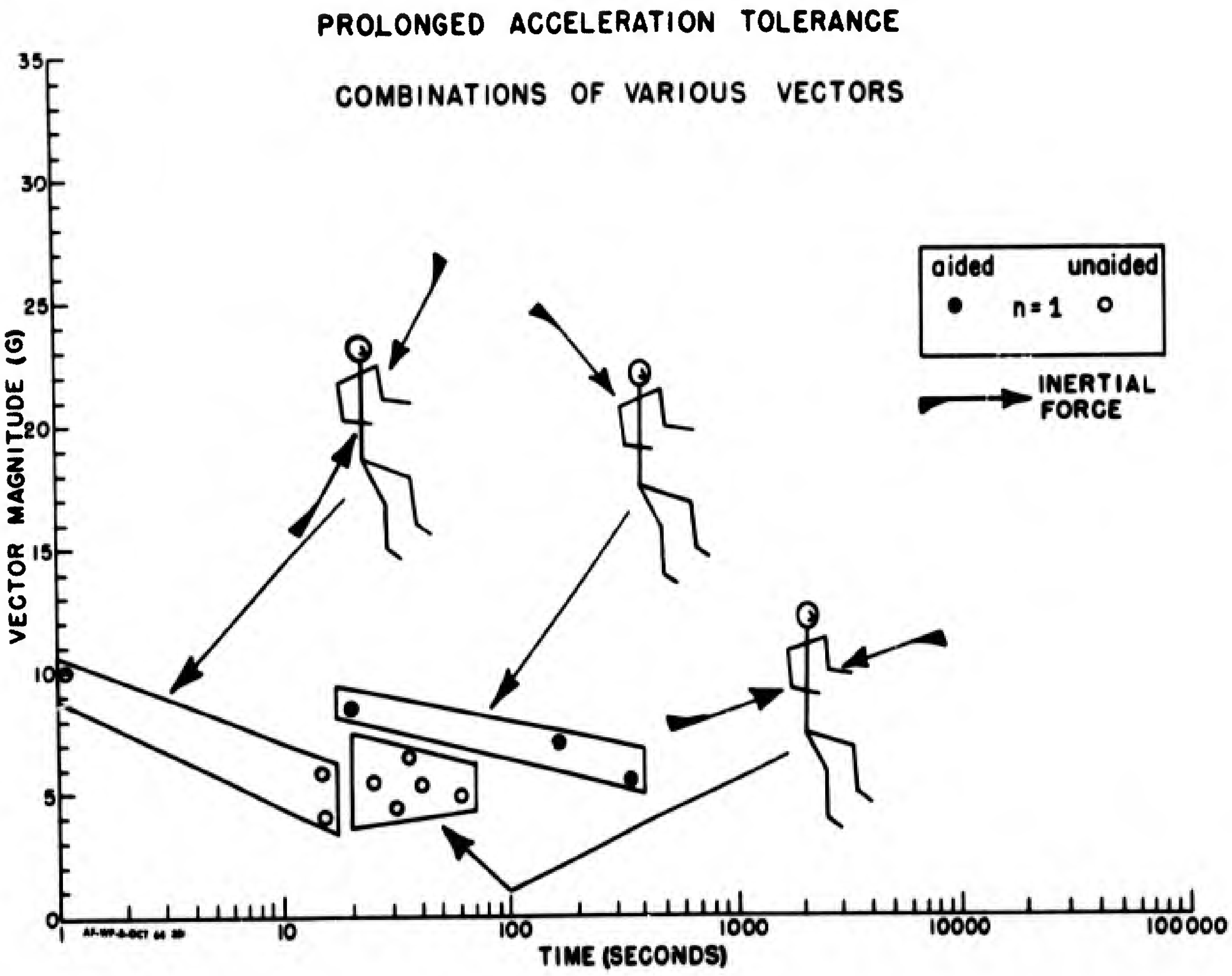


Figure 13. $\pm G_Y$

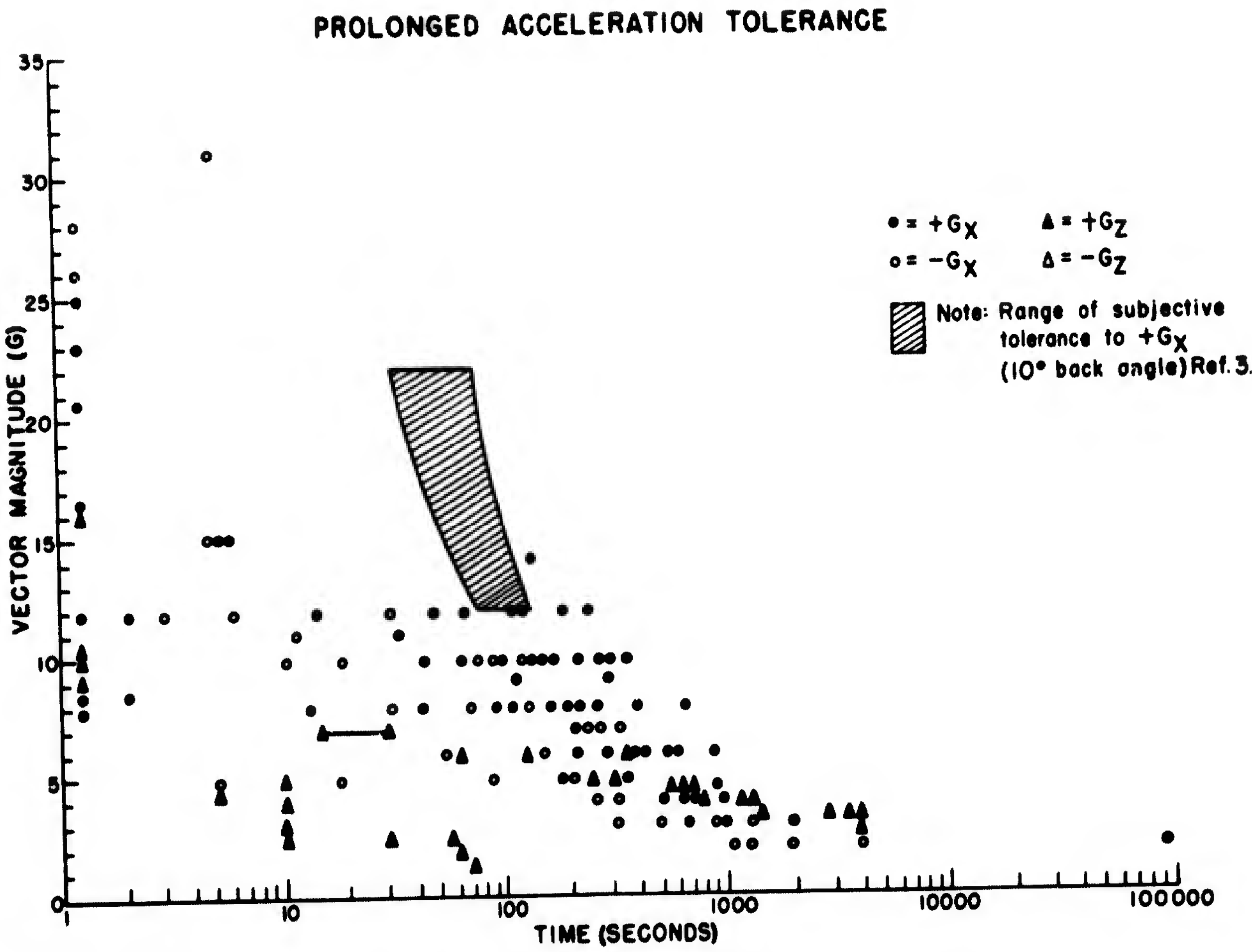


Figure 14. Summary: $\pm G_x$ and $\pm G_z$

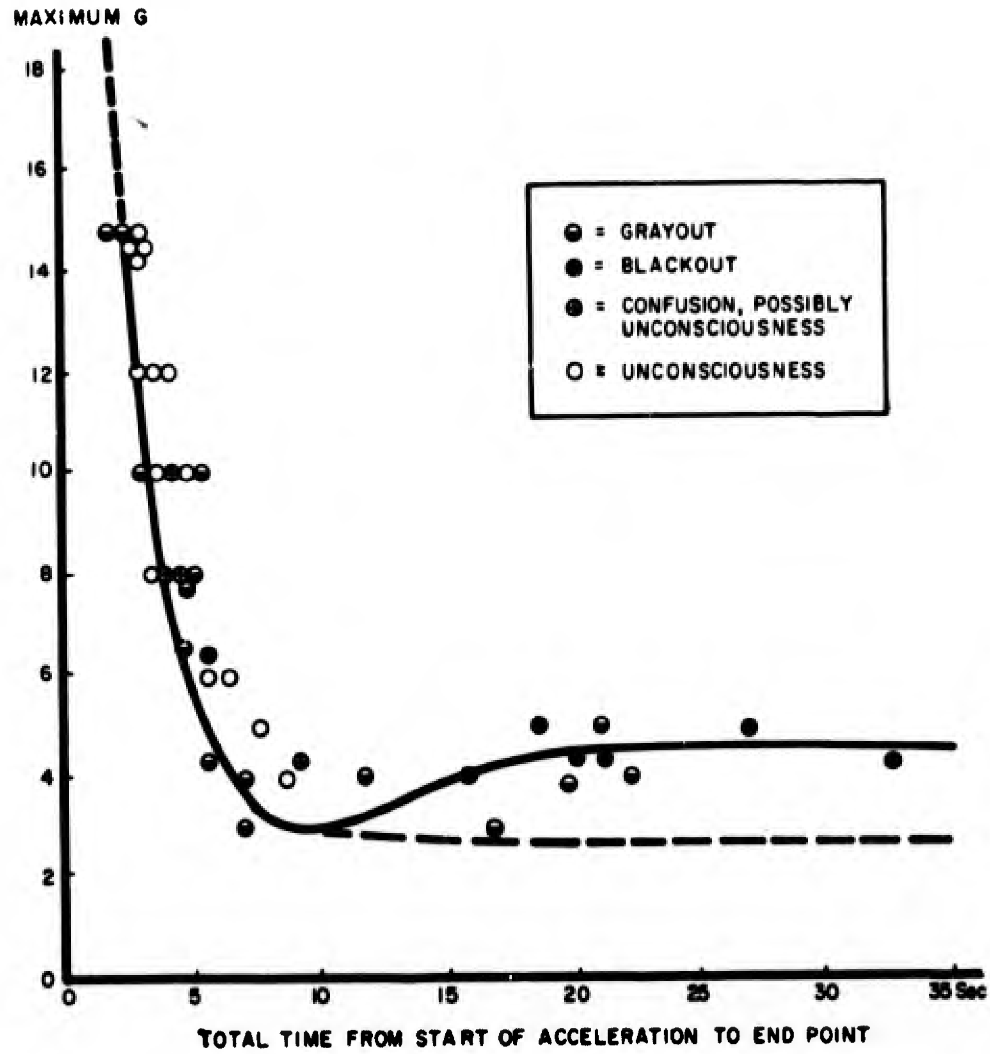


Figure 15. Human Tolerance to $+G_z$ (Redrawn from Stoll, A.M., Ref. 24)

REFERENCES

1. AMRL Centrifuge Record Books, Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio.

2. Ballinger, E.R. and C. A. Dempsey, The Effects of Prolonged Acceleration on the Human Body in the Prone and Supine Positions, WADC TR 52-250 (AD 5352), Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, July 1952.

3. Barer, A.S., G.A. Golov, V.B. Zubavin, K.I. Murahovsky, S.A. Rodin, E.I. Sorokina, and E.P. Tihomurov, "Physiological Reactions of the Human Organism to Transverse Acceleration and Some Means of Increasing Resistivity to Its Influence," presented at the 15th International Astronautic Congress, Warsaw, Poland, 7-12 September 1964. Note: Also available as AMD-TR-64-21, Aerospace Medical Division, Brooks Air Force Base, Texas, 31 December 1964.

4. Bondurant, S., W.G. Blanchard, N.P. Clarke, and F. Moore, Effect of Water Immersion on Human Tolerance to Forward and Backward Acceleration, WADC TR 58-290 (AD 155808), Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, July 1958.

5. Bryson, A.E., W.F. Denham, F.J. Carroll, and K. Mikami, "Determination of the Lift or Drag Program that Minimizes Re-entry Heating with Acceleration or Range Constraints Using a Steepest Descent Computation Procedure," presented at the 29th annual meeting of the IAS, Paper No. 61-6, 23-25 January 1961, New York.

6. Clarke, N.P., S. Bondurant, and S.D. Leverett, "Human Tolerance to Prolonged Forward and Backward Acceleration," Journal of Aviation Medicine, Vol 30, pp 1-21, January 1959.

7. Clarke, N.P., A.S. Hyde, N.S. Cherniack, and E.F. Lindberg, A Preliminary Report of Human Response to Rearward-Facing Re-entry Accelerations, WADC TN 59-109 (AD 231651), Wright Air Development Center, Wright-Patterson Air Force Base, Ohio.

8. Collins, C.C., R.J. Crosbie, and R.F. Gray, Pilot Performance and Tolerance Studies of Orbital Re-entry Acceleration, Letter report TED · ADC AE 1412, US Naval Air Development Center, Johnsville, Pennsylvania, 19 September 1958.

9. Creer, B.Y., H.A. Smedal, and R.C. Wingrove, Centrifuge Study of Pilot Tolerance to Acceleration and the Effects of Acceleration on Pilot Performance, NASA TN D-337 (AD 245411), National Aeronautics and Space Administration, Washington, D.C., 1960.

10. Dorman, P.J. and R.W. Lawton, "Effect of G Tolerance on Partial Supination Combined with the Anti-G Suit," Journal of Aviation Medicine, Vol 27, No. 6 pp 490-496, December 1956.

11. Duane, T.D., E.L. Beckman, J.E. Ziegler, and H.N. Hunter, Some Observations on Human Tolerance to Exposures of 15 Transverse G, NADC-MA-5305, Phase III, (AD 20518), US Naval Air Development Center, Johnsville, Pennsylvania, 30 July 1953.

12. Gell, C.F., "Table of Equivalents for Acceleration Terminology," Recommended for General International Use by the Acceleration Committee of the Aerospace Medical Panel, AGARD. Aerospace Medicine, Vol 32, No. 12, pp 1109-1111, December 1961.

13. Giovanni, C.D., Jr. and R.M. Chambers, "Physiologic and Psychologic Aspects of the Gravity Spectrum," New England Journal of Medicine, Vol 270, No. 1, pp 35-41, 2 January 1964.

14. Gray, R.F. and M.G. Webb, High G Protection, NADC-MA-5910 (AD 235338), US Naval Air Development Center, Johnsville, Pennsylvania, 12 February 1960.

15. Hardy, J.D., "Acceleration Problems in Space Flight," presented at XXI Congreso Internacional de Ciencias Fisiologicas (21st International Congress of Physiological Science), Buenos Aires, Argentina, August 1959.

16. Hegenwald, J.F., Jr. and S. Oishi, Human Tolerance to Accelerations: A Practical Tool for the Engineer, Report No. NA-57-425, North American Aviation Inc., 6 May 1957.

17. Hershgold, E.J., "Roentgenographic Study of Human Subjects during Transverse Accelerations," Aerospace Medicine, Vol 31, pp 213-219, March 1960.

18. Hyde, A.S., The Effect of Back Angle, Molded Supports, and Staged Evisceration upon Intrapulmonary Pressures in Dogs and a Monkey during Forward ($+G_x$) Acceleration, AMRL-TDR-62-106 (AD 289337), Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, September 1962.

19. Kornhauser, M., "Theoretical Prediction of the Effect of Rate-of-Onset on Man's G-Tolerance," Aerospace Medicine, Vol 32, No. 5, pp 412-421, May 1961.

20. Miller, H., M.B. Riley, S. Bondurant, and E.P. Hiatt, "The Duration of Tolerance to Positive Acceleration," Journal of Aviation Medicine, Vol 30, pp 360-366.

21. Sieker, H.O., Devices for Protection Against Negative Acceleration: Part 1, Centrifuge Studies, WADC TR 52-87, Part 1 (AD 2135), Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, June 1952.

22. Smedal, H.A., B.Y. Creer, and R.C. Wingrove, Physiological Effects of Acceleration Observed during a Centrifuge Study of Pilot Performance, NASA TN D-345 (AD 247140), National Aeronautics and Space Administration, Washington, D.C., December 1960

23. Smedal, H.A., H.C. Vykukal, R.P. Gallant and G.W. Stinnett, "Crew Physical Support and Restraint in Advanced Manned Flight Systems," American Rocket Society Journal, Vol 31, pp 1544-1548, November 1961.

24. Stoll, A.M., Human Tolerance to Positive G as Determined by Physiological End Points, NADC-MA-5508 (AD 75326), US Naval Air Development Center, Johnsville, Pennsylvania, 30 August 1955.

25. Watson, J.F. and N.S. Cherniack, Effect of Positive Pressure Breathing on the Respiratory Mechanics and Tolerance to Forward Acceleration, ASD TR 61-398 (AD 268565) Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio, August 1961.

26. Webster, A.P. and H.N. Hunter, "Acceleration Chart," Journal of Aviation Medicine, Vol 25, pp 378-379, 1954.