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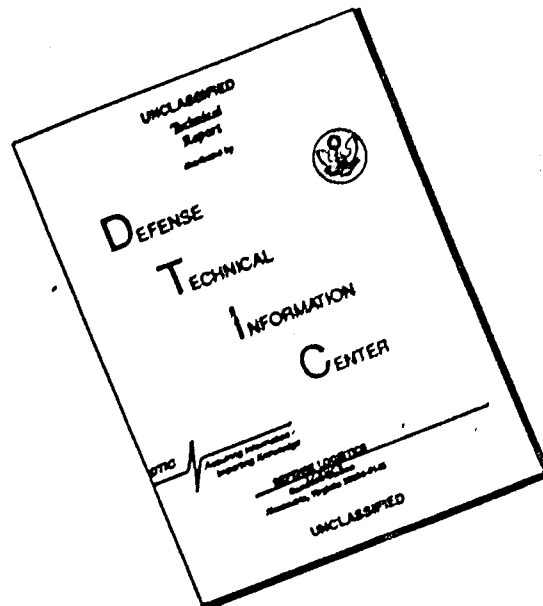
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HUMAN TOLERANCE
TO ACCELERATIONS:
A PRACTICAL TOOL
FOR THE ENGINEER



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NORTH AMERICAN AVIATION, INC.

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ENGINEERING DEPARTMENT

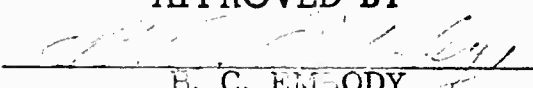
HUMAN TOLERANCE
TO ACCELERATIONS:
A PRACTICAL TOOL
FOR THE ENGINEER

XEROX

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No. of Pages 30

REVISIONS

Date 6 May 1957

DATE	REV. BY	PAGES AFFECTED	REMARKS
13 JUNE 1957	S. O.	24, 26	AMENDMENTS TO CLARIFY AND CORRECT CORR.

**HUMAN TOLERANCE TO ACCELERATIONS:
A PRACTICAL TOOL FOR THE ENGINEER**

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AND
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NORTH AMERICAN AVIATION, INC.
LOS ANGELES, CALIFORNIA**

**PRESENTED ON MAY 6, 1967, AT THE
28th ANNUAL MEETING OF THE
AERO MEDICAL ASSOCIATION,
DENVER, CO.**

HUMAN TOLERANCE TO ACCELERATIONS:

A PRACTICAL TOOL FOR THE ENGINEER

Several elements must be considered in predicting the effect of acceleration upon the human body: the magnitude of the acceleration, its time duration, the associated rate of onset, the direction of the accelerating force, the density and location of application to the body surfaces, and cyclic diminutions and reversals. The element which provides the greatest opportunity to the engineering designer is direction of application of the force producing the acceleration, optimization of which yields important physiological dividends.

A study of reports on laboratory experiments, survived falls, and an escape from an airplane at supersonic speed has been conducted and data accumulated to provide a practical tool for the engineer in evaluating human tolerance to accelerations.

Magnitudes from 1.5 G to 200 G, time durations from 0.001 to 1000 seconds, rates of onset from 0.10 to 5000 G/second and various directions of resultant acceleration vectors are compared with permanent injury threshold, limits of voluntary tolerance, and limits of useful consciousness as criteria.

DEFINITIONS

PERMANENT INJURY THRESHOLD is here defined as the threshold of trauma irreversible by surgery or therapy.¹³ The specific physiological limits establishing the permanent injury threshold vary from hemorrhage to shock, anoxia, and mechanical injury.

LIMIT OF VOLUNTARY TOLERANCE is defined as the area of human capacity within which applied accelerations can be expected to produce no worse than short periods of extreme discomfort or unconsciousness. The specific limits include petechiae, pain, difficulty of respiration, blackout-to-unconsciousness, and threshold of shock and mechanical injury.

LIMIT OF USEFUL CONSCIOUSNESS is the boundary of awareness sufficient for proper response to stimuli which normally generate familiar, well-indoctrinated reactions. Physiological symptoms at the defined limits are petechiae, pain, difficulty of respiration, and blackout.

The four acceleration parameters treated are:

- (1) Magnitude - The force in multiples of gravity or G units.
- (2) Duration - The time, in seconds, at the G plateau.
- (3) Rate of Onset - The rate of change of acceleration in G/second units, as measured on the significant slope of the acceleration versus time curve.
- (4) Direction - Angles, in degrees, varying from zero degrees, when the external accelerating force acts transversely from chest-to-back (H+), to ± 180 degrees when the force is produced from back-to-chest (H-). At $+90$ degrees, force direction is seat-to-head (V+); at -90 degrees, force is head-to-seat (V-), as shown diagrammatically on graphs 9 through 18.

All these parameters are related to direct experience by the subject; they are not values measured on the test vehicle, seat, or other external bodies.

The restraint harness is assumed to be at least equivalent to that recommended by Stapp in 1951: shoulder harness of 1.75-inch width, No. 13 nylon webbing, with lap belt and inverted "V" leg strap of 3-inch width nylon of adequate strength.²⁶ Head and limb retention aids are presupposed for acceleration levels exceeding 30 G.

A dearth of experimental data precludes other than a theoretical analysis of cyclic diminutions and reversals - consequently, no attempt is made here to determine effects in that area.

METHOD

Interpretation and methodology employed are similar to those of an earlier, related study.¹⁴

Graphs 1 through 8 relate directly the parameters of magnitude, duration, and direction in a manner originated by Lombard.¹⁸ The limits were derived by evaluating the plotted data, which include both human and animal subjects. All lines, except one, are well substantiated by available information. In the one case, the H- permanent injury threshold was extrapolated from the corresponding H+ threshold.

Elliptic resolution of forces¹³ was adopted to predict values undefined by graphs 1 through 8, which set the limits at only zero, +90, -90 and ± 180 degrees.

For the permanent injury threshold, a purely elliptic resolution was applied for all durations, as shown in graphs 9 through 11.

Voluntary tolerance limits were derived by the unmodified elliptic method for durations less than 0.20 second, graphs 12 and 13. For these short durations, body fluid movements are assumed to be negligible.²⁹ However, for longer time periods, fluid movement becomes evident and the end points become governed by the heart-to-retina line, inclined approximately 28 degrees forward from the axis of the vertebral column.^{6, 12, 16} Consequent shifts in the ellipse major and minor axes are indicated, as shown in graph 14. However, the region from +90 to +180 degrees has been explored by extensive tests and found to be divorced from the conventional elliptic resolution.^{4, 12, 17, 20, 22, 30}

The limits of useful consciousness were determined by the modified elliptic method, graph 15. Again, the region from +90 to +180 degrees differs in the same fashion as for voluntary tolerance.

Graph 16 studies rates of onset and their effect on the limits of voluntary tolerance. From the plotted points, representing data on human subjects only, significant limits for H_±, V₊ and V₋ jolts have been derived. It should be noted that placement of the limit traces is such as to produce conservative values for jolt in the equation of graph 18.

The series of curves indicating the permanent injury threshold (graph 17) show characteristic maxima occurring at zero and ± 180 degrees, and minima at ± 90 degrees.

- (1) In the vicinity of zero and ± 180 degrees, retinal hemorrhage occurs at low G, long duration, and at moderate rates of onset; shock and injury occur at higher G, shorter duration, and higher rates of

onset. 2, 5, 18, 26, 27, 28, 29, 30

- (2) Near ± 90 degrees, hemorrhage occurs at low G, long duration, and at moderate rates of onset. 2, 10, 15, 19 Anoxia may occur at the long duration exposures due to stress on the lungs. 11 Spinal injury is sustained at high G, short duration, and high rates of onset. 19, 28

Stapp has exposed chimpanzees to acceleration peaks of 100 G or more at jolts approximating 20,000 G/second. In selected experiments, severe shock was experienced in the V- direction of application, moderate shock in the H+ direction, and no injury at H-. 28 These results suggest that jolt ceilings up to 10,000 G/second would not be unconservative in relation to the human permanent injury thresholds of graph 17.

The series of curves delineating the limits of voluntary tolerance (graph 18) show the usual maxima at zero and ± 180 degrees, and minima at ± 90 degrees for short durations (less than 0.2 second). With increased durations, a shift of maxima occurs from zero to approximately +28 degrees and from +90 to +118 degrees. 12, 16 A slight shift also is shown in the vicinity of -90 degrees. 16

- (1) Zero Degrees - At low G range for long duration and low rates of onset, severe petechiae in the extended arms, or in the eyes, are the initial symptoms defining voluntary tolerance boundaries. 1,7,8 With increase in acceleration magnitude, decrease in duration and increase in the rates of onset, the limits are governed by severe pain, due to distended organs, and extreme difficulty of

respiration. ^{1, 7, 8, 19, 29} At high G, short duration, and high rate of onset, the threshold of shock is approached. ^{15, 26, 28, 29}

- (2) +90 Degrees - Blackout-to-unconsciousness and severe petechiae determine the limits as the condition changes from low G, long duration, and low rates of onset to higher G, shorter duration, and higher rates of onset. ^{3, 4, 6, 33} At high G, short durations, and high rates of onset, the threshold to injury is approached. ^{19, 32} Injury is usually fracture of vertebrae. ¹⁹
- (3) ± 180 Degrees - The approach from +90 to +180 degrees shows a lag in the increase of G tolerance for conditions of low G, long duration, and low rate of onset. However, a sharp increase occurs from +167 to +180 degrees. ¹² The physiological symptoms vary from severe pain and petechiae to extreme difficulty in breathing. ^{1,7,8} The threshold of shock establishes the limit for high G, short duration, and high rates of onset. ^{26, 27, 28}
- (4) -90 Degrees - Severe petechiae and pain, at low G, long duration, and low rates of onset, change to threshold of injury at high G, short duration, and high rates of onset, as the physiological limits of negative acceleration. ^{10, 15, 16, 28, 33}

An empirical equation and curve, derived from the rate of onset study (graph 16) permit calculation of the maximum allowable jolts related to a given maximum acceleration.

The series of curves indicating the limits of useful consciousness (graph 19) again are produced by elliptic resolution of forces. Due to the critical

heart-to-eye axis, maxima and minima are displaced from zero and ± 90 degrees.

- (1) Zero Degrees - Mild petechiae are the first physiological symptoms determining useful consciousness boundaries under conditions of low G, long duration, and low rates of onset.^{1, 23} With increased acceleration, shorter duration, and low rates of onset, pain becomes predominant.^{1, 23} High G magnitude, with corresponding short duration and moderate rates of onset, reaches the point where respiration becomes difficult.^{1, 15, 16, 22}
- (2) +90 Degrees - Blackout and mild petechiae are the limiting symptoms.^{4, 6, 9, 12, 17, 20, 21, 30, 31} The minimum points are reached at approximately +118 degrees, when the direction of the accelerating force acts coincident with the heart-to-retina line.^{12, 16}
- (3) ± 180 Degrees - A lag in the increase in acceleration tolerance prevails up to +167 degrees; a sharp increase is noted thereafter.¹² The end point of mild petechiae, at low G, long duration, and low rate of onset, changes to pain and difficulty of respiration with increase in G, shorter duration, and moderate rates of onset.^{1, 12, 23, 30}
- (4) -90 Degrees - Mild pain and petechiae are the limiting symptoms.^{10, 16, 24, 25}

The rate of onset for these series of curves is assumed to be between one G/second and 100 G/second. Gradual rates of onset of less than one G/second have been found to increase tolerance by approximately 2 G.^{9, 21} The reason for the increase is due to the cardiovascular reflex activity having ample time to develop fully before the critical plateau of blackout is

reached. ^{9, 21} The time to develop has been found to be approximately
6 to 7 seconds. ^{9, 21}

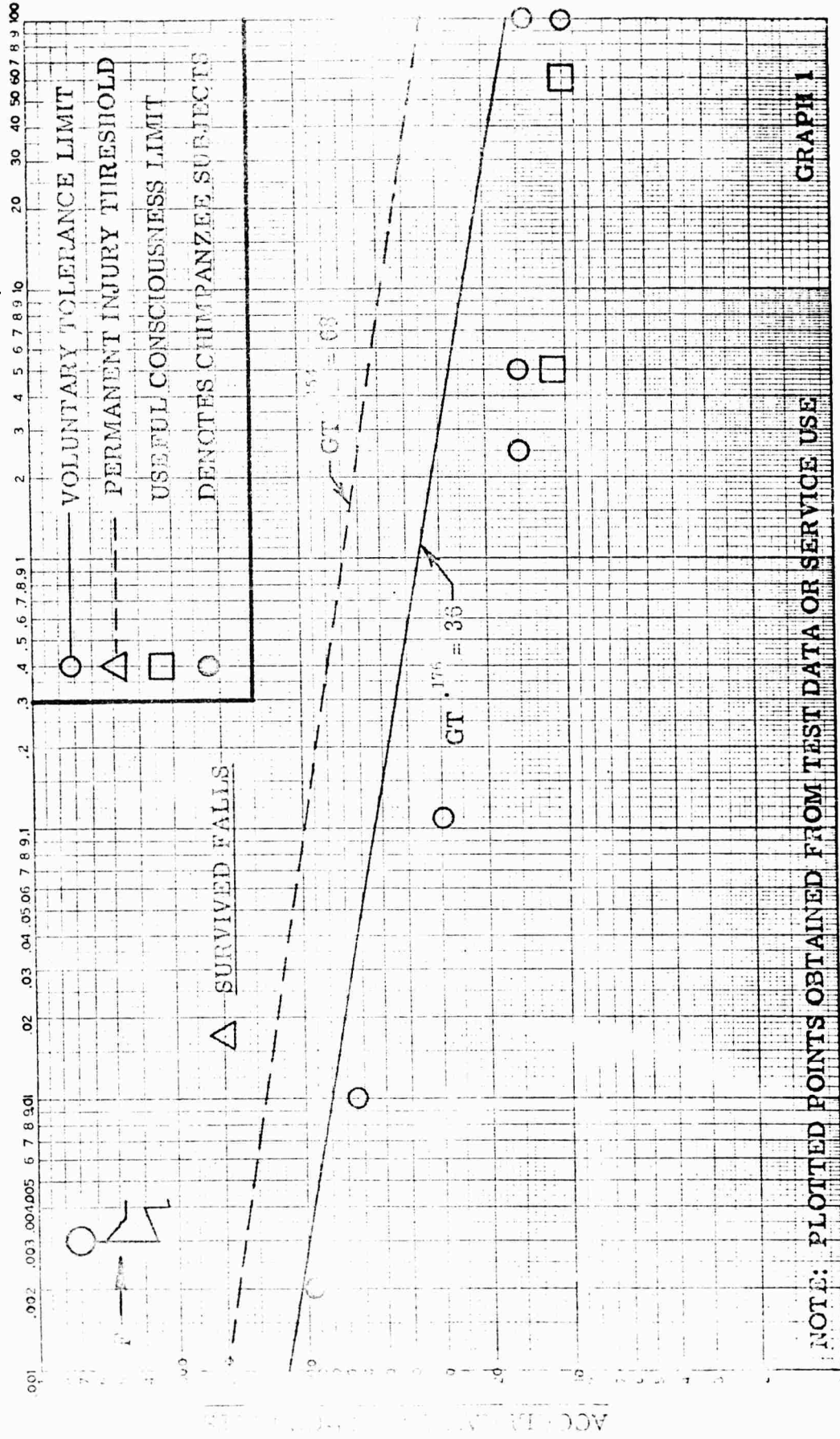
CONCLUSIONS

A scarcity of information on human accelerative effects necessitates
extrapolation from isolated experimental results. Fortunately, this
extrapolation may be founded on logical patterns formed by existing datum
points.

KRUPP & BEER CO., N. Y. NO. 285-1180
 Isostatic, 6 X 3 Cycle
 MADE IN U.S.A.

II - INJURY

TIME IN SECONDS

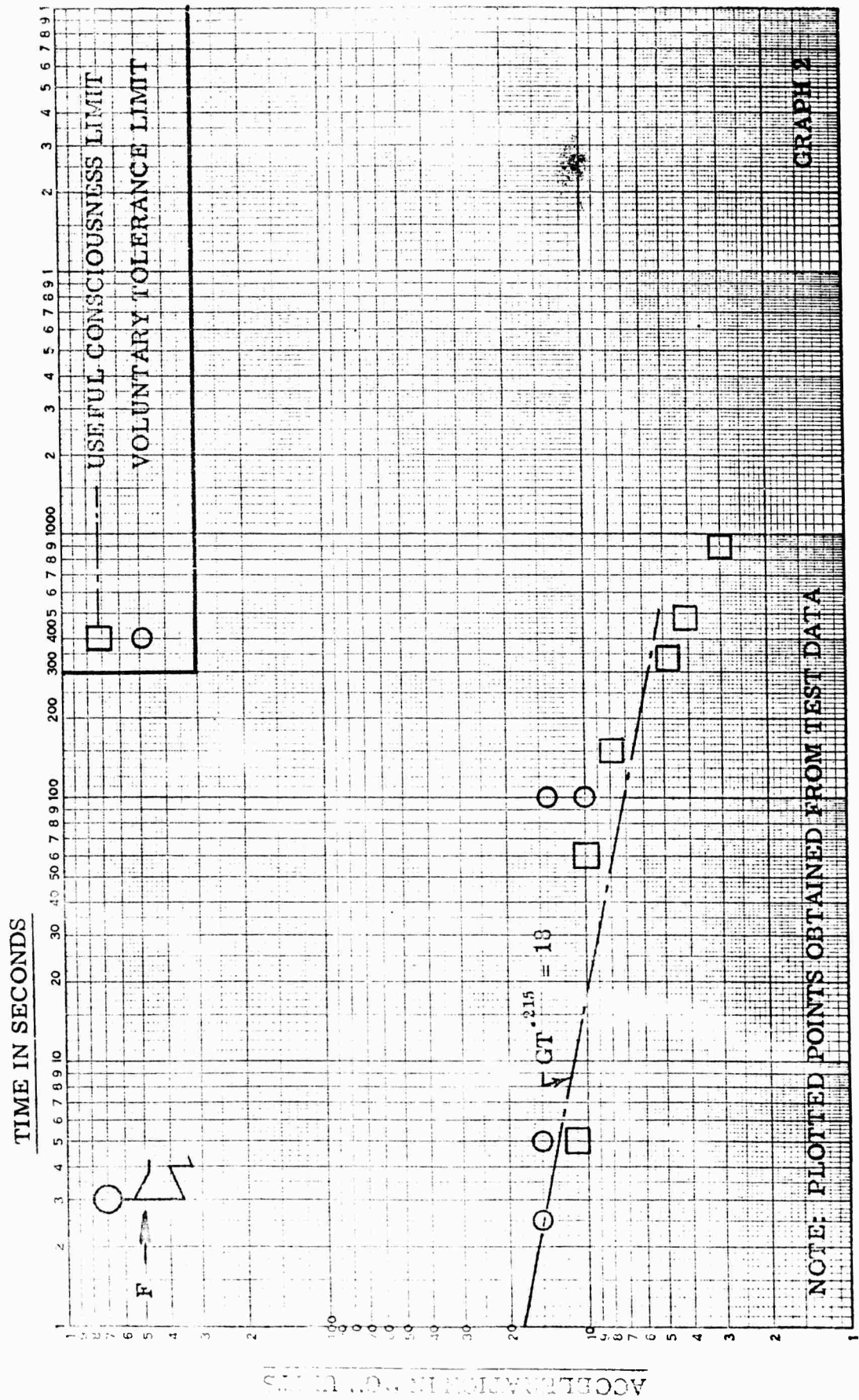


NOTE: PLOTTED POINTS OBTAINED FROM TEST DATA OR SERVICE USE

GRAPH 1

KRUPP & BERBER CO., N. Y. NO. 389-1884
 Frequency, 6 X 3 Cycles.
 MADE IN U. S. A.

H- USEFUL CONSCIOUSNESS LIMIT



GRAPH 2

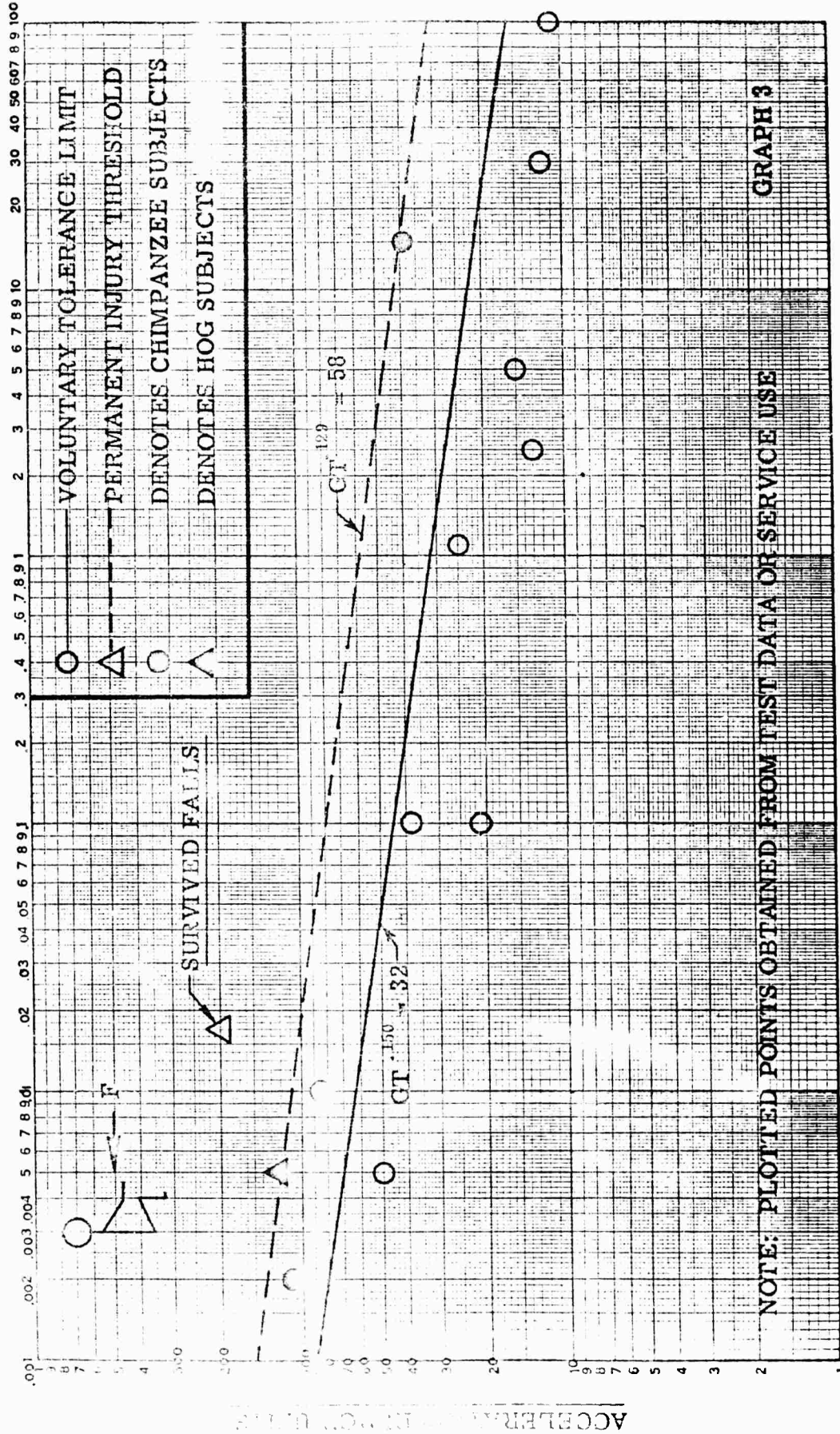
NOTE: PLOTTED POINTS OBTAINED FROM TEST DATA

ACCELERATION IN G (Y-AXIS)

K&E LOGARITHMIC 359-125G
 KEUFFEL & ESSER CO. MADE IN U.S.A.
 3 X 5 CYCLES

H + INJURY

TIME IN SECONDS

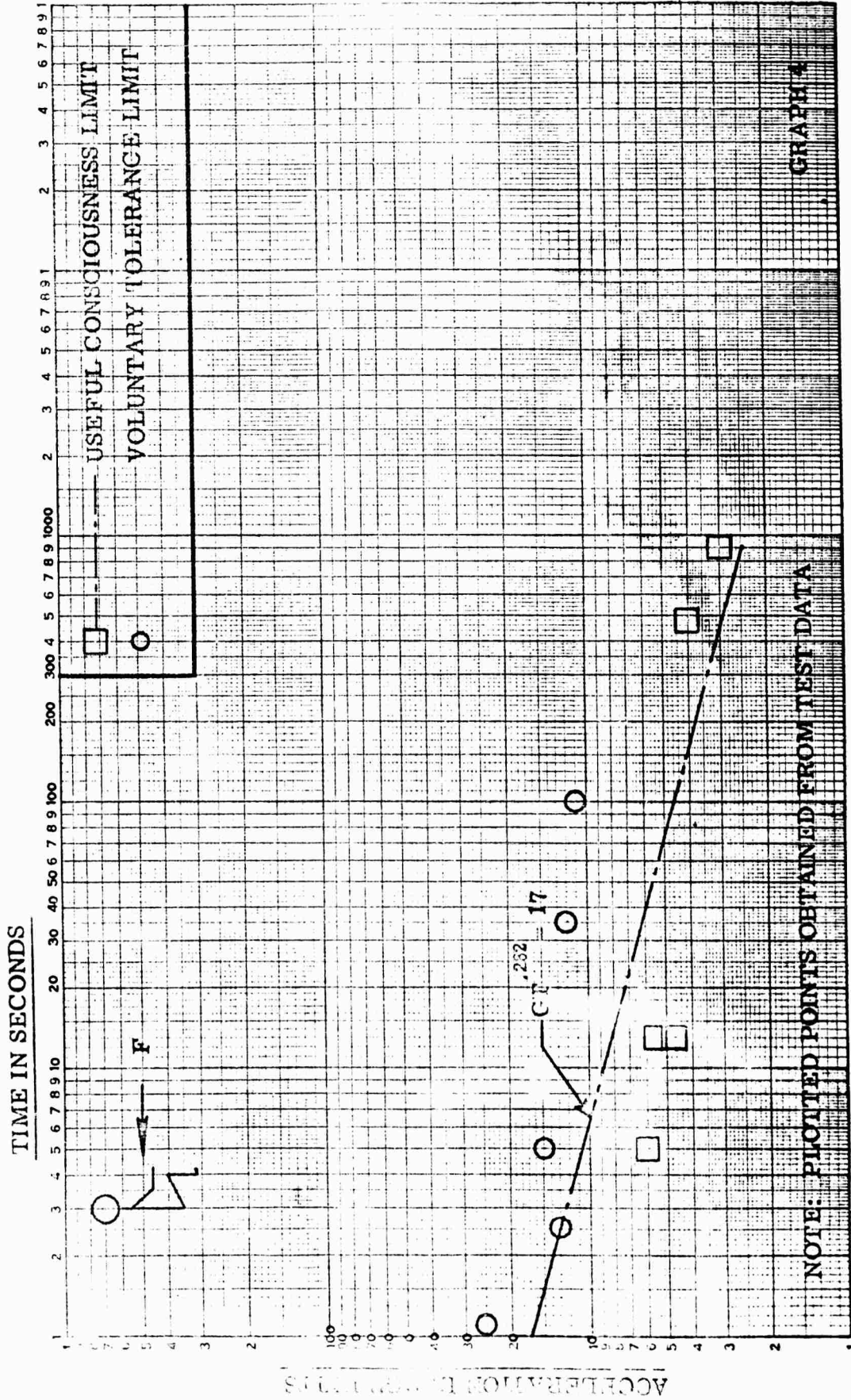


NOTE: PLOTTED POINTS OBTAINED FROM TEST DATA OR SERVICE USE

GRAPH 3

REUFFEL & ESSEX CO., N. Y. NO. 888-1858
 Isoarithmic, 5 X 3 Cycle,
 MADE IN U. S. A.

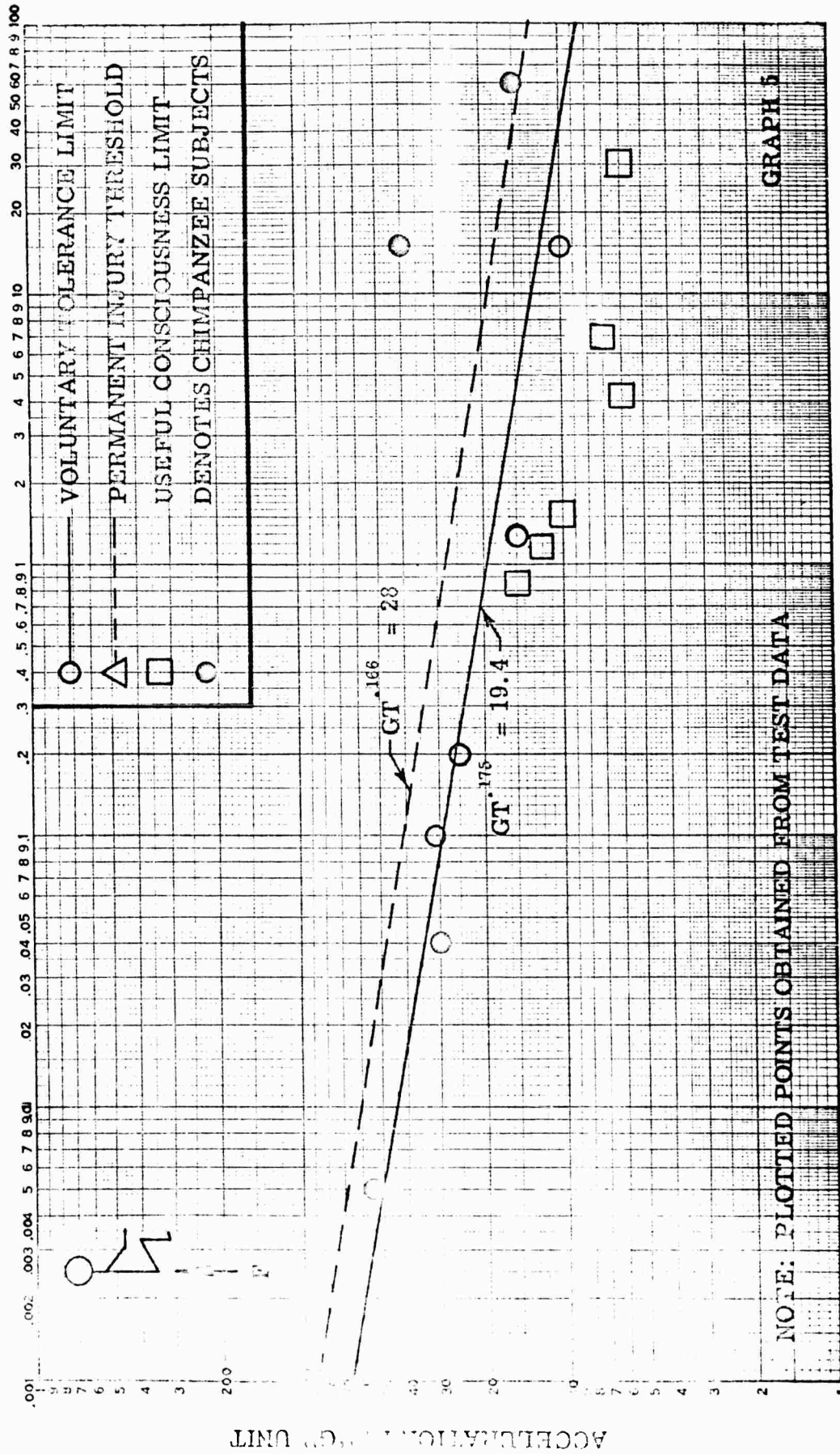
II+ USEFUL CONSCIOUSNESS LIMIT



HEUFFEL & ESSER CO., N. Y. NO. 385-1580
 Logarithmic, 5 X 8 Cycles
 MADE IN U. S. A.

V + INJURY

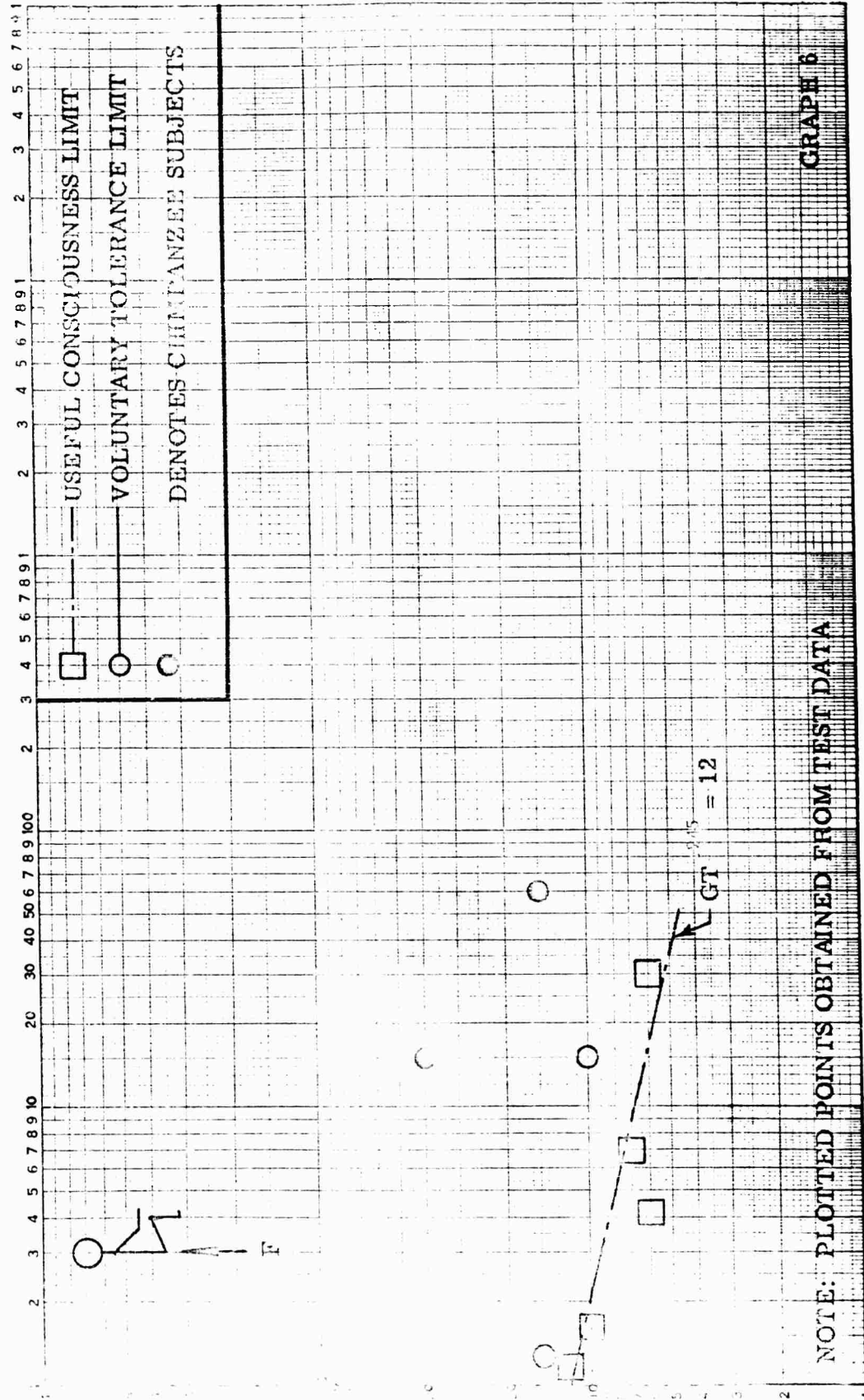
TIME IN SECONDS



KEUFFEL & ESSER CO., N. Y. NO. 99-1850
 Logarithmic, 5 X 5 Cycle.
 MADE IN U. S. A.

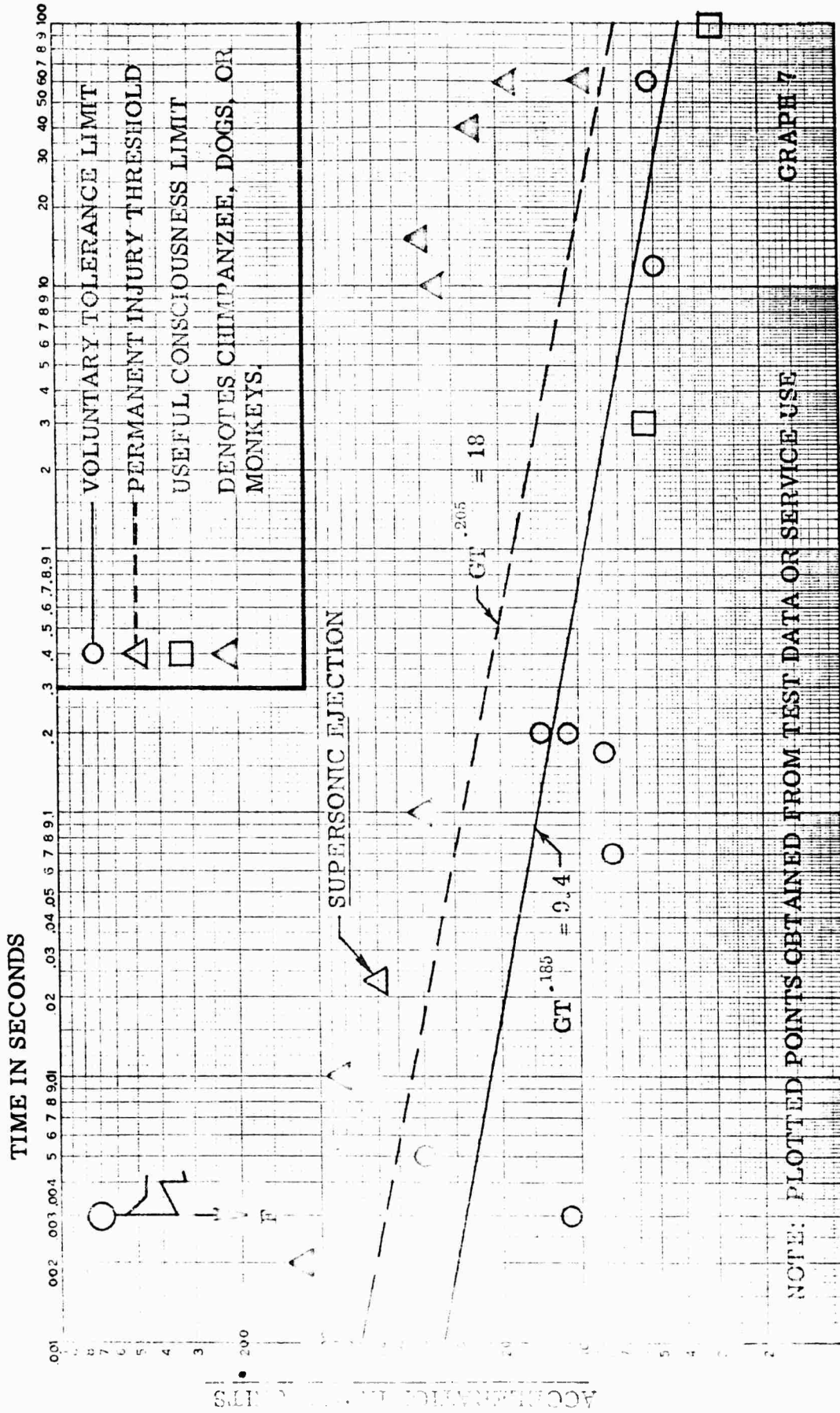
V+ USEFUL CONSCIOUSNESS LIMIT

TIME IN SECONDS



REUPPEL & ESEN CO., N. Y., NO. 288-1226
 Logarithmic, 5 X 5 Cycle
 MADE IN U.S.A.

V- INJURY



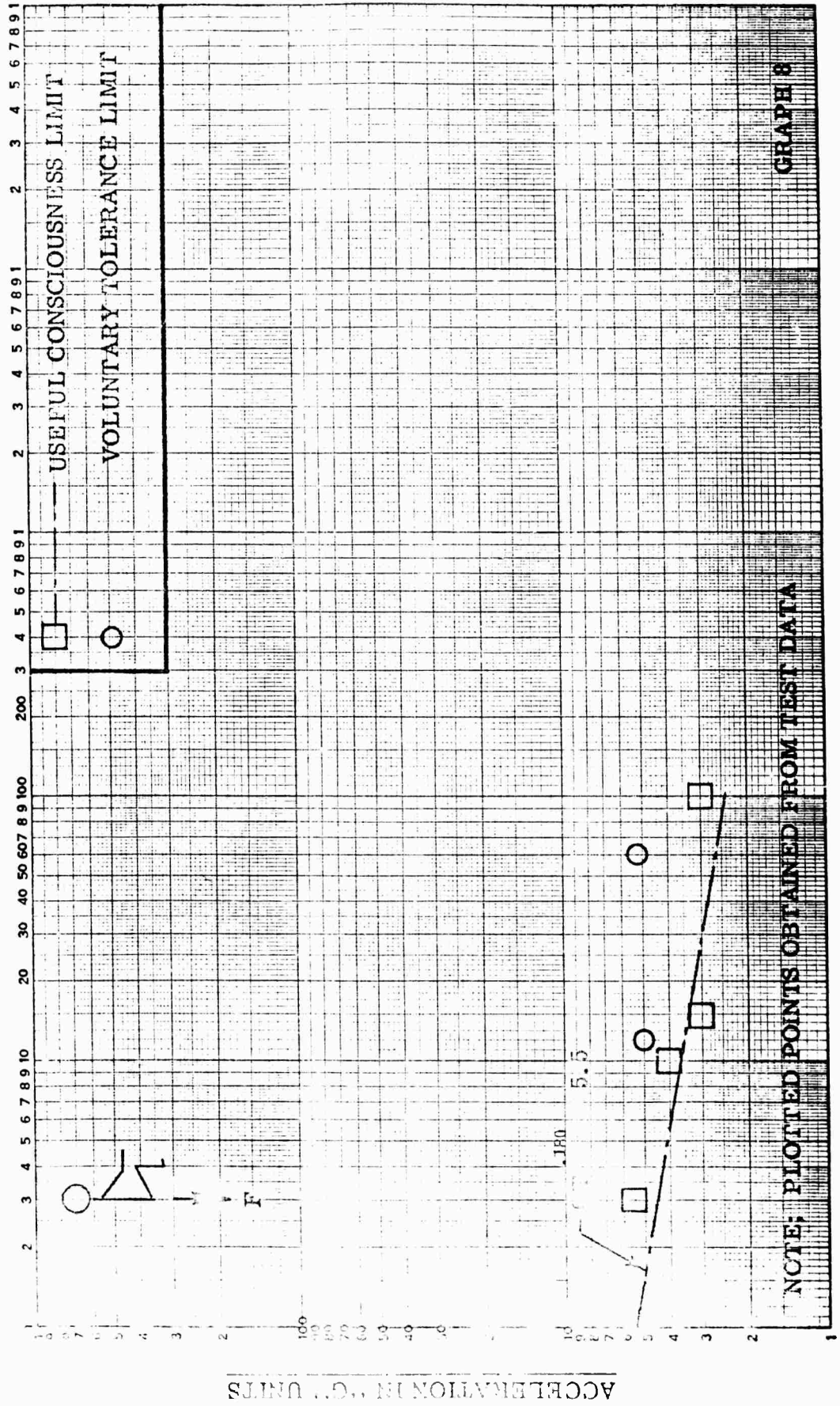
NOTE: PLOTTED POINTS OBTAINED FROM TEST DATA OR SERVICE USE

GRAPH 7

KE LOGARITHMIC 359-125G
 KEUFFEL & ESSER CO. MADE IN U.S.A.
 3 X 5 CYCLES

V- USEFUL CONSCIOUSNESS LIMIT

TIME IN SECONDS

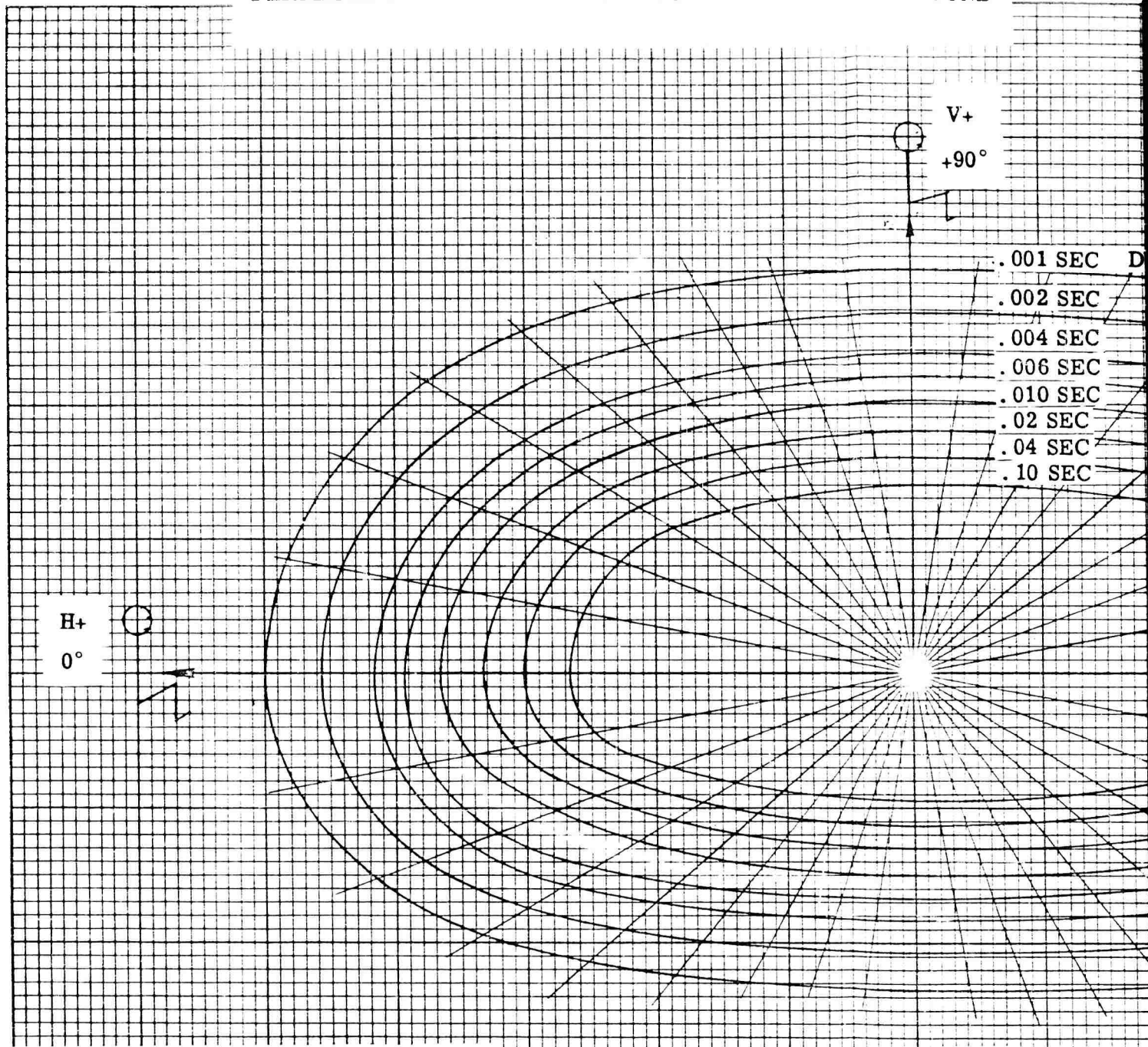


ACCELERATION IN "G" UNITS

GRAPH 8

NOTE: PLOTTED POINTS OBTAINED FROM TEST DATA

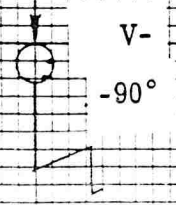
PERMANENT INJURY THRESHOLD DURATION .001 - .10 SECOND



NOTES

- 1. SCALE 1" = 30 "G"
- 2. "G" MEASURED RADIALLY

1



DURATION .001 - .10 SECOND

V+
+90°

- .001 SEC DURATION
- .002 SEC
- .004 SEC
- .006 SEC
- .010 SEC
- .02 SEC
- .04 SEC
- .10 SEC

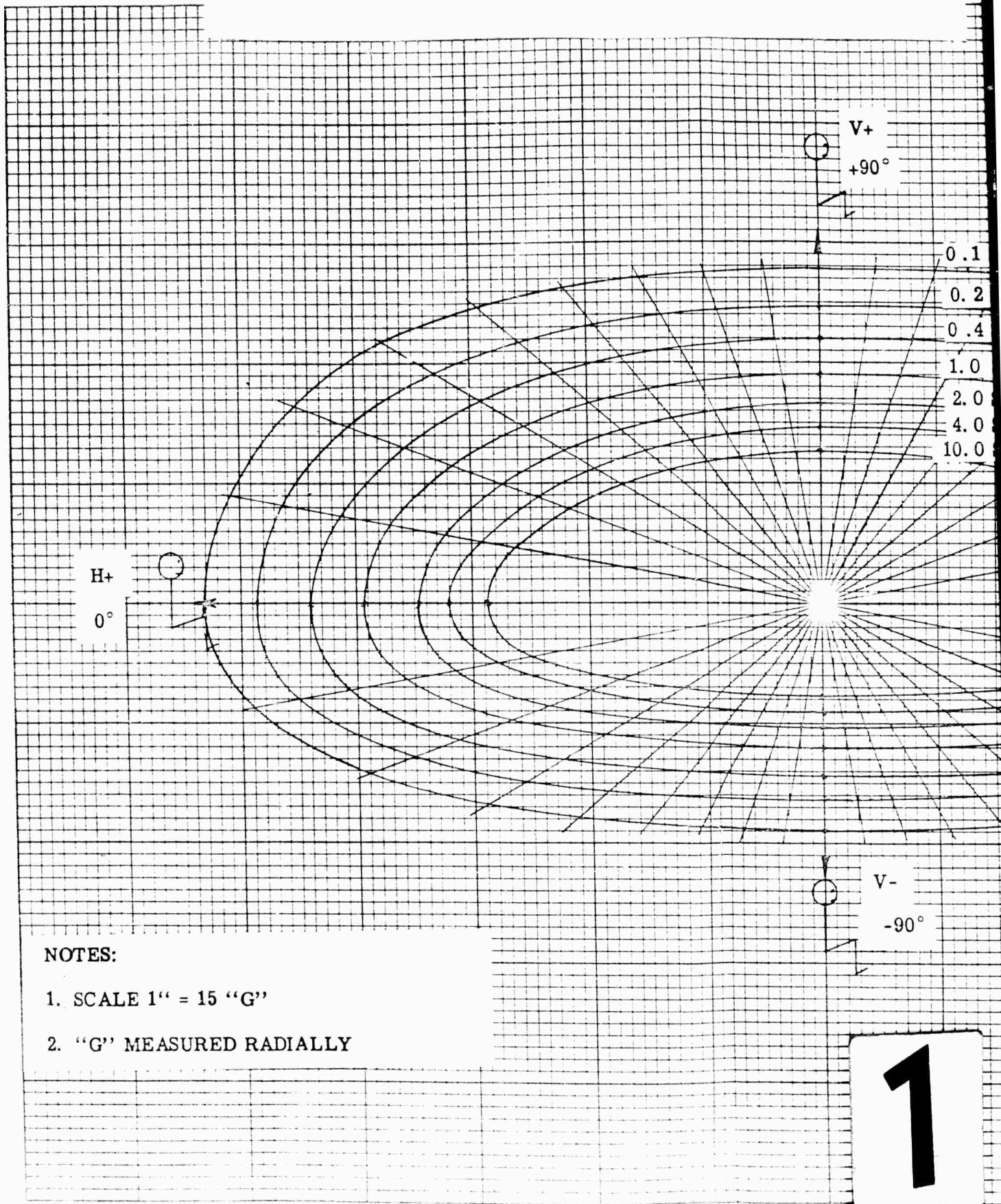
H-
±180°

V-
-90°

2

GRAPH 19

PERMANENT INJURY THRESHOLD - DURATION 0.1 - 10.0 SECONDS

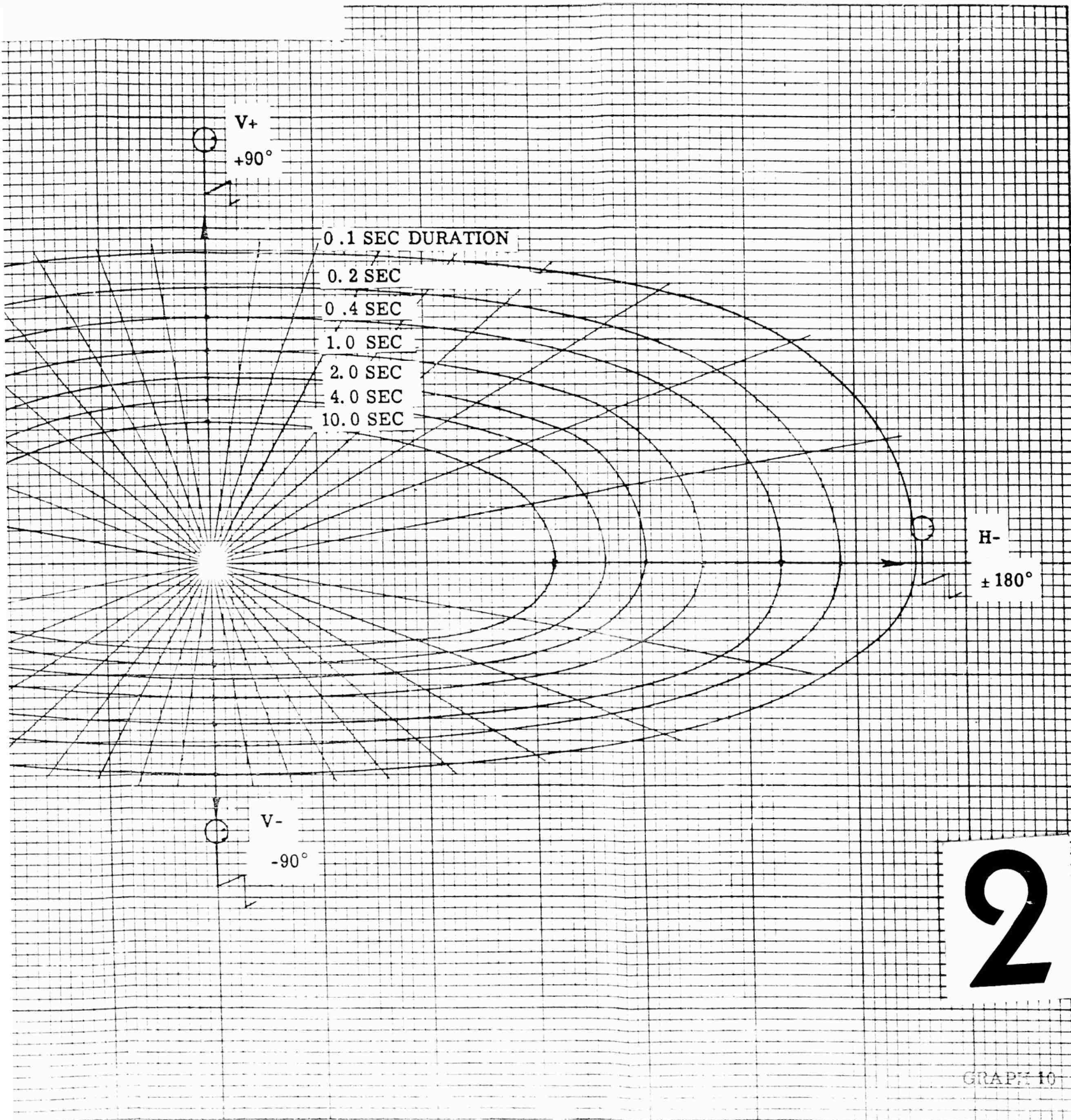


NOTES:

1. SCALE 1" = 15 "G"
2. "G" MEASURED RADIALLY

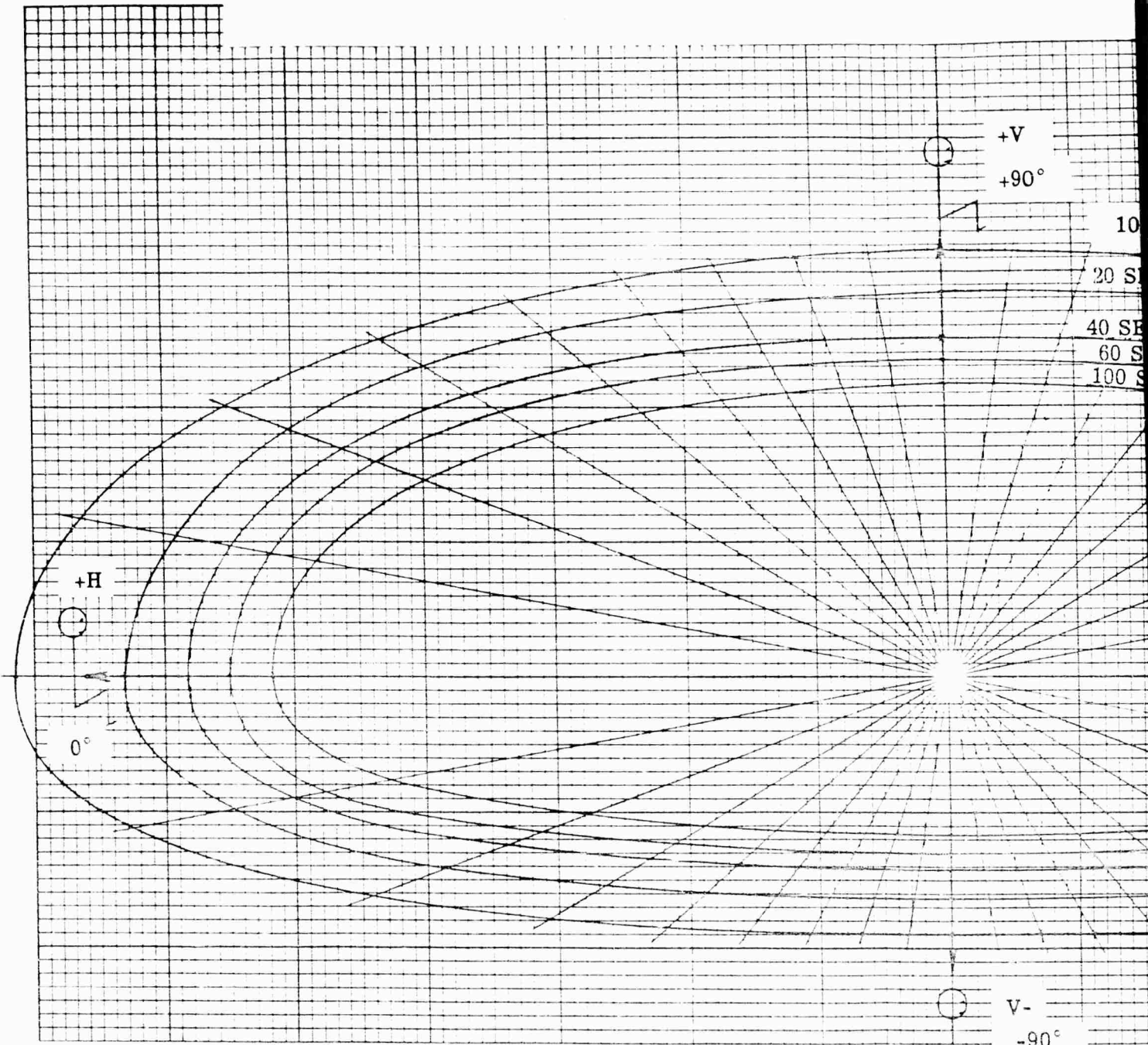
1

DURATION 0.1 - 10.0 SECONDS



2

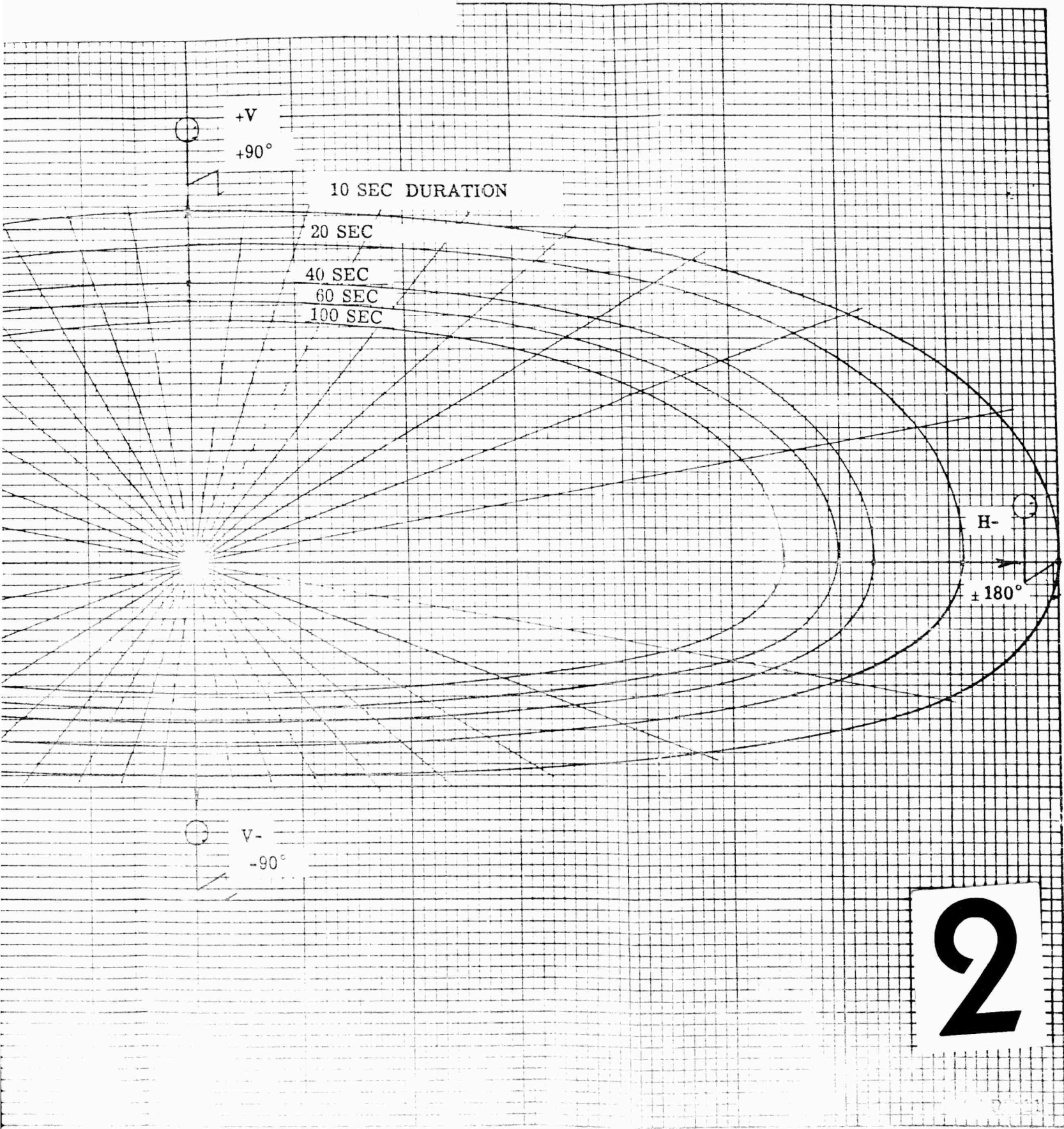
GRAPH 10



NOTES:

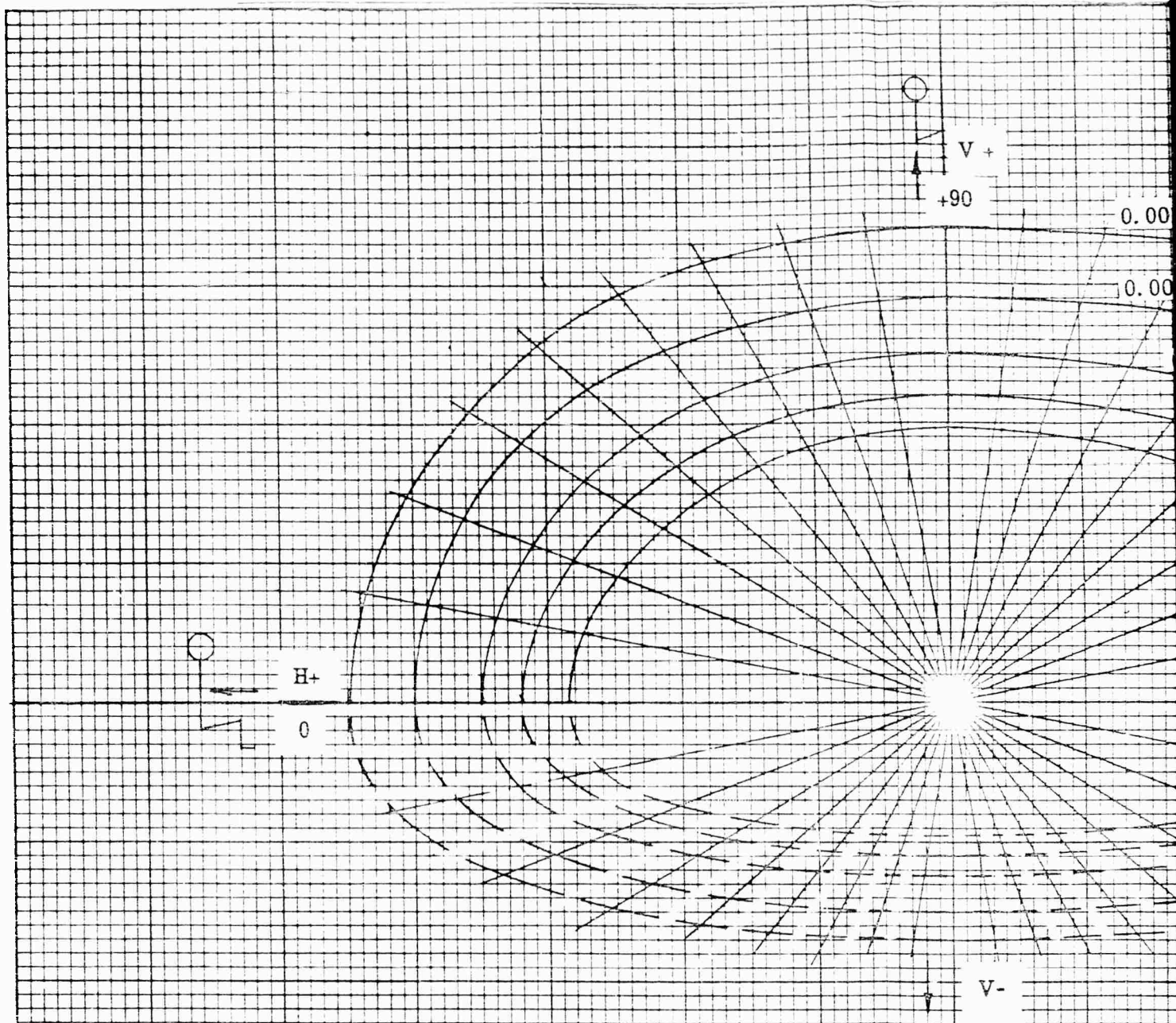
- 1. SCALE 1" = 6 "G"
- 2. "G" MEASURED RADIALLY

ENT INJURY THRESHOLD - DURATION 10-100 SECONDS



2

VOLUNTARY TOLERANCE TO ACCELERATIONS - DURATIONS 0.001 - 0.02 SEC

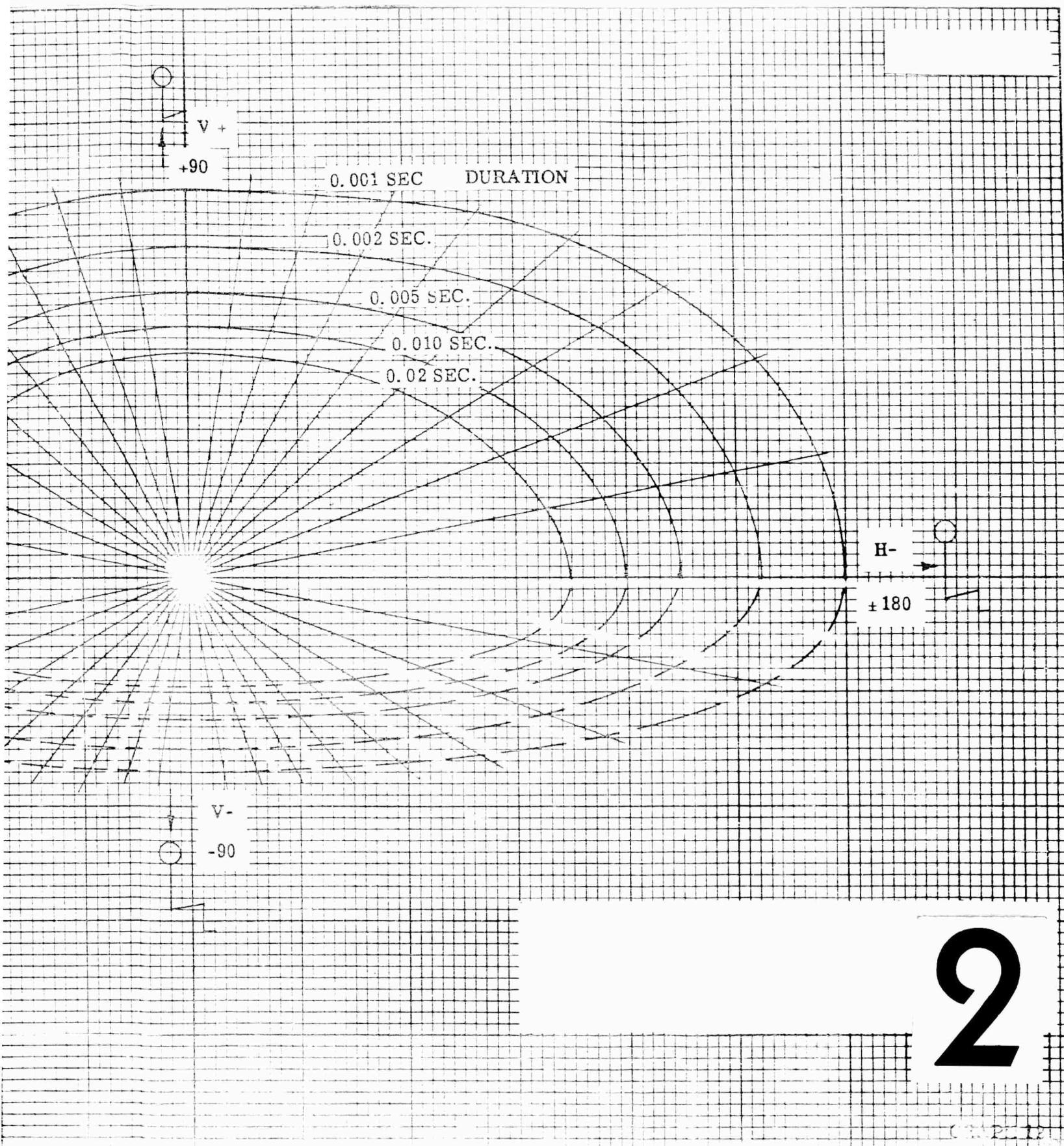


NOTES:

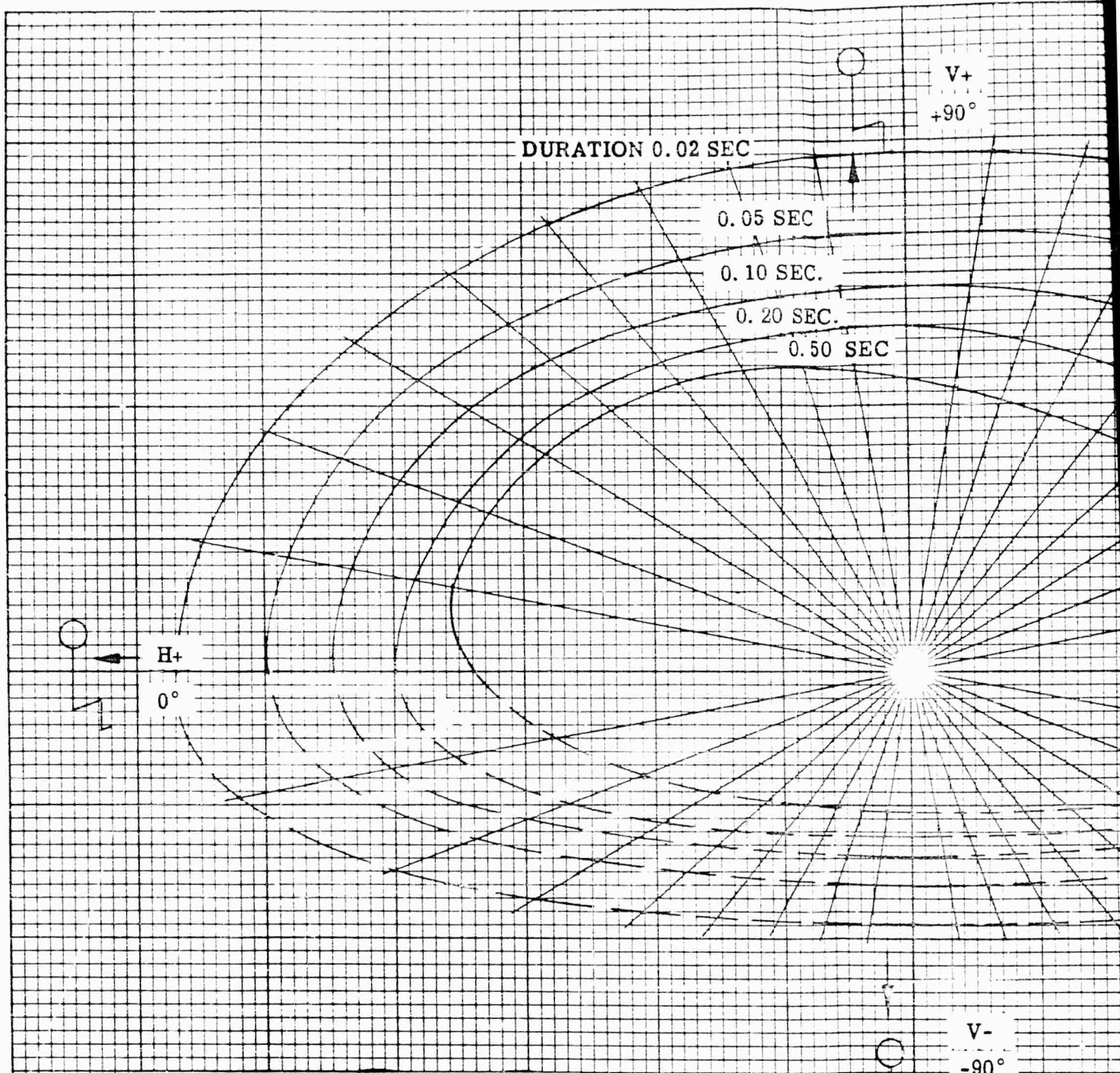
1. SCALE 1" = 20 "G"
2. "G MEASURED RADIALLY

1

ATIONS - DURATIONS 0.001 - 0.02 SECOND



VOLUNTARY TOLERANCE TO ACCELERATION

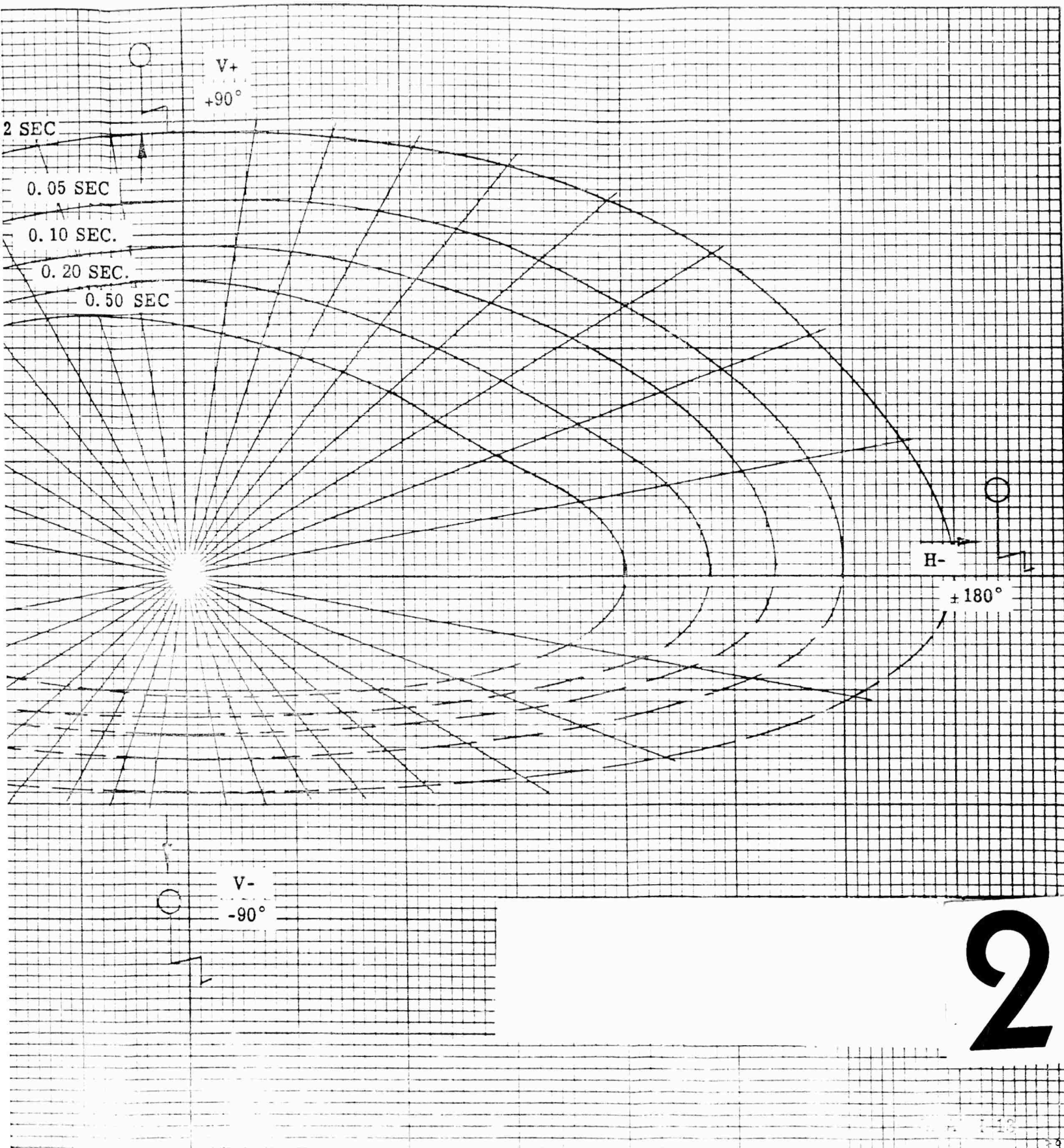


NOTES:

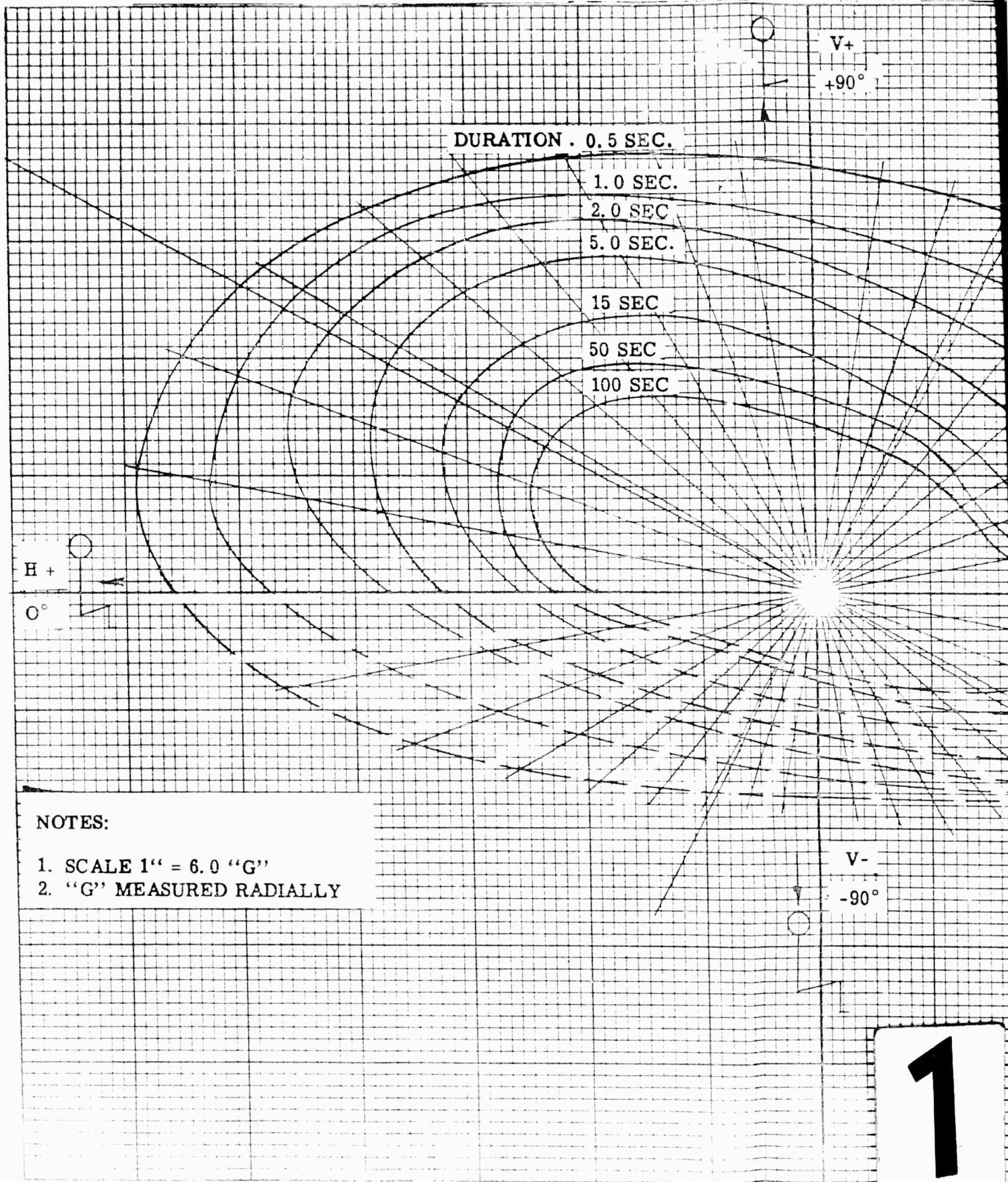
- 1. SCALE 1" = 10 "G"
- 2. "G" MEASURED RADIALLY

1

Y TOLERANCE TO ACCELERATION - DURATION 0.02 - 0.50 SECOND



VOLUNTARY TOLERANCE TO ACCELERATIONS - DURATION

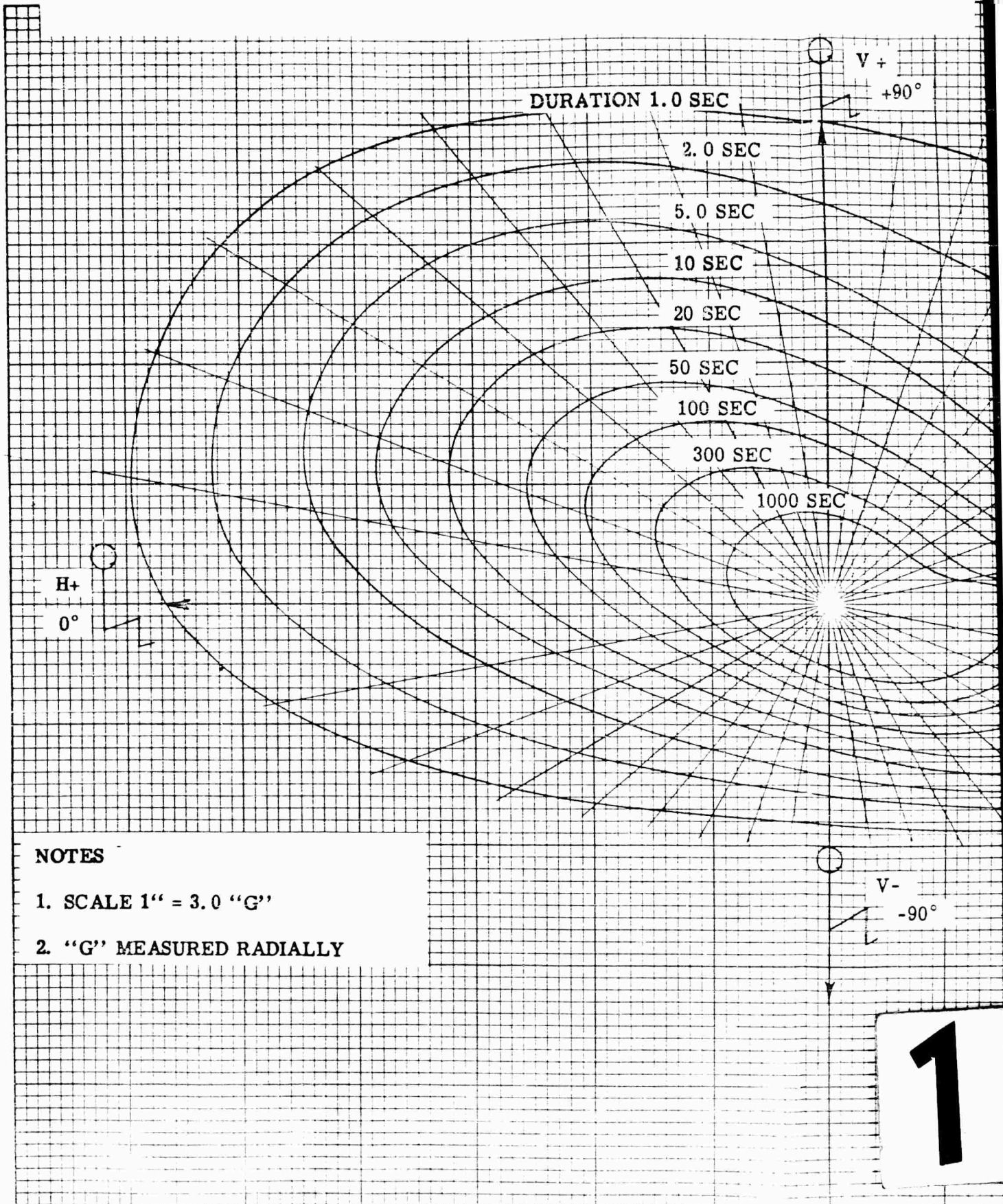


NOTES:

1. SCALE 1" = 6.0 "G"
2. "G" MEASURED RADIALLY

1

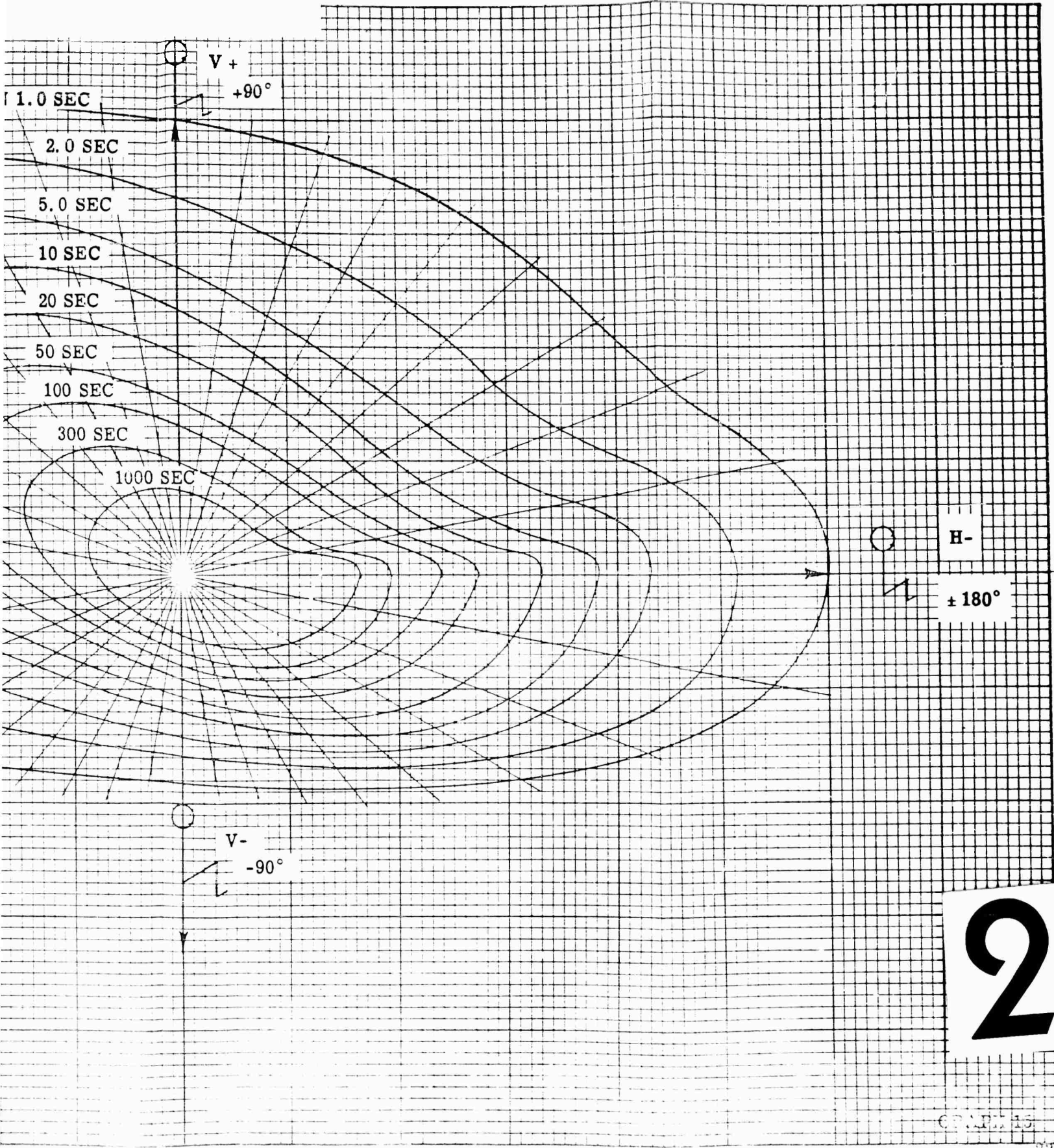
LIMITS OF USEFUL CONSCIOUSNESS DURATION 1.



NOTES

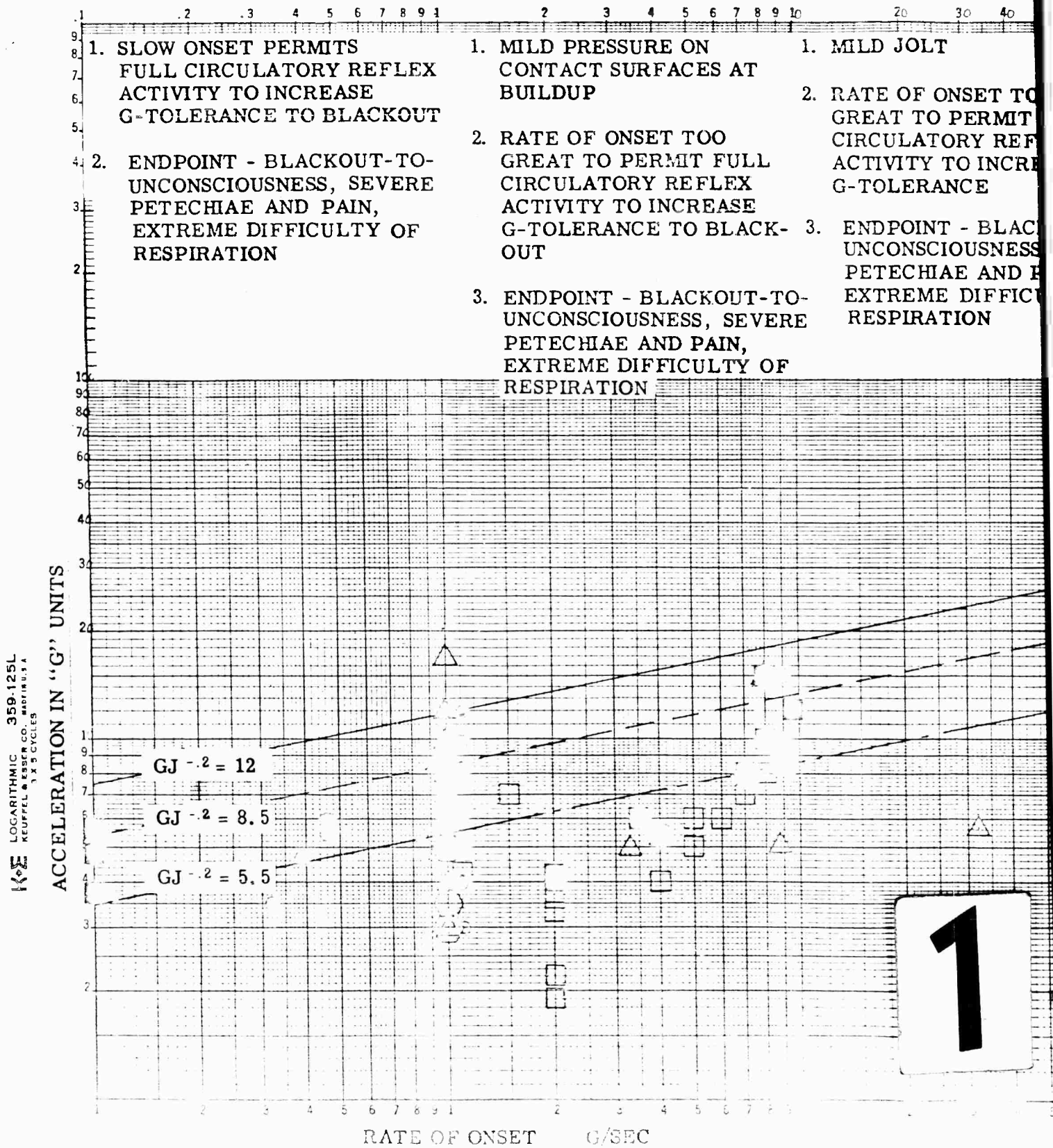
1. SCALE 1" = 3.0 "G"
2. "G" MEASURED RADIALLY

VUL CONSCIOUSNESS DURATION 1.0 - 1000 SECONDS



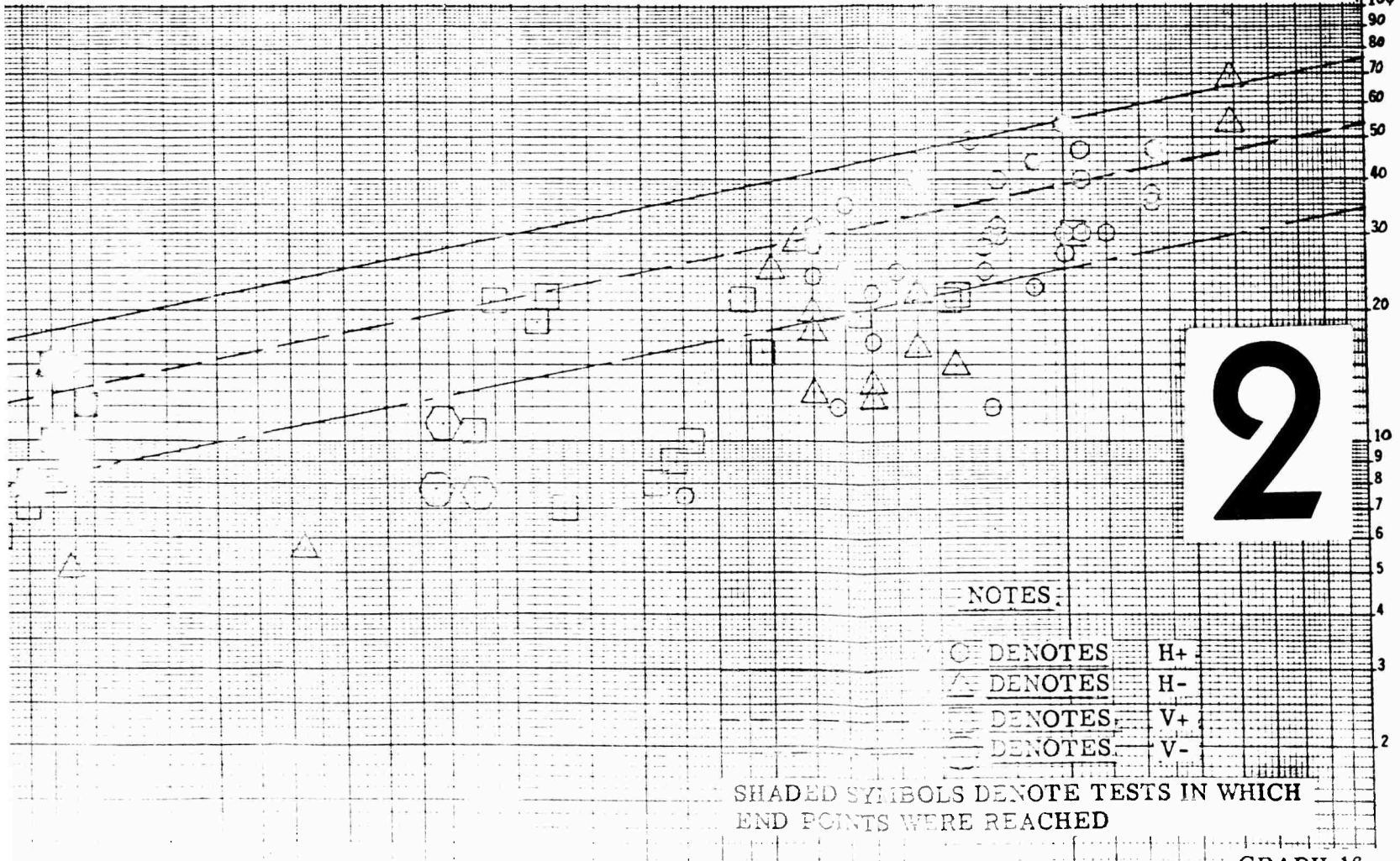
2

VOLUNTARY TOLERANCE TO ACCELERATION - RATE OF ONSET



ACCELERATION - RATE OF ONSET STUDY

- | | | | |
|--|---|---|---|
| <p>AT</p> <p>ULL
EX
SE</p> <p>LACK-</p> <p>UT-TO-
SEVERE</p> <p>N,
TY OF</p> | <p>1. MILD JOLT</p> <p>2. RATE OF ONSET TOO GREAT TO PERMIT FULL CIRCULATORY REFLEX ACTIVITY TO INCREASE G-TOLERANCE</p> <p>3. ENDPOINT - BLACKOUT-TO-UNCONSCIOUSNESS, SEVERE PETECHIAE AND PAIN, EXTREME DIFFICULTY OF RESPIRATION</p> | <p>1. MODERATE TO SEVERE JOLT</p> <p>2. ENDPOINT - SEVERE PETECHIAE AND PAIN THRESHOLD TO SHOCK AND SPINAL INJURY</p> | <p>1. SEVERE JOLT</p> <p>2. END POINT - PROBABLE LIMITS TO SHOCK AND INJURY</p> |
|--|---|---|---|



NOTES:

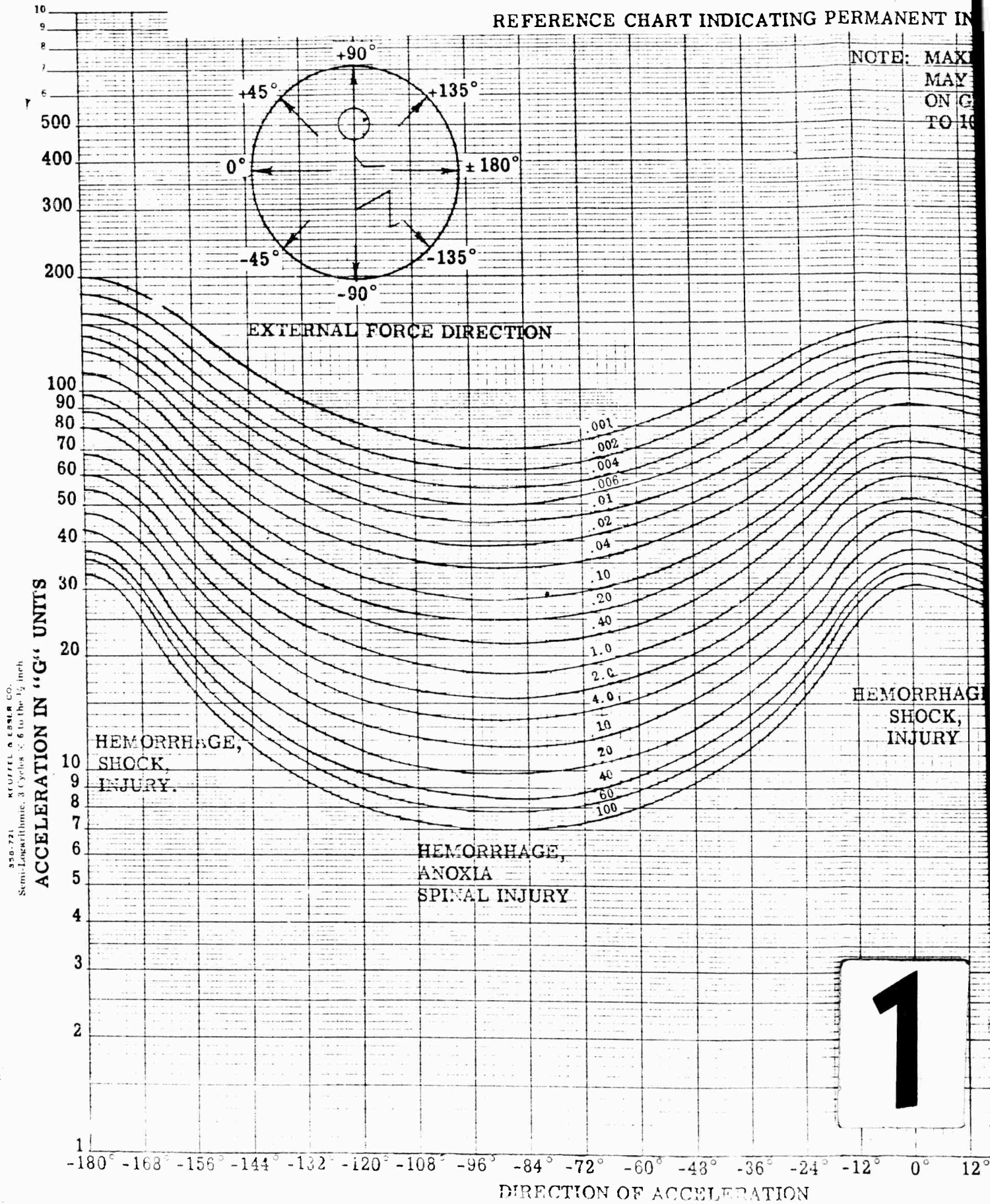
- DENOTES H+
- △ DENOTES H-
- DENOTES V+
- ◻ DENOTES V-

SHADED SYMBOLS DENOTE TESTS IN WHICH END POINTS WERE REACHED

GRAPH 16

HUMAN TOLERANCE TO ACCELERATION
 REFERENCE CHART INDICATING PERMANENT INJURY

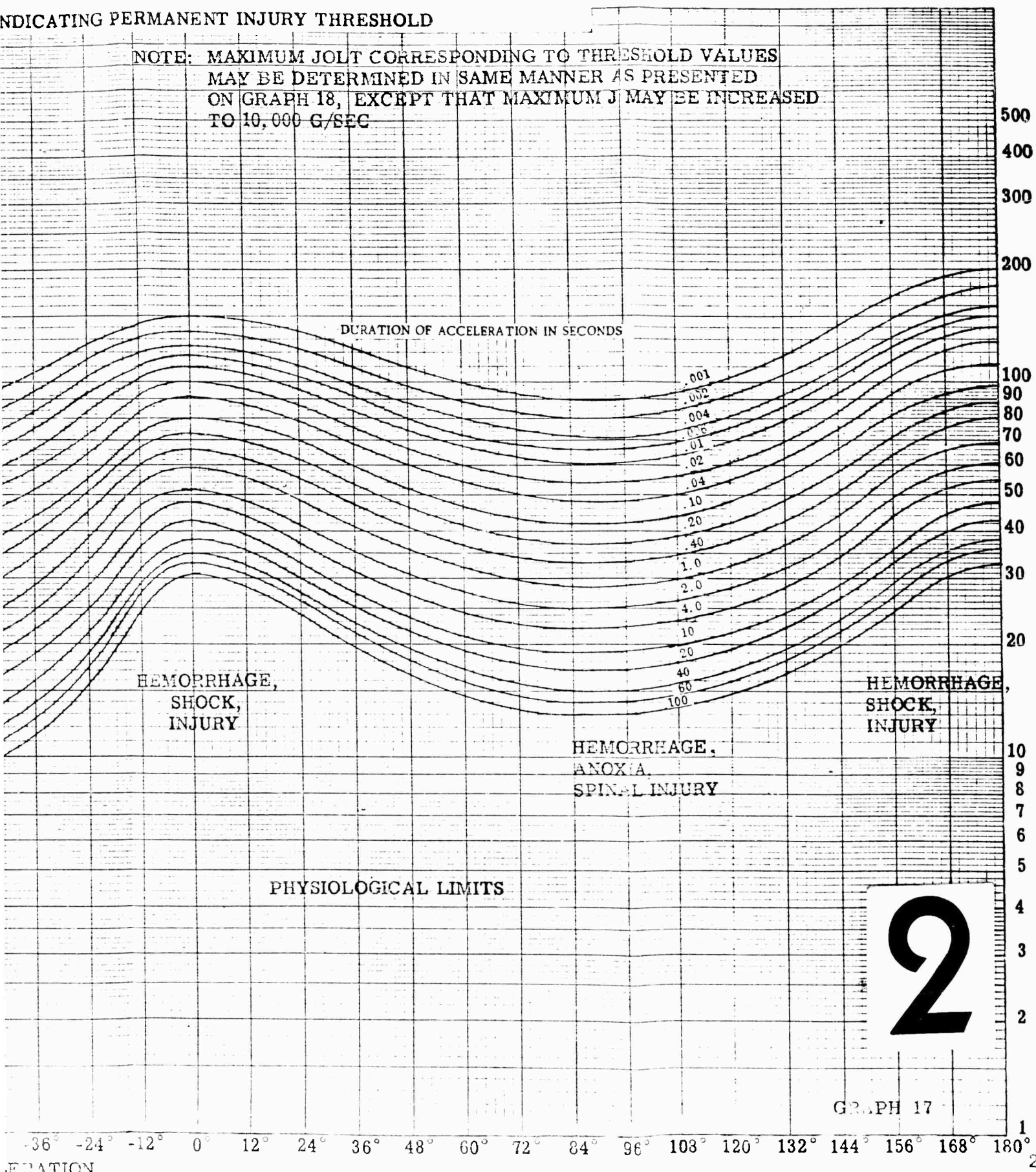
NOTE: MAXIMUM
 MAY VARY
 ON GRAVITY
 TO 10%



1

TOLERANCE TO ACCELERATION
 INDICATING PERMANENT INJURY THRESHOLD

NOTE: MAXIMUM JOLT CORRESPONDING TO THRESHOLD VALUES
 MAY BE DETERMINED IN SAME MANNER AS PRESENTED
 ON GRAPH 18, EXCEPT THAT MAXIMUM J MAY BE INCREASED
 TO 10,000 G/SEC

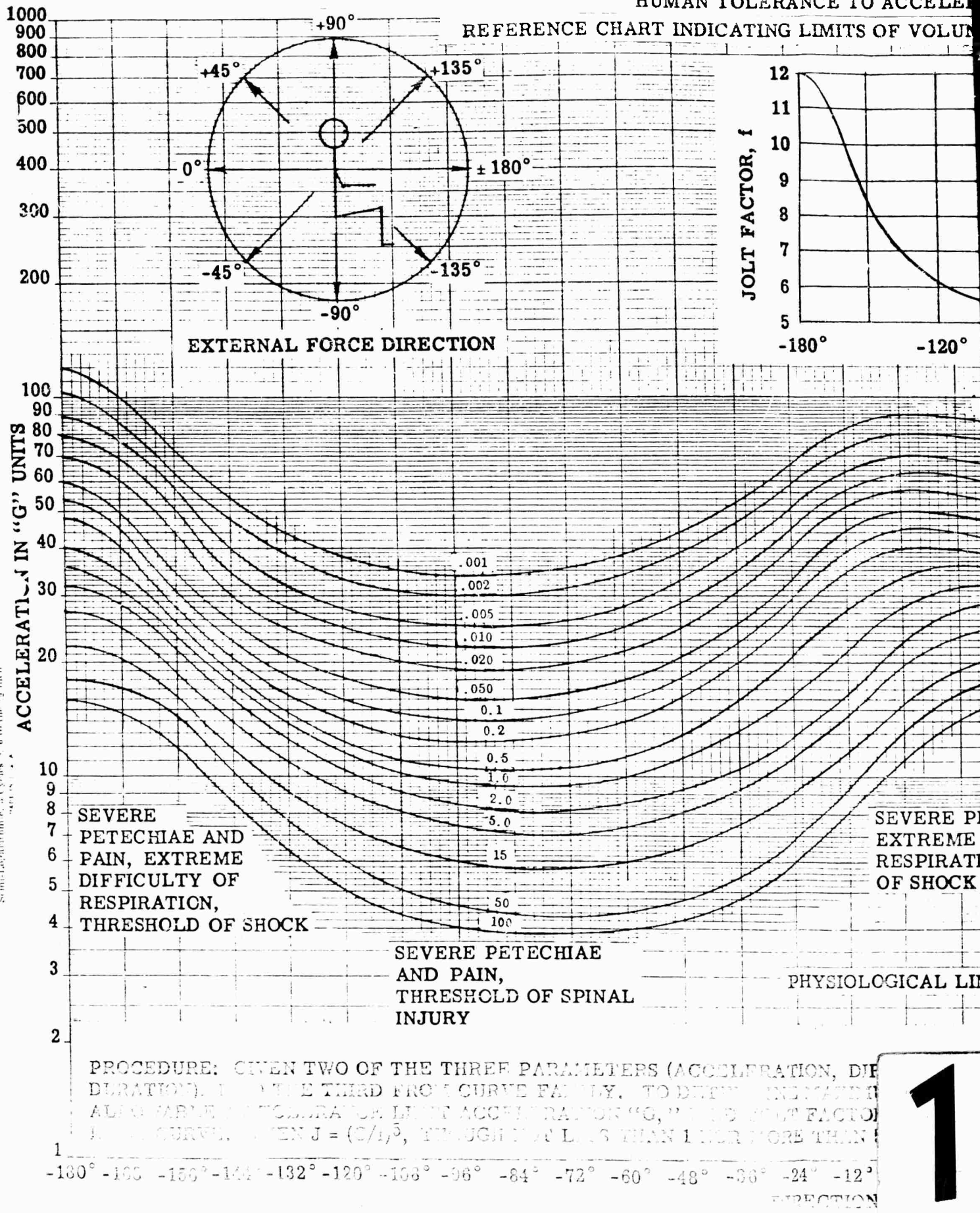


2

GRAPH 17

HUMAN TOLERANCE TO ACCELERATION

REFERENCE CHART INDICATING LIMITS OF VIBRATION

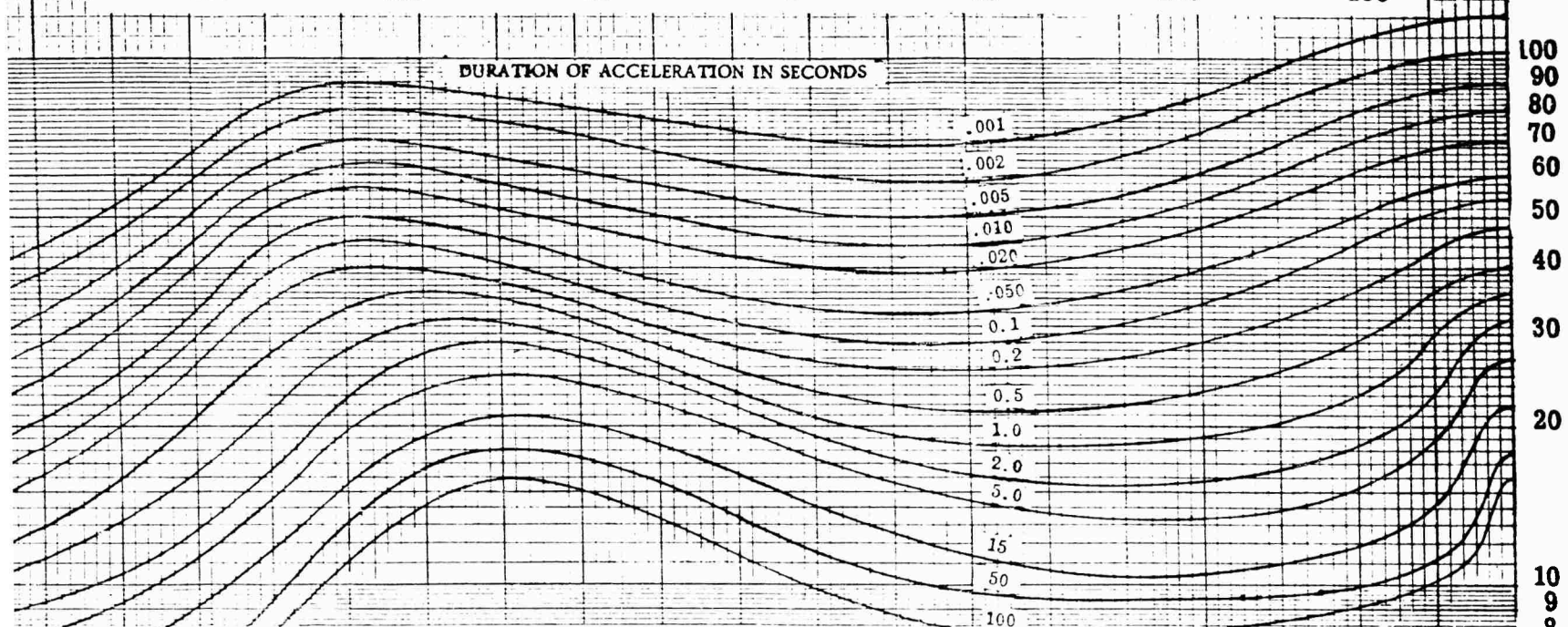
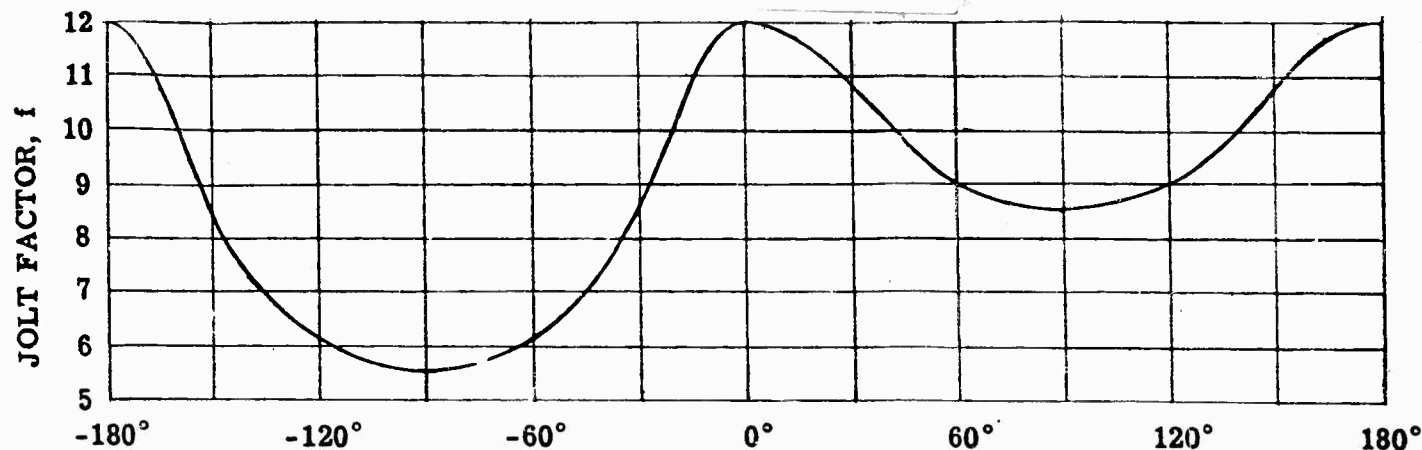


100-721 KEUFEL & ESSER CO.
Scale: Acceleration in G, Cycles per Sec. to the 1/2 inch

1

2

HUMAN TOLERANCE TO ACCELERATION INDICATING LIMITS OF VOLUNTARY TOLERANCE



SEVERE PETECHIAE AND PAIN,
EXTREME DIFFICULTY OF
RESPIRATION, THRESHOLD
OF SHOCK

BLACKOUT-TO-
UNCONSCIOUSNESS,
SEVERE PETECHIAE,
THRESHOLD OF SPINAL
INJURY

SEVERE PETECHIAE
AND PAIN, EXTREME
DIFFICULTY OF
RESPIRATION,
THRESHOLD OF
SHOCK

PHYSIOLOGICAL LIMITS

G = ACCELERATION MAGNITUDE

J = JOLT, OR RATE OF ONSET OF G

f = JOLT FACTOR, FROM INSET CURVE

$$J = (G/f)^5 \text{ BUT } \geq 1 \text{ \& } \leq 5000$$

GRAPH 18

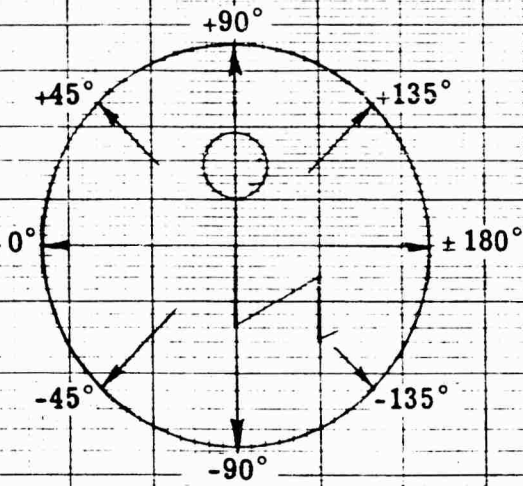
(ACCELERATION, DIRECTION,
DURATION, AND MAGNITUDE) JOLT "J"
"G" AND JOLT FACTOR "f" ON
X-AXIS MORE THAN 5000 G/SEC

-48° -36° -24° -12° 0° 12° 24° 36° 48° 60° 72° 84° 96° 108° 120° 132° 144° 156° 168° 180°

DIRECTION OF ACCELERATION

HUMAN TOLERANCE TO ACCELERATION REFERENCE CHART INDICATING LIMITS OF USEFUL CON

NOTE: RATE
BETW
SIGN



EXTERNAL FORCE DIRECTION

1

35-772 KUFFEL & ESSER CO.
Some Escherichia, 1 Cycle, 7.6 to the 1/2 inch

ACCELERATION IN "G" UNITS

10
9
8
7
6
5
4
3
2
1

-180° -168° -156° -144° -132° -120° -108° -96° -84° -72° -60° -48° -36° -24° -12° 0° 12° 24°

PAIN,
PETECHIAE

PETECHIAE
PAIN,
DIFFICULTY OF
RESPIRATION

PETECHIAE, PAIN,
DIFFICULTY OF RES

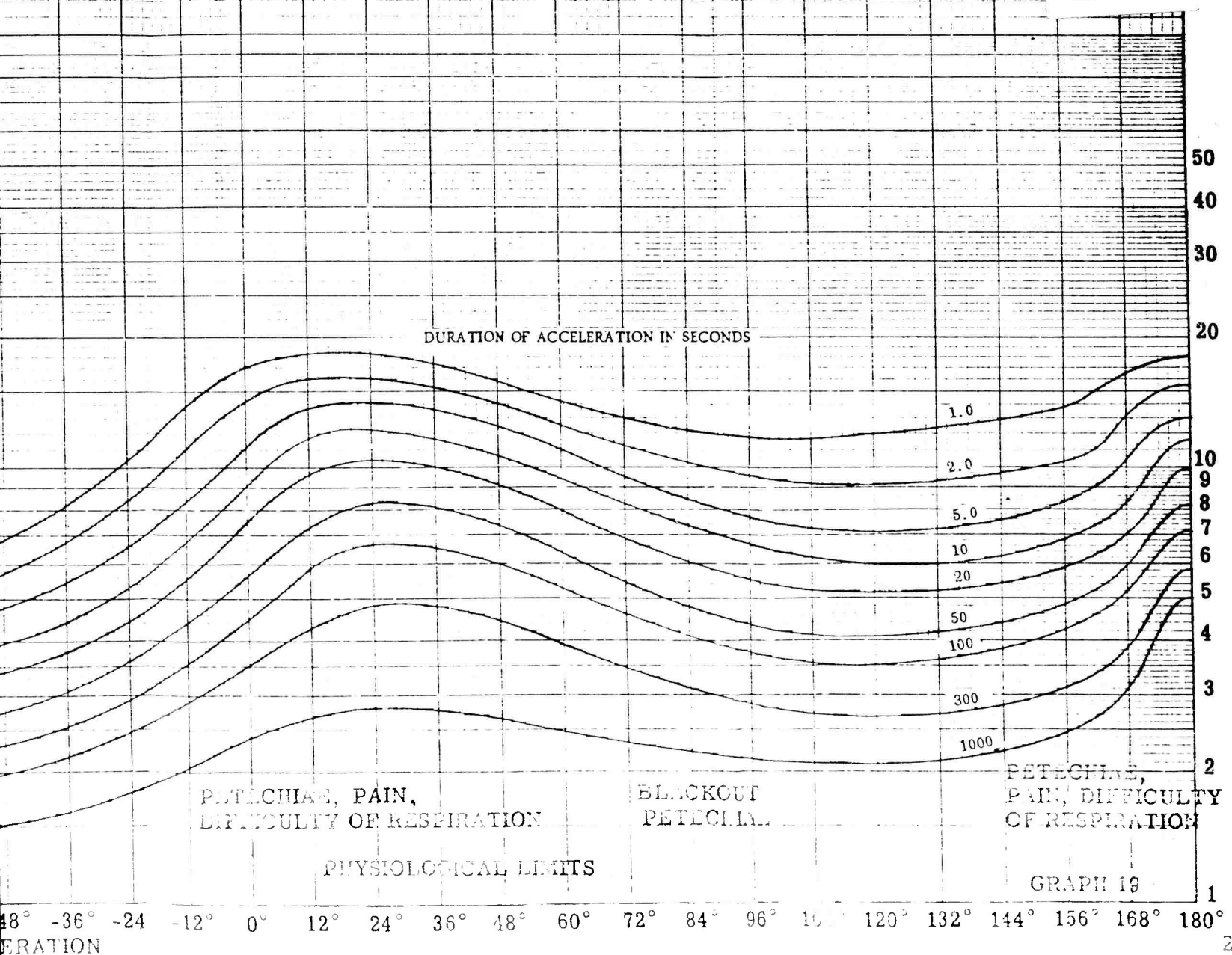
PHYSIOLOG

1.0
2.0
5.0
10
20
50
100
500
1000

TOLERANCE TO ACCELERATION
INDICATING LIMITS OF USEFUL CONSCIOUSNESS

NOTE: RATE OF ONSET OF ACCELERATION OR "JOLT" IS ASSUMED TO BE
BETWEEN 1 G/SECOND TO 100 G/SECOND, AS MEASURED ON THE
SIGNIFICANT SLOPE OF THE ACCELERATION-TIME CURVE

2



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