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NAVAL AIR DEVELOPMENT CENTER

Johnsville, Warminster, Pennsylvania

REPORT NO. NADC-AC-7010 11 JUNE 1970

DEFINITION OF DESIGN CRITERIA FOR ENERGY ABSORPTION SYSTEMS

PHASE REPORT
FOUNDATIONAL RESEARCH PROJECT
TASK AREA NO. R011-01-01 WORK UNIT NO. CC1-01

PREPARED BY

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DEPARTMENT OF THE NAVY
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JOHNSVILLE
WARMINSTER, PA. 18974

Aerospace Crew Equipment Department

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This report concerns Phase III, Part II of a research program to determine systems and materials that can be used to attenuate to a tolerable limit, the forces imposed by high impact in both ejection and non-ejection seats. The goal of this research effort was to determine the optimum design criteria for energy absorbers that would best protect the pilots and passengers of fighter, helicopter and troop transport aircraft.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. SUMMARY

1.1 INTRODUCTION

It has been known for some time that the number of injuries sustained during potentially survivable crashes could be reduced if a proper energy absorber were placed between the seated man and fuselage to dissipate the energy that is present in a plane crash. The problem of what type of energy absorber should be used and what characteristics should it have becomes apparent immediately but does not lend itself to an easy solution. Does an energy absorber with a square wave force-deflection curve offer the best protection or do the dynamics of the seated man system dictate an energy absorber with variable force-deflection characteristics to adequately protect the man. To solve this problem, a design criteria for energy absorbers that would best protect the pilots and passengers of fighter, helicopter, and transport aircraft was the main goal of the research effort conducted on this project, but before any optimum energy absorption criteria could be developed several pertinent questions had to be answered.

The first of these was how to easily evaluate a given energy absorber's performance under the dynamic conditions that exist during an airplane crash.

The solution to this problem is to utilize a digital computer. A computer program was written using the MIMIC routine to solve the equations of motion of a seated man model placed in series with a seat and an energy absorber and excited by an arbitrary input acceleration. The man model used was a 10 HZ, 30 percent critically damped single degree of freedom system that can be used to calculate the forces generated by a seated man and the acceleration input is put into the program as a series of acceleration-time pairs. The program allows characteristics of any energy absorption device to be entered into it as a number of force-deflection pairs and the program then calculates the response of the seated man-energy absorber system to a given input.

The next question was what kind of response could a man survive and the answer comes from an injury model of a seated man which calculates a Dynamic Response Index (D. R. I.) of a man for any arbitrary input acceleration. One result of the computer program is the seat acceleration which the program then uses as an input to the injury model, an 8 HZ, 22 percent critically damped single degree of freedom system. The compression of the spring element is indicated by the D. R. I. and this provides a means of evaluating the probability of injury of the generated seat acceleration.

The final problem to be solved was to find crash acceleration time profiles which represented survivable crashes for the different types of aircraft. Many sources of actual crash data were reviewed and examined to select typical survivable input acceleration waveforms. Several waveforms were collected for helicopter, fighter and transport type aircraft; and these were used as input to the computer program with the selection of the waveform for each aircraft made on the basis of the D. R. I. output.

With the selection of an input waveform for each aircraft type and a means of evaluating the effect of the energy absorber upon the seated man, the definition of an optimum energy absorber design criteria was undertaken. The resulting design criteria was then used with the D. R. I. to analyze test records of existing energy attenuators. The force-time data available were re-evaluated and force-displacement curves generated which were entered into the computer program and the D. R. I. was calculated for each device with various man and seat weight for each of the three types of aircraft.

1.2 RESULTS AND CONCLUSIONS

There are several significant results that have been found during the research.

The most significant are related to current energy absorber design criteria. Energy absorbers are currently designed to the criteria that a constant force device will generate a constant acceleration profile and therefore create the maximum energy absorption for minimum stroke. This, because of the dynamic response of the man, is false. If an absorber is designed assuming that the man is a rigid mass that can sustain a constant and tolerable acceleration of 18 g, then the developed digital computer program can demonstrate that: (1) the acceleration to the man is not constant, and (2) the response of the man in terms of probability of injury can be ten times greater than anticipated.

Another interesting aspect is that some commercially available energy absorbers approach the theoretically "optimum" force-displacement profiles calculated. This is not because they were designed that way, but because they simply turned out that way. Several absorbers have large amplitude force "spikes" at the beginning of the stroke. This could, based upon current design criteria, have caused their rejection as unacceptable. However, the study has shown that this is, in fact, a reason for making them more acceptable than the square waveform criteria they were designed to meet. Their distorted waveforms as generated by the physical hardware are superior to any square-wave device which may be designed.

The research has shown that it is possible to determine a force-displacement profile for a given set of conditions which is superior to any square wave or peak and plateau force-displacement curve. Because of the response of the human, the optimum profile will have a "notched" appearance to take advantage of human dynamics. Any other waveform, in order to not exceed the same tolerance limit, will have a greater stroke length.

The results just mentioned were found using a computer program that synthesizes the human body, both force and injury aspects, the crash input and the energy absorber force-displacement characteristics. The program is a research tool in that it accepts as input; man weight, seat weight, any acceleration-time profile of the crash, and any force-displacement curve for the absorber. In addition, the program can recognize multiple absorbers and a stroke limit. If the absorber "bottoms" the seat responds as though impacting a more rigid structure. The absorber is assumed to be capable of attenuating energy in both compression and tension.

The literature was surveyed and representative crash acceleration pulses of survivable crashes were tabulated. Four waveforms are presented for the helicopter and transport.

Two are presented for the fighter. A specific waveform for each type was selected by using the program and determining the most severe based upon the injury response.

The review of human tolerance data resulted in the selection of the D. R. I. method of evaluating injury. By this means it is possible to quantitatively evaluate the probability of injury to the man without recourse to trapezoidal approximations. A value of 18 for the D. R. I. was selected as the initial criteria for optimization. This is indicative of a five percent probability of spinal injury.

As mentioned, it was possible to show that force-deflection profiles of optimum energy absorption devices could be developed for particular crash profiles, men and seat weights. However it was not possible to select any one optimum force-displacement profile for each vehicle type (transport, helicopter, and fighter) that would be best for all possible conditions. Optimums could not be firmly established because of the effects of variations of the input accelerations. It has been shown that the response of a dynamic man upon an elastic energy absorber is more complex than anticipated. The input acceleration thought to be most severe based upon peak acceleration or velocity change does not necessarily generate the greatest response of the man, either inertially or in terms of injury.

1.3 RECOMMENDATIONS

It is recommended that the following tasks be performed.

1. The developed computer program should be utilized to study the probability of injury due to selected variations of input waveform and payload masses. The results should be compiled in terms of cumulative probability of injury and stroke length in order to make a quantitative judgment of the tradeoff between the two.

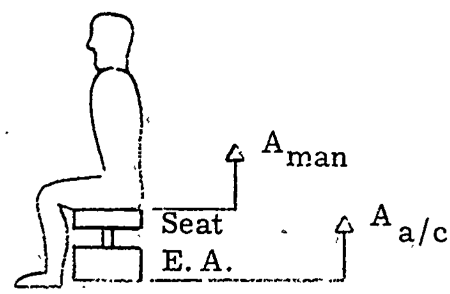
2. Prototype hardware should be developed to determine whether or not fabrication of an energy absorber with the notched force-displacement characteristic is practical.

3. Additional studies should be conducted to determine whether or not a hardware design can be developed that will passively satisfy many input and payload configurations.

2. DISCUSSION

2.1 COMPUTER PROGRAM

One of the objectives of the research was to develop a computer program that would synthesize the crash acceleration, a generalized energy absorption device, and the human. Schematically this is shown below:



The acceleration at the ground acts upon the energy absorber to develop forces within it which accelerate the seat. The seat then accelerates the man. The energy absorber is represented by a force-displacement curve either from measured data or as represented by some analytical function. The acceleration is similarly represented by acceleration-time data points. The seat motion is described by the equation.

$$M_2 \ddot{X}_2 = C_1 \dot{X}_1 + K_1 X_1 - C_1 \dot{X}_2 - K_1 X_2 + F_{ea} + F_{st} - W_2$$

where M_2 = the mass of the seat

W_2 = the weight of the seat

C_1 = the damping factor of the 10 HZ man

K_1 = the stiffness of the 10 HZ man

X_2 = the displacement of the seat

X_1 = the displacement of the 10 HZ man

F_{ea} = the force developed by the energy absorber

$F_{st.}$ = the force developed by the structure when the energy absorber bottoms.

All dotted values are time derivatives of the variable. The man is represented by a 10 HZ, 0.3 damping ratio single degree of freedom system. This has been shown to duplicate man's force response to impact. The equation for the man is:

$$M_1 \ddot{X}_1 = -K_1 X_1 - C_1 \dot{X}_1 + K_1 X_2 + C_1 \dot{X}_2 - W_1$$

W_1 = the weight of the man

M_1 = the mass of the man

If we were only interested in forces, this would be sufficient. However, we are also interested in injury and this requires an additional element. This is accomplished by incorporating another single degree of freedom system into the program that is driven by the seat acceleration. This is written:

$$M_3 \ddot{X}_3 = C_3 \dot{X}_2 + K_3 X_2 - C_3 \dot{X}_3 - K_3 X_3 - W_1$$

M_3 = M_1

C_3 = the damping factor of the 8 HZ man

K_3 = the stiffness of the 8 HZ man

X_3 = the displacement of the 8 HZ man where the seat motion X_2 drives the system but is not coupled to it. The coefficients for the model are those of an 8 HZ, $\zeta = 0.22$ system. This is then the D. R. I. or injury model for the program. The D. R. I. is a measure of the force developed in the spring and equal to $K_3(X_3 - X_2)/M_3 g$.

These are the basic equations required for the program. They were written in a format compatible with a MIMIC routine and the remainder of the program is the logic required to properly input, output and control the calculations. A flow diagram of the program is shown in Figure 1 and a complete users guide is contained in Appendix I.

2.2 DEFINITION OF ACCELERATION PROFILES AND HUMAN TOLERANCE LEVELS

2.2.1 HUMAN TOLERANCE LEVELS

Many tolerance curves have been developed to indicate acceleration limits that must not be exceeded. These are available in terms of peak G, rise time and pulse duration. The unfortunate aspects of these are that it is not always possible to relate the characteristics of the measured acceleration waveform directly to the waveform of the tolerance curve. It was because of this difficulty that analytical models of the human body were developed to provide a quantitative means of estimating injury.

If an analytical model were available that possessed a response parameter related to injury, then the model could be subjected to the acceleration waveform desired and the response calculated. Such a model is available and is currently being used to predict the probability of injury. The model is the one developed several years ago by Mr. Peter Payne and currently included within Air Force specification MIL-S-9479A.

The history of the model begins in 1961 when Stanley Aviation Corporation conducted a research program to study human tolerance to abrupt accelerations and published a report describing their results. This was an attempt to collect all existing tolerance information and from it infer analytical models that could be utilized. This was indeed accomplished and the model concept helped to explain various regimes of human response. From this work Payne developed several later papers that continued the effort and eventually these led to the adoption by the Air Force of the D. R. I. model.

As a portion of this program Beta Industries, Inc., was required to determine tolerance levels and waveforms in accordance with the best available documented data. The D. R. I. model was originally proposed as the means of examining tolerance and no additional information collected altered that selection.

Later reports, such as The Crash Survival Design Guide, USAAVLABS TR-67-22, reference data already contained within the D. R. I. model development. Specifically, NASA Memorandum 5-19-59E, Human Tolerance to Rapidly Applied Acceleration: A Summary of the Literature, was referenced in both Stanley Aviation's Report and the Crash Survival Design Guide. Hence, the model development includes the experimental data and by using it we satisfy the standard tolerance curves that utilize arbitrarily selected trapezoidal waveforms. From MIL-S-9479A the allowable D. R. I. of 18 is established as a value associated with a five per cent or less probability of spinal injury based upon operational ejection data and was used as the tolerance level to be desired. For other D. R. I. values the relationship between D. R. I. and probability of injury is given in Figure 39.

The selection of the D. R. I. model eliminates the need of specifying an acceleration waveform as a portion of the tolerance criteria. The purpose of the model is to calculate the response of a single degree of freedom system to whatever acceleration waveform is desired. The response is calculated in terms of relative displacement, δ , and the D. R. I. is calculated by multiplying by the natural frequency of the system and dividing by the gravitational constant. The frequency and weight are specified such that the relative displacement is analogous to spinal compression and hence the D. R. I. limit of 18 is in effect a limit on the force carried in the spine.

The model responds with the correct relative displacement and velocity as a function of its stiffness, damping and inertial characteristics, so that regardless of the input waveform the D. R. I. is indicative of the force in the spine.

In the computer program the D. R. I. model is included and responds to the seat accelerations calculated. It is not the system used in calculating energy absorber response because it is not a force model but a tolerance or physiological model. The 10 HZ system is used to calculate how the seat accelerates and this is then used as input to the tolerance model. Both a force and a physiological model are necessary because the system dynamics must be found using a force model but the question of injury probability is best answered by the tolerance model. This can be explained as follows:

First, suppose it is desired to be able to predict the force response of the human body in a seated position. It has been shown that a 10 HZ system responds properly. If a 10 HZ system is accelerated and the force developed is measured, it is similar to that developed by man. This was established by conducting tests with humans and measuring the forces developed. Secondly, to evaluate the possibility of injury to a man's back due to transient acceleration, it is necessary to use an 8 HZ system.

This is not a directly measured phenomena but has come about from observing the breaking strength and stiffness of vertebral bodies. If these values are known, body weight distribution and calculated whole body response will result in an 8 HZ system which provides a model indicative of the force developed in the spine. The model is an analytical tool. Any given acceleration waveform input can be used to calculate an internal force. By establishing limits on displacement, velocity, or force, calculations can be made to determine whether or not the model (spine) exceeds its limit. The limit usually used is the D. R. I.

$$\text{D. R. I.} = \frac{w^2 \delta \text{ max}}{g}$$

W = the natural frequency (8 HZ)

δ = the spring displacement (spine)

g = the gravitational constant

Since $w^2 = \frac{K}{M}$

$$\text{D. R. I.} = \frac{K \delta \text{max}}{Mg} \quad \text{which means}$$

$$\text{D. R. I.} = \frac{\text{Force in the spring}}{\text{Body Weight}}$$

and is similar then to an acceleration. The present Air Force limit is 18; the force in the spring is 18 times body weight.

Two models must be used. If the 8 HZ model is used in the seat to calculate the response of the total seat, man, energy absorber system, the acceleration of the seat would be the result of forces developed by a 8 HZ system. The results would be invalid since only the 10 HZ develops the proper forces and therefore generates the proper seat acceleration. The seat acceleration then can be used as input to the 8 HZ model. The computer printout presents D. R. I. versus time and indicates the force and displacement generated within the spine.

2.2.2 CRASH ACCELERATION PROFILES

Another portion of this program was to determine input acceleration waveforms representative of potentially survivable crashes for troop, fighter and helicopter type aircraft. This information came from reports containing full scale crash test data. In attempting to define the environment from test information it is necessary to realize the exact nature of the measured data as well as the plausibility of approximations that can be made.

Typically the environment in a vehicle is presented as acceleration versus time at particular locations within the vehicle. This automatically indicates that the "crash" acceleration is a function of vehicle type and location within the vehicle.

It is also known that the acceleration level is a function of the airspeed and attitude at impact. There have been several analytical studies that attempt to relate fuselage crush strength, impact angle and velocity. These techniques could have been utilized, but would have possibly caused additional assumptions to be included into the data. For this reason, only measured data was utilized unless detailed analysis showed that waveform approximations could be used.

The accelerations that are recorded at a particular station are assumed to be representative inputs to the energy absorber. This is not rigorously accurate. As the vehicle impacts, the crushing of soil and vehicle dissipate energy and generate a basic acceleration waveform. At the station of interest the energy is received as transmitted by fuselage rigid body motion and structural response. The fuselage may rotate rather than translate, and the fuselage bending modes may be of such a low frequency that the impact is greatly attenuated. Locally, the instrumentated area may be very "soft" structurally, that is, the floor may not have appreciable stiffness. If this is true, then the addition of an elastic system to that station would cause the measured acceleration on the floor to be altered.

The measured acceleration we call input is actually a response that may or may not be influenced by the payload. If the floor is "stiff" structurally, this may appear as high frequency "ringing" in the data and, although a true indication of the input to the man, it does not appreciably influence the response of the low frequency man. All of these factors were recognized in determining representative input waveforms for each aircraft type although little could be done about some of them. Without a more rigorous structural analysis it is impossible to evaluate the effects of the payload on floor acceleration and hence it was assumed that the measured data would be indicative of the floor acceleration desired.

To define the input waveforms representative of potentially survivable crashes for transport, helicopter, and fighter type aircraft, a literature search for reports and documents which might have contained full-scale crash test data was performed. The primary source for pertinent information was a Report Bibliography requested from the Defense Documentation Center which covered publications of full scale crash tests of aircraft for the last twenty-five years. This bibliography listed several publications covering full scale testing which were subsequently obtained through the DDC.

These reports along with documents supplied by the Naval Air Development Center are listed in Tables 1, 2, 3, and 4.

Several acceleration pulses of various shapes were obtained from crash data presented in some of the reports. Since there are several acceleration pulses for each type aircraft, a means of selecting the proper waveform for the separate aircraft types had to be determined. The crash input waveforms must be correctly defined for any energy absorber evaluation or optimization to take place. The form of the input acceleration and energy absorber characteristics determine the response of the seated man, which is used to determine the probability of injury to the man and show whether or not the energy absorber functioned correctly. However, the answer to the question of which waveform should be used for each type of aircraft is not immediately clear due to a lack of a definitive criteria for selecting input waveforms which are indicative of potentially survivable crashes.

The Crash Survival Design Guide states that the input acceleration waveform for the major impact in accidents involving transport and helicopter type aircraft can be represented as a symmetrical triangular pulse for most enginering calculations.

But for this program the actual input conditions were to be simulated which meant a review of available crash data from existing literature and in examining the reports it soon became apparent that not all of the data could be realistically described by triangular pulses. In these cases, the best linear approximation which "filtered out" the high frequency structural response was used. The exact linearizing technique is described in Appendix II. The result of inspecting and reducing the available full scale crash test data was a group of input acceleration profiles for each type of aircraft. The time histories of these waveforms, normalized so that every pulse starts at time, t=o, are shown in the graphs in Appendix III. All of the input pulses came from measured data taken during controlled crashes which were defined as potentially survivable crashes. But which pulse is most representative of a survivable crash for each aircraft type? Is the peak g level, pulse duration, onset rate, decay rate, or velocity change the best parameter to use in choosing the proper input waveform?

The waveforms obtained were of such a variety of shapes that none of the above parameters could be used to clearly determine a good input pulse to use. Therefore, as a starting point it was decided the inputs which caused the most severe environment for the seated man in each type of aircraft would be used to evaluate and define optimum energy absorption systems.

This does not mean that the various inputs were applied directly to the injury model of the man. The inputs would have to be applied through an energy absorber. To apply the various inputs directly to the man would be unrealistic. A 30 "g" peak input of one waveform and a 50 "g" peak of another, when applied to man, will both probably easily exceed man's tolerance limit. To select the worst would be ridiculous since neither would be permitted to exist without some attenuation from an energy absorbing device. Therefore the criteria for selection of the input requires the calculation of system response, man-seat-absorber, not just man alone. The question then becomes how to select an absorber when it is the characteristics of the absorber that are to be eventually selected. At this point in the program it was necessary to select an energy absorber with characteristics that would be indicative of the eventual force-displacement criteria. From the force-displacement curves available, Boeing test Number 3 was selected as representative of the commercially available absorbers. The force-displacement curve has an initial spike, which was suspected to be desirable, and then has a relatively constant force level. It was realized that the selection of an absorber would probably influence the selection of input waveforms. However, to ignore the absorber would be wholly unrealistic. The use of any commercially available waveform or even a theoretical square wave is more desirable than ignoring the absorber.

The technique used to find the harshest input acceleration was simply to put each pulse into the computer program, and using the selected energy absorber for each input, compare the peak D. R. I. output of all the waveforms of a particular aircraft. The input acceleration pulse which produced the highest D. R. I. was the one producing the most severe condition for a seated man and was chosen as the input waveform for that particular type aircraft. These input acceleration profiles are shown in Figures 2, 3, and 4.

2.3 ESTABLISHMENT OF DESIGN CRITERIA FOR ENERGY ABSORPTION DEVICES

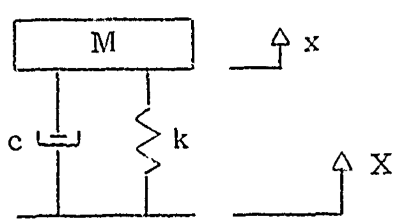
One of the primary purposes of the research conducted on this program was to develop an optimum energy absorber for a helicopter, fighter, and transport type aircraft. The digital computer program previously developed along with the input acceleration profiles and human tolerance levels defined in the preceding paragraphs were used to establish the design criteria for these energy absorbers. However, the questions of what an optimum device should accomplish and how it should achieve the desired results become difficult to answer when examined in detail, but must be resolved to determine the characteristics of an optimum energy absorber.

What an optimum energy absorber should accomplish is quite obviously the protection of the seated man from severe input accelerations, but is there a criteria by which this can be achieved optimally. The answer is yes. The seated man will react to an input acceleration as a dynamic system (i. e. his response will differ from the response of a rigid mass of the same weight). What is happening physiologically to the man can be predicted by the output of a 8 HZ man model, developed by Payne, and is referred to as the Dynamic Response Index (D. R. I.).

The D. R. I. versus time curve then gives a time history of the load carried in the spine since the D. R. I. is indicative of the spinal forces. The criteria used to determine injury probability is only the maximum level or peak the D. R. I. reaches. (i. e. for a peak D R. I. of 18 the probability of injury is five per cent) which means the injury probability is independent of the length of time the D. R. I. is at a given level.

Another point to consider is what happens when the D. R. I. varies as opposed to being constant. When the D. R. I. varies with respect to the time, the physiological model is dissipating energy through the motion of the damper. This can be shown as follows:

D. R. I. Model



$$\text{D.R.I.} = \frac{W^2 \delta}{g} = \frac{k\delta}{Mg}$$

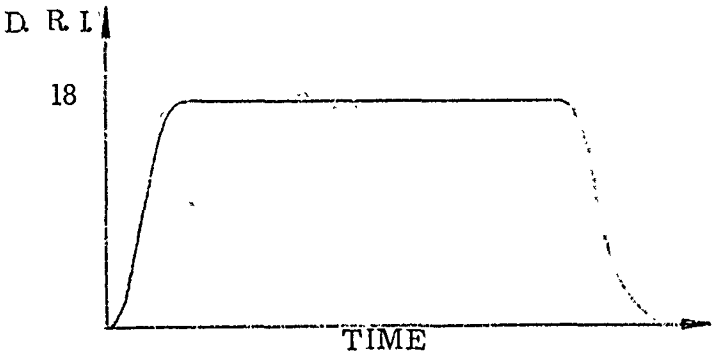
$$\delta = X - x$$

$$\text{D.R.I.} = K_1 \delta = F(\delta) \qquad (1)$$

$$E = \text{Energy dissipated}$$

$$E = \int_{t_1}^{t_2} (c\dot{\delta}) \cdot \dot{\delta}\, dt \qquad (2)$$

From equation (1) it is seen that the D. R. I. varies directly with the displacement δ. When the D. R. I. varies, δ has a first derivative and energy is dissipated by the system, but if the D. R. I. is constant, δ is constant, $\dot{\delta}$ is zero, and no energy is dissipated by the model. If no energy is being dispelled by the man, then the energy present in the seated man-energy absorber system can only be dissipated in the energy absorber. When this condition exists, maximum use of the energy absorber is attained, since the total energy of the system is being dissipated as the energy absorber actuates.



The curve does not have an infinite rise time or decay time. This is because the square wave is not physically realizable. The D. R. I. is the result of the response of an elastic system and hence even if the input were a "step" input, the response would have a finite rise time.

Some energy will be dissipated by the man in reaching and declining from the maximum level, but this cannot be eliminated from a dynamic system and is negligible when compared with the total energy of the system.

How the energy absorption device achieves the desired optimum results depends not only on the energy absorber itself but also on the seated man system that is attached to it. The first results achieved in trying to define an optimum energy absorber indicated the magnitude of solving this problem and raised several questions which were considered pertinent.

1. What weights are to be used?
2. What stroke length is desirable?
3. What force levels are required?
4. What input waveform should be used?
5. What forces can the floor carry?

There are several independent variables involved and combinations of these could be considerable. If 3 seat weights, 3 man weights, 3 acceleration waveforms, and 3 stroke lengths, are used, there are 81 possible conditions for just one energy absorber and for evaluating the nine existing devices there are over 700 combinations.

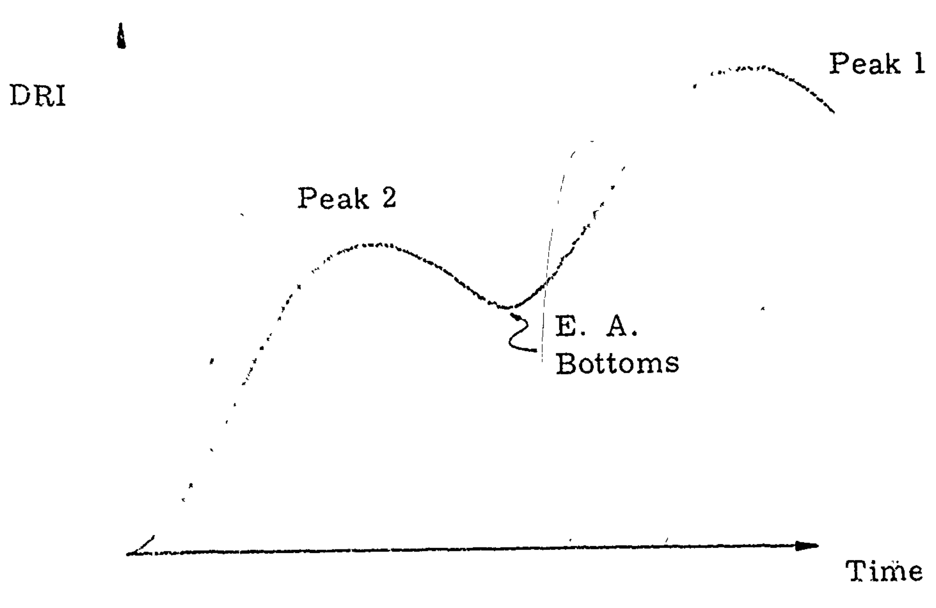
Additional complications occur due to the fact that the total system is nonlinear. By doubling the force in the energy absorber the response is not necessarily doubled. The response may be dictated by a "bottoming" action or by a relaxation phenomena, which occurs when the energy absorber stroke changes direction. Hence if the response of the system is to be interpreted and understood, conditions must be selected that will best represent the real world. The following figures were selected to be most representative.

	Seat Weight	Man Weight
Fighter	250 lbs.	170 lbs.
Helicopter	150 lbs.	170 lbs.
Transport	50 lbs.	170 lbs.

These values together with a stroke length of 10 inches were used for the initial optimization and criteria development. It was known that actual seat weights would vary from the values listed or change in the future and that the weight of the man would vary from 135 lbs. to 205 lbs., which are indicative of the 5th and 95th percentile. Therefore, an effort was made to find the effect of the seat and man weight on the D. R. I. using the computer program. Several cases using one energy absorber (Boeing #3) for all three aircraft types were tried with the seat and man weight being varied.

These results are shown graphically in Figures 5 thru 16.

Figures 5, 6, and 7 are plots of seat weight versus D. R. I. for the three types of aircraft with the different curves representing different body weights. The points connected by the solid lines are data points actually calculated by the computer of an energy absorber with 10 inches of stroke. In examining these curves it appears that the D. R. I. increases quite drastically as seat weight becomes greater. However, in all cases where the D. R. I. increases with seat weight the energy absorber "bottomed out" and exposed the man to high input accelerations. For those cases the D. R. I. time curve was of the general form shown below.



It appears from the shape of this curve that if the stroke length could be extended the D. R. I. would be reduced to the level of Peak 2. If this is the case, then the points connected by the dashed lines would represent the true effect of seat weight which appears to decrease the D. R. I. with added weight. This hypothesis was tried using a stroke length of 25 inches for a few cases and the results given in Figures 8, 9, and 10 show that the D. R. I. does vary inversely with seat weight if the stroke length is long enough.

The graphs in Figures 11, 12, and 13 show the effects of man weight on the D. R. I. for different seat weights. Here again the same problem with the stroke length arises. If the stroke length is 10 inches, the D. R. I. increases with body weight, but the energy absorber "bottoms out." This condition is depicted by the solid graphs, while the dashed lines show what could be expected if the stroke length was longer. Several cases using a stroke length of 25 inches were tried and the results given in Figures 14, 15, and 16 do show that increasing the man weight will decrease the D. R. I.

The consequence of the preceding results is that some restrictions can be placed on some of the system's parameters for purposes of optimization and design criteria definition without loss of generality since the previous data predicts a trend when either seat or man weight is varied and stroke length is long enough to prevent the energy absorber from "bottoming." These qualifications along with knowing what an optimum device should accomplish now ease the problem of optimization and definition of design criteria.

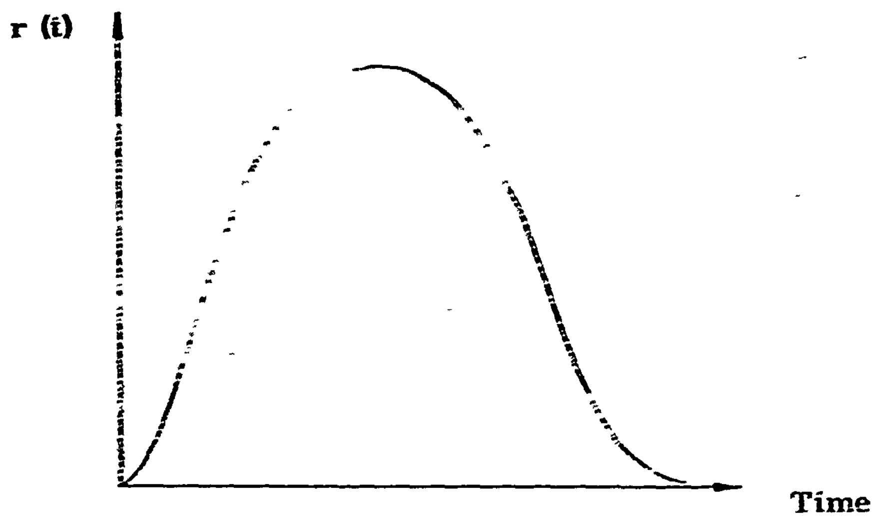
For optimization purposes, the primary effort was to determine whether or not energy absorber criteria could be developed to take advantage of the dynamic response of the subject. Is it possible that the standard square wave energy absorber force-displacement curve is not the optimum? Does the man's response significantly influence the design of the absorber? The digital program developed was generated to test the hypothesis that a force-displacement curve exists that is better than the generally accepted constant force absorber.

The initial approach to the problem was an intuitive one. We realize, first of all, that we are attempting to develop an absorber which will have a minimum stroke while creating a tolerable environment for the man. This is true because if we wished to maintain tolerable accelerations only we could have low force, levels but extremely long stroke length absorbers.

Unfortunately, we realize that by reducing the stroke we are also raising the forces, decreasing the time duration, and generating the force overshoot of the man.

Since a long duration acceleration pulse is undesirable, what will the short duration pulse cause? The limit of a short duration pulse is the impulsive input. The duration of the pulse is so short that the system responds not to the waveform but rather to its area, the velocity change.

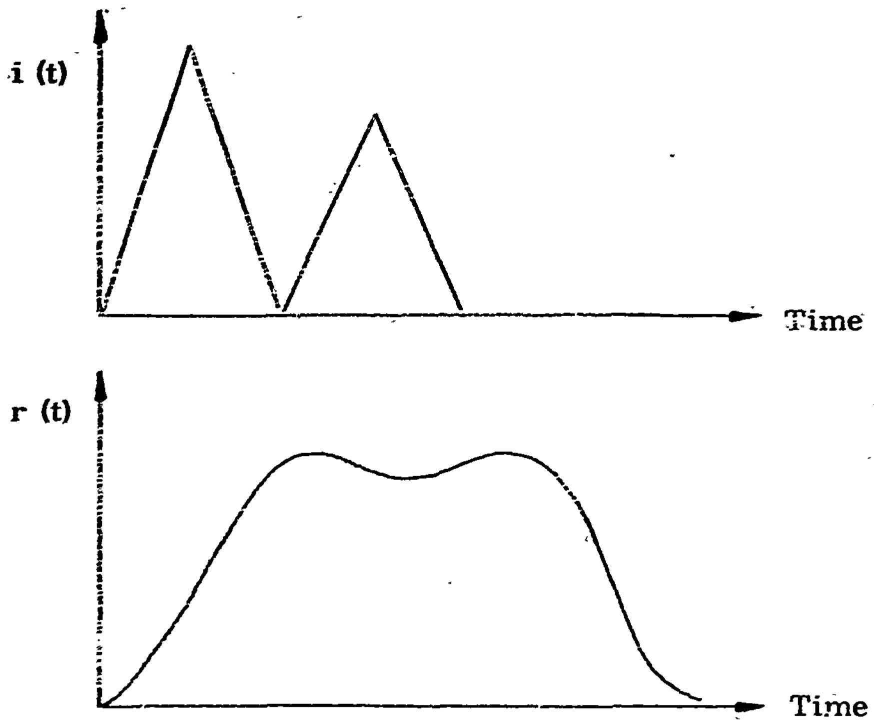
The response is as shown.



This infers that if we impulsively strike the system it will reach a peak value and then decrease to zero. If the peak is a limit, it is desirable to get up to the peak and then hold it.

If this is achieved, we are maintaining a constant acceleration level on the man and hoping that we will not exceed his limit. Since we have a linear system we can use superposition and add other input impulses to create a constant output.

As an example, two inputs and their responses are shown as:



It is apparent that the first pulse can be used to achieve the desired level and that subsequent pulses can be added to maintain that level. Can pulses be added initially to get the response more quickly up to the desired level? If this is possible, we are approaching a square wave output which implies greatest energy absorption for least stroke.

Unfortunately, it is not possible. The initial pulse clearly dictates the peak acceleration level and adding additional pulses can only be attempted when their response and the initial pulse response collectively will not exceed the desired level. This means that there will be a large initial spike, a valley or "notch" and then a series of lower level pulses as required to maintain a constant value. The input accelerates the mass but before the acceleration becomes too great the input is removed and the acceleration "coasts" into the tolerable limit.

The description given is directly applicable to the man and seat. We want an acceleration to the man that causes him to compress up to a given level and then hold it. If this is to be achieved the acceleration of the seat must have the "notched" appearance. Since the seat acceleration is dictated by the forces of the energy absorber and the dynamic response of the man, the energy absorber force-displacement curve must create the force-time "notch" desired. During the initial acceleration, the man will lag the input and not generate large forces. However, the seat will have accelerations nearly equal to the input and hence the forces generated by the energy absorber will approximately equal the seat mass times its acceleration. Therefore, the force-time profile of the energy absorber must have the same "notch."

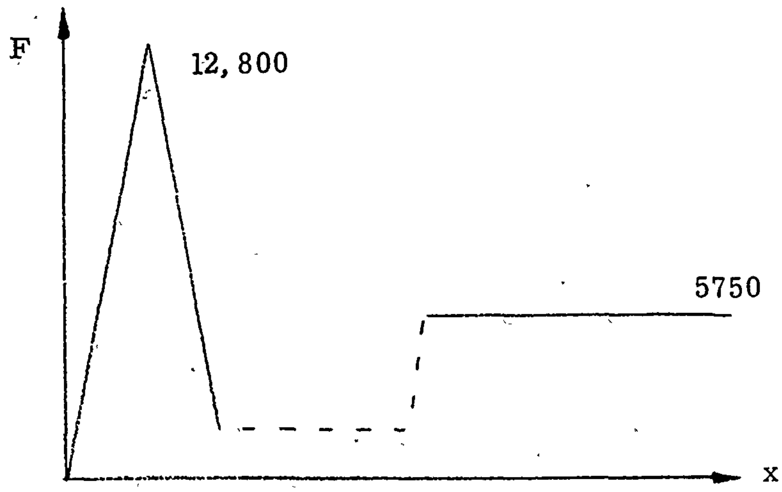
With a "notched" absorber the seat acceleration will generate approximately the proper response of the man.

2.3.1 WAVEFORM DETERMINATION - HELICOPTER

The next step was to quantitatively define a force-displacement profile for an optimum energy absorber. From existing crash criteria the 40 g level was used as a first estimate of the permissible acceleration that could be carried by the energy absorber structure. Assuming a helicopter configuration with a 150 pound seat and a 170 pound man, the peak force due to inertial response of the total dead weight would be 12, 800 pounds. Existing energy absorber data indicated possible loading rates of 60, 000 pounds per inch for the initial crush of the absorber. This infers 0. 213 inches to a peak force of 12, 800 pounds. Assuming a symmetrical pulse the total impulse displacement is then 0. 420 inches.

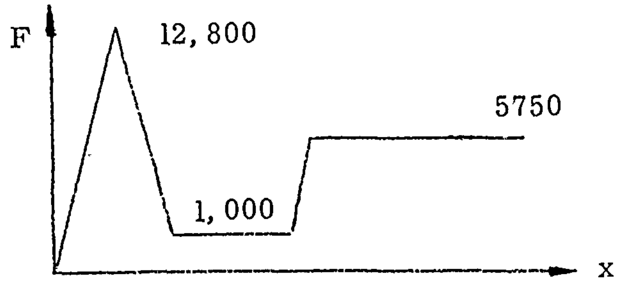
The plateau portion of force-displacement curve is dictated partially by the impulsive response but is also the asymptotic limit for the inertial forces of man and seat. After the transient response has decayed, the D. R. I. limit must be indicative of the accelerations of the seat. A D. R. I. of 18 was used as the limit. Since this is the inertial acceleration of the man and seat, after transient response, the force level of the absorber must be approximately 18 x 320 = 5, 750 pounds.

The profile to be developed must appear as:



From data collected on the Boeing #3 energy absorber it was known that about 75, 000 pound-inches of energy would have to be dissipated to develop a severe but tolerable D. R. I. By adding the energy increments of the force-displacement curve it was determined that at least 12. 5 inches of stroke would be required if another 0. 213 inches were used in getting from the force valley to the plateau magnitude of 5, 750 pounds.

Based upon the estimate discussed, the following waveform was selected as a curve for the helicopter.



It was not known where or how big the "notch" should be and so several variations of "notch" location and impulse peak form were attempted. The best response was achieved when the "notch" immediately followed the impulse and had a stroke of nearly three and one half inches. The plateau value was decreased from the initially assumed 5, 750 pound level and the peak was increased to 14, 200 pounds. The selected waveform and its response are shown in Figure 17 and 18.

The curve in Figure 18 indicates that it is possible to develop an energy absorber force-displacement profile which will generate a nearly constant D. R. I.

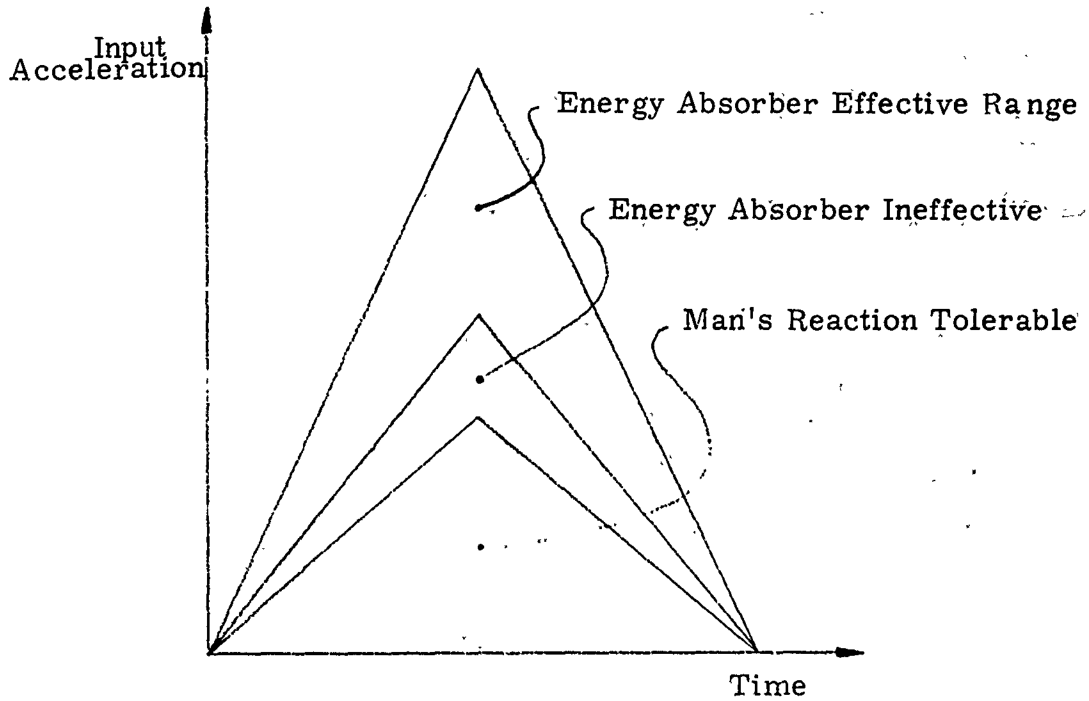
The waveform of Figure 17 is the "optimum" for a 170 pound man, a 150 pound seat, and the helicopter acceleration input shown in Figure 3. It is assumed that the 150 pound seat is the parameter of least variability. The variation of response with man's weight and acceleration input as variables has to be examined.

Consider first the effects of changes in the acceleration input. The acceleration for the helicopter was assumed to be 115 g and .030 seconds duration. This is a severe but potentially survivable environment. Suppose the acceleration input is of less severity.

First, "less severity" must be defined. If we assume that the waveform generated as input to the energy absorber is a function of the elastic characteristics of the helicopter, then it is reasonable to assume that even a less severe crash will generate the same time duration of the response. A system subjected to a transient input will respond by oscillating at its own natural frequency regardless of the magnitude of the input. It is not completely independent of the waveform of the input, but for this investigation it seems more reasonable to assume that "less severity" implies reduced amplitude only and not scaled magnitude and time. Therefore, acceleration inputs were examined having the same time base but with scaled amplitude.

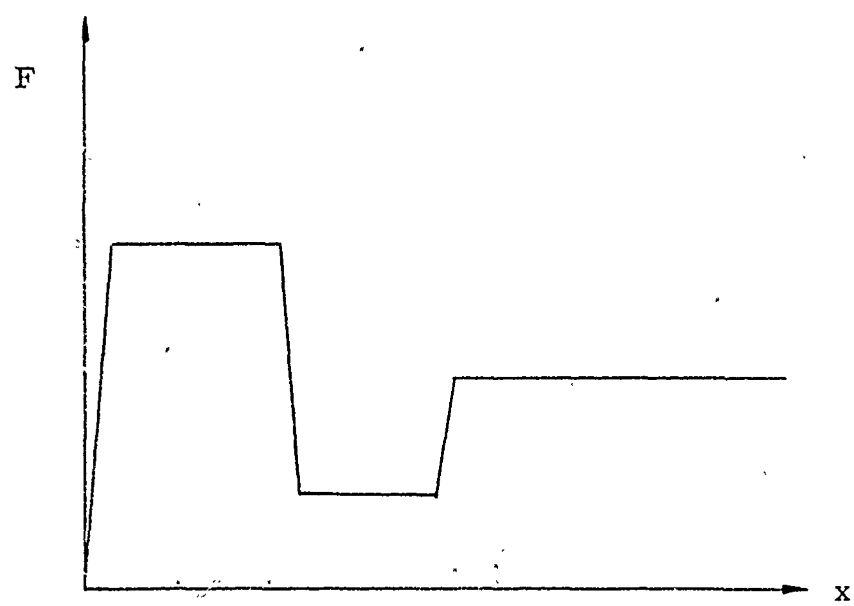
The energy absorber found has an initial force spike of 14, 200 pounds. This requires a certain amount of input acceleration to get the absorber to actuate. As the input acceleration is reduced, a point is reached where the input is insufficient to generate the 14, 200 pounds. The absorber then acts as a high stiffness element and the man overshoots the input. As the input is further reduced, even the "overshoot" of the response will not exceed allowable limits. Hence, if a large force spike exists on the energy absorber it may be extremely efficient in getting the man "up to speed" quickly.

But it may create a band of acceleration inputs where the most critical human response occurs with less severe input.

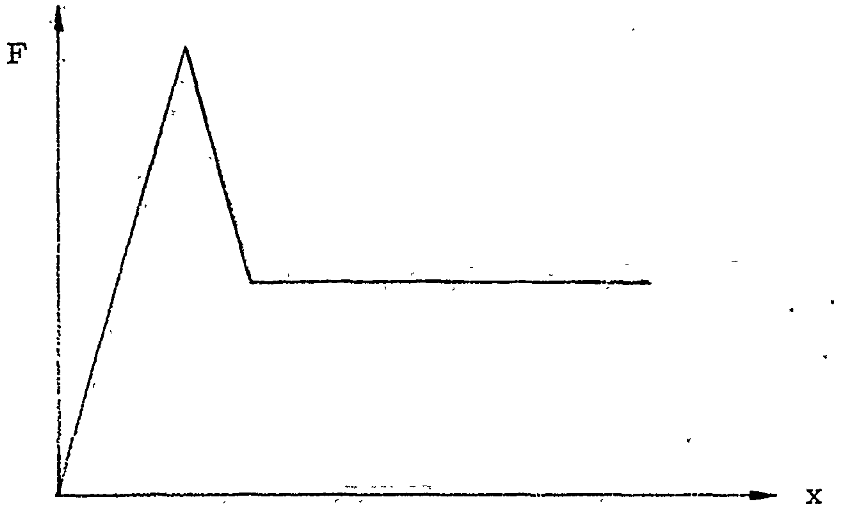


In order to investigate this problem, it was necessary to study several variations of absorber waveform and input acceleration. The first attempt made was to reduce the peak force magnitude to one half of the "optimum" value and examine variations of the "notch." By reducing the peak value, the loss of strain energy would have to be introduced elsewhere and hence the notch variation was examined to determine how and where the lost energy could be reintroduced.

The response curves given in Figure 19 for a reduced energy absorber waveform with a 7, 100 pound peak show that the initial energy loss does cause the response to be distorted and the optimum D. R. I. waveform becomes a curve with a slight dip at 40 milliseconds and peak at 80 milliseconds and a 5 per cent greater response. The form of this response suggests that the man should be subjected to a greater acceleration onset rate in the beginning of the energy absorber stroke and a lower acceleration at the end. In terms of the energy absorber characteristics this means that more energy should be dissipated in the first part of the stroke and less energy in the last part. This means the energy absorber characteristics curve should have the following form.



If the stroke ($\triangle L$) of the "notch" of the energy absorber used for Figure 19 is reduced, the response becomes more representative of the desired D. R. I. time profile. This suggests that two approaches should be looked at. The "notch" waveform approach can be continued to examine the effects of input variations, and a peak and plateau absorber of the following form can also be examined.



The next step was to find what happens when the input is reduced.

The results of a preliminary investigation with a "notched" energy absorber are presented in Figure 20. The curves shown are the responses that are generated by reducing the input waveform. That is, the amplitude of the acceleration input is multiplied by 0.9, 0.8, etc., to observe the response as the input is reduced.

The curves demonstrate that a reduction in input does not always generate a reduction in response. Even though the input is reduced to less than half of the original magnitude, it is possible to have a response that exceeds the levels generated at maximum input acceleration as shown by the curve with 0.4 of the maximum input. The response has a D. R. I. of 21.2 while the maximum input only generated a D. R. I. of 18.2.

Knowing that the reduction in acceleration inputs can have a dangerous effect on a seated man and that a "notched" and un-notched energy absorber should be examined, the ratio inputs were tried with both types of energy absorbers. The results are shown in Figures 21 and 22. The characteristic curve for each energy absorber was determined by finding a waveform for the maximum input that matched the energy absorber curves in Figure 19. That is the response for RA-1.0 in Figure 21 and 22 matches the response for $\triangle L = 3.8$ and 0.8 respectively in Figure 19. This correspondence now provides a means of comparison between the two energy absorber types, "notched" and "un-notched."

Examination of the curves presented in Figures 21 show that the "notched" absorber D. R. I. responses fall below a peak level of 19.2 except the curve for RA=0.4 which has a peak D. R. I. of 19.9.

Since these peak D. R. I. levels can be adjusted down to a level of 18 by slightly lowering the forces of the energy absorber, it appears that the "notched" type absorber can be optimized to protect a 170 pound man from any crash waveform up to the maximum expected providing the stroke length is long enough. The un-notched energy absorber generates the responses shown in Figure 22 which demonstrate that successively lower inputs generate approximately the same peak D. R. I. (19.8) until the input is reduced to 0. 3 of the initial value. Here again the force levels of the absorber could be adjusted to bring the peak D. R. I. level down to 18 for the maximum expected input, but lower inputs would still generate responses which had peak D. R. I. levels equal to 18. This means that the probability of injury will remain the same for the "un-notched" energy absorber even though the input is reduced. The "notched" energy absorber does not exhibit this characteristic because a reduction in the input results in a lower D. R. I. except for cases where the energy absorber's stroke is very small (RA = 0. 4 and 0. 3). However, in these cases, the peak D. R. I. level still remains below the peak generated by the initial input. Therefore, it appears that the "notched" type energy absorber is an optimum for a 170 pound man and 150 pound seat with the selected helicopter input waveform.

The next point to consider is the variation of the man's weight. From all the data collected and that specifically shown in Figures 14 thru 16, it is apparent that an increase in the man's weight will lower the D. R. I. but increase the stroke. Therefore, it can be said that the optimum energy absorber designed for a 170 pound man would also work for a 205 pound (95th percentile) man providing the stroke length is long enough. If the stroke length is critical, it can be shortened provided the force levels of the energy absorber are raised so that the amount of energy dissipated is similar to the previous absorber. The D. R. I. may or may not increase depending on how the force levels are adjusted, but levels can be found which will generate responses that have a D. R. I. of 18 or less for a 205 pound man.

The reaction of a 135 pound (5th percentile) man with an energy absorber designed for a 170 pound man presents the opposite situation from that of the heavier man. The data previously presented (Figures 14 thru 16) very definitely shows an increase in D. R. I. with a decrease in man weight. A case was tried to see if this trend held for the energy absorber designed for a 170 pound man and is shown in Figure 21. The results was a 10 percent increase in D. R. I. for a 135 pound man, therefore, an optimum energy absorber designed for a 170 pound man will not work for a lighter man, but an absorber designed for a 135 pound man will protect heavier subjects provided the stroke length is long enough. Since the response of the 135 pound man generated a peak D. R. I. of 21.3 with the "notched" energy absorber used above, the force levels were slightly reduced to bring the peak D. R. I. down and the responses found to a variation of inputs. The results are shown in Figure 23 and indicate that this absorber would protect the 5th thru 95th percentile man (135 to 205 pound) seated in a 150 pound seat and subjected to the selected helicopter input waveform.

2.3.2. WAVEFORM DETERMINATION - TRANSPORT

A similar approach was taken for the transport configuration with more immediate success. An optimum characteristic curve shown in Figure 24 was found for the baseline 170 pound man and 50 pound seat. The D. R. I. response using this energy absorber is shown in Figure 25 and indicates that the curve is not as flat as the helicopter. However, this could be achieved with additional manipulation of the "notch" location. After the optimum was found two variations were again examined. One was the peak with no notch, and the other a "notched" configuration. The ones found were not capable of generating identical peak D. R. I. The optimum generated a maximum value of 18.4, the peak-plateau a value of 18.7, and the "notched" a value of 16.9. Hence, the two curves are 1.6 percent high and 8.1 percent low.

Both configurations were examined for less severe inputs. Once again, ratios of the input were examined and the results shown in Figures 26 and 27. The "un-notched" waveform (Figure 27) generates extreme values of D. R. I. at all values of input acceleration less than the maximum and greater than one half the input. An acceleration input with less peak acceleration and less velocity change than the selected maximum, generates a greater response.

This phenomenon is not observed for the "notched" waveform. (Figure 26). As the input peak is reduced, the maximum response does increase but never exceeds the maximum allowable of 18.0. This type energy absorber appears to be an optimum for baseline conditions of a 50 pound seat, a 170 pound man and the selected transport input acceleration.

As for the helicopter, the variation in man weight was also considered and the same conclusions reached. The responses of a 135 pound man are shown in Figure 28 for an energy absorber with slightly lower force levels than the one above. The curves illustrate that a 135 pound man can be protected using an energy absorber with a "notched" type characteristic curve. A heavier man of 205 pounds would also be protected by this device if the stroke was long enough.

2.3.3 WAVEFORM DETERMINATION - FIGHTER

The baseline configuration for the fighter, 170 pound man and 250 pound seat was best fitted with the notched absorber configuration of Figure 29, which generated a response shown in Figure 30. A truncated configuration, Figure 31, was also developed to study the effects of less severe inputs. No attempt was made to determine an "un-notched" waveform since the commercially available configurations were approximately comparable to the force-displacement levels required. The optimum curve does maintain a relatively constant D. R. I., but the truncated waveform does require improvement. If the truncated waveform were to be improved, the initial plateau value of 5400 should be raised. This would cause the peak response at lower input levels to more closely approach a D. R. I. of 18. The present curve is nearly 18.0 (18.6) for the extreme inputs, but only reaches a value of 14.2 when the input is three tenths of the maximum. If the plateau were raised, the 18.6 value would be changed only slightly but the response to reduced inputs raised. This would result in a more efficient absorber waveform because more energy is dissipated within the same stroke. The response of a 135 pound man to the initial and reduced waveforms was also tried for the truncated "notched" energy absorber. The results are presented in Figure 32 and the conclusions are the same as those mentioned for the helicopter and transport.

2.4 ANALYSIS OF EXISTING ENERGY ABSORPTION DEVICES

The force-time profiles of existing energy absorbers previously tested by ACED and documented in Report No. NADC-AC-6905 "Dynamic Testing of Energy Attenuating Devices" were reduced to provide force-deflection curves and these were properly formatted for entry into the digital program. The technique used for deriving the force-deflection curves is completely described in Appendix IV. This method consists of plotting the relative acceleration between the test platform and the dead weight and then graphically integrating twice to obtain the deflection-time profile of the energy absorber. This curve and the load cell force-time history are then used to generate the force-deflection curves by finding force and deflection values that occur at the same time.

The calculation of the force-deflection curves required that the load cell record and the acceleration records of the platform and dead weight be complete. For cases where overshoot occurred and the trace disappears, the force-deflection curves could not be obtained. These tests are listed below:

1. ARDE - Test No. 4
2. BOEING - Test No. 2
3. ALL AMERICAN - Test No. 1

The calculation of the force-displacement curve for the ARDE torsional energy absorber for Test No. 1 indicates that the data is invalid beyond approximately 52 milliseconds, since relative velocity changes directions and therefore relative displacement becomes smaller starting at this point. It was indicated in the report that for Test No. 1 not enough energy was imparted to the device to allow it to respond properly. The device deflected only a total of 3/8 of an inch as compared to over 3 inches for Tests 2 and 3.

The remaining nine energy attenuating devices have their force-deflection curves calculated and put in the proper format for use in the computer program. These devices are listed below and their characteristics are shown in Appendix IV.

1. ARDE - Test No. 2
2. ARDE - Test No. 3
3. BOEING - Test No. 1
4. BOEING - Test No. 3
5. MECHANICS RESEARCH INC.
6. ARA INC. - Test No. 1
7. ARA INC. - Test No. 2
8. ARA INC. - Test No. 3
9. ALL AMERICAN - Test No. 2

Upon completion of putting the force deflection curves in the proper format for the computer program each energy absorber was entered into the program and evaluated for each aircraft type with three body weights of 135, 170, and 205 pounds which represent the 5th, 50th and 95th percentile man.

The results of these 81 cases are presented in Appendix V as graphs which show how the D. R. I. varies with man weight providing the stroke lengths are long enough. Also it appears that the devices manufactured by the same company provide similar response and therefore for purposes of comparing with the design criteria only the following devices were considered.

1. ARA INC. #3
2. ARDE #2
3. ALL AMERICAN
4. BOEING #3
5. M. R. I.

These devices along with a square wave that had a peak force of 3960 pounds were evaluated for a 170 pound man, 50 pound seat, and the transport input waveform. To match the design criteria for optimum energy absorbers, the inputs were reduced and the response recorded for a maximum stroke length of 25 inches. The results are shown in Figures 33 thru 38. All the devices tested generated D. R. I. responses in excess of 18 which indicates that none of the energy absorbers would protect the man for the transport conditions. Three of the energy absorbers exhibit the phenomena of producing higher peak D. R. I. 's when the input is lowered.

These are ARDE #2, ALL AMERICAN and BOEING #3. The MRI absorber response curves appear indicative of the impulse response of a single degree of freedom system. This is to be expected since the force level of the MRI device is so high (10,000 pound) that the energy absorber is essentially a rigid link between the point where the input is applied and the seat.

The square wave absorber whose responses are shown in Figure 38 was found by considering the man as a rigid mass. If we say we want the maximum seat acceleration to be 18 g's then the following calculations will determine the force level of the energy absorber.

$$W_t = W_1 + W_2 \qquad \text{Total Weight}$$

$$W_t = 50 + 170 = 220 \text{ lb.}$$

$$F_{ea} = 18 \cdot 220 \qquad \text{Energy Absorber Force}$$

$$F_{ea} = 3960 \text{ lb.}$$

This is the force level that was used for the square wave absorber. The responses show that four of the eight curves overshoot a D R I. level of 18 and the overshoot is due to the man responding as a dynamic system and not as a rigid mass.

A square-wave energy absorber that generated a D. R. I. of 18 or less would have a lower force level than the one used in Figure 38, but the stroke would be longer.

A comparison table of the existing energy absorbers and the optimum absorbers developed which lists peak D. R. I., stroke length, and aircraft type is given in Table V. The absorbers listed under the commercial heading were the devices evaluated on this program while the theoretical heading lists energy absorbers described by the design criteria discussed in the previous section. A direct comparison of individual energy absorbers is somewhat difficult since the D. R. I. man weight and stroke length vary, but some general conclusions can be drawn for each aircraft type. For the fighter with a 170 pound man the ARA INC. #2 energy absorber and the fighter optimum have the same D. R. I. but the ARA INC. device requires two more inches of stroke. The remainder of the commercial absorbers except the M. R. I. all have lower D. R. I. values for the same man weight, but show stroke lengths of 20 inches or greater. The M. R. I. device has a lower stroke (9. 7 inches) and a higher D. R.I. (33. 3) which is expected because it is a much stiffer absorber than the others. The two "notched" energy absorbers, designed to handle reduced inputs, have acceptable D. R. I. values, but very long stroke lengths.

A direct comparison with other devices is not possible since the calculation time is twice as long. The square wave absorber designed for a rigid mass and an 18 g seat acceleration compares unfavorably with the fighter optimum because it results in a much higher injury probability. The probability of injury for the fighter optimum is only 0.06 and for the square wave it is 0.5.

By making similar comparisons with the helicopter optimum and the transport optimum it is seen that these devices are apparently better for their respective aircraft than any of the other commercial devices listed. The optimum energy absorbers maintain a tolerable level for the man and use less stroke than the commercial devices. Again the square wave absorber D. R. I. values show that higher injury probabilities will result when this device is used.

The values in Table V can become deceiving should the conditions under which they were found be forgotten. The optimum energy absorber for each aircraft was determined for one man weight and seat weight for the maximum input. The "notched" absorbers, on the other hand, were designed to handle peak and reduced input accelerations. All of the numerical values in Table V were calculated by the computer program using the maximum accelerations, but several devices listed generate higher D. R. I. values with reduced inputs. Figures 33 thru 38 should be checked for this phenomenon.

If the above conditions are kept in mind when using the table, comparisons of the different energy absorbers can be made.

2.5 DISCUSSION

It has been shown that for a given set of conditions, man weight, seat weight and input acceleration waveform; an optimum force-displacement curve can be found. As long as the input is of short duration, less than a tenth of a second, the dynamic response of the man creates a force overshoot and this can be compensated for by having a "notched" absorber. This type device differs quite drastically from the traditional square wave force-displacement absorber. The square wave device will dissipate the most energy for a given stroke length, but will generate an acceleration input to the seated man which will result in a high probability of injury. Because the man responds as a lightly damped dynamic system, a square wave absorber causes higher seat accelerations than anticipated. This also subjects the man to greater accelerations which generates higher forces in the spine. This means a greater probability of injury. The design criteria developed in the previous section takes the man's response into account; and, for an energy absorber that is a passive, elastic element, the optimum for a given set of conditions is a "notched" force-displacement absorber.

Unfortunately, it is usually not possible to design for a given set of fixed parameters and a range of values must be considered. The absorber must act in conditions of less severe inputs. If the absorber has a high peak value initially it is possible that an injurious input could be less than the actuation level of the absorber and hence the absorber would act as a stiff elastic element rather than a energy dissipating device. This can be overcome by truncating the initial peak value and compromising on the efficiency of the absorbers.

The truncated and notched absorber will work for all acceleration input levels provided that the forces levels of the absorber are low enough. The levels are not necessarily dictated by the maximum input but by some lesser input that creates a maximum response.

If it is desired to develop the passive, plastic absorber there are three methods of approach that can be followed.

1) Design for the ultimate response. This is the approach that was taken in the previous section. An absorber curve is found that will not create a response greater than a selected D. R. I. value, regardless of the severity of the input.

This approach results in long stroke lengths and an absorber that is the result of compromising various segments of the curve in order to insure that three-tenths or seven-tenths of the maximum input doesn't overshoot the allowable.

2) Additional passive elements can be .cluded into the energy absorber. Just as a peak-valley-plateau was found for a maximum input, a peak-valley-plateau can be found for each level of the input. Is it then possible to develop an absorber with not only elastic but viscous elements that can create all of the optimum force-displacement curves? If the worst condition exists at a less severe input, then it is possible that a viscous element might improve the system. At high levels of input with relatively large velocity changes the damper would generate large forces which when added to the elastic forces would create the peak values required. At lesser input levels the damper would not contribute significantly and hence the elastic force could be set at a magnitude that would not create an injurious overshoot of the man.

Additional emphasis should be placed upon finding the optimum for many levels of input. It was originally anticipated that the peak magnitude of the absorber would have to be reduced mainly to insure that reduced acceleration inputs could permit some stroking of the absorber. However, in the analysis it was seen that the dynamics of the system can generate more severe responses with less severe inputs.

It is not necessary that the absorber fail to stroke to get an increased response. The dynamics of the system alone can generate greater response for lesser inputs. This makes the total problem more complex in that it is difficult to say what the worst environment really is.

3) A statistical approach can be taken. The D. R. I. concept has associated with it a statistical measure of injury. Similarly the man's weight and the input acceleration have statistical distributions. Is it possible that a cumulative injury criteria can be established as a criteria for energy absorber design? As an example consider the truncated and notch helicopter waveform for a 170 pound man. The response at maximum input is a D. R. I. of 19. This has a probability of injury of greater than five percent. As the input is reduced the response eventually overshoots and develops a D. R. I. of nearly 20 for an input equal to four-tenths of the maximum. From other criteria such as the Army's Crash Survival Design Guide, there is a probability curve associated with magnitude of the input. In other words, there is a finite probability that the crash will indeed be near four-tenths of the assumed maximum. Is the cumulative probability of injury, a D. R. I. of 20, and the occurrence of an input of four-tenths of the assumed maximum, sufficient to compromise the absorber waveform.

This approach ultimately leads to a cumulative injury criteria as a basis for energy absorber criteria. The probability of being at or near the "maximum" input acceleration is a value. At that level the D. R. I. will be another value with an associated probability. Assuming these are statistically independent, there is then a cumulative probability of injury at that particular input acceleration band width which is the product of the two. If this is duplicated for all band widths and the numbers summed, an injury potential of the absorber is developed. In this manner it is possible to quantitatively tradeoff probability of injury with absorber design characteristics. If it can be shown that the four-tenths overshoot does not significantly influence the total injury potential, then the absorber design can be more efficient. If the occurrence of an input is remote, then the probability of injury at that input can be high and the absorber can be designed to take advantage of it.

4) There is another means of achieving the desired force-displacement for various combinations of conditions. This is of course the active feedback system. Just as it was mentioned in connection with passive elements, active feedback control elements could also be designed to adjust the response as functions of relative velocity or force generated. Active systems are usually equated with complex and expensive systems. However, it is a means that could and should be pursued.

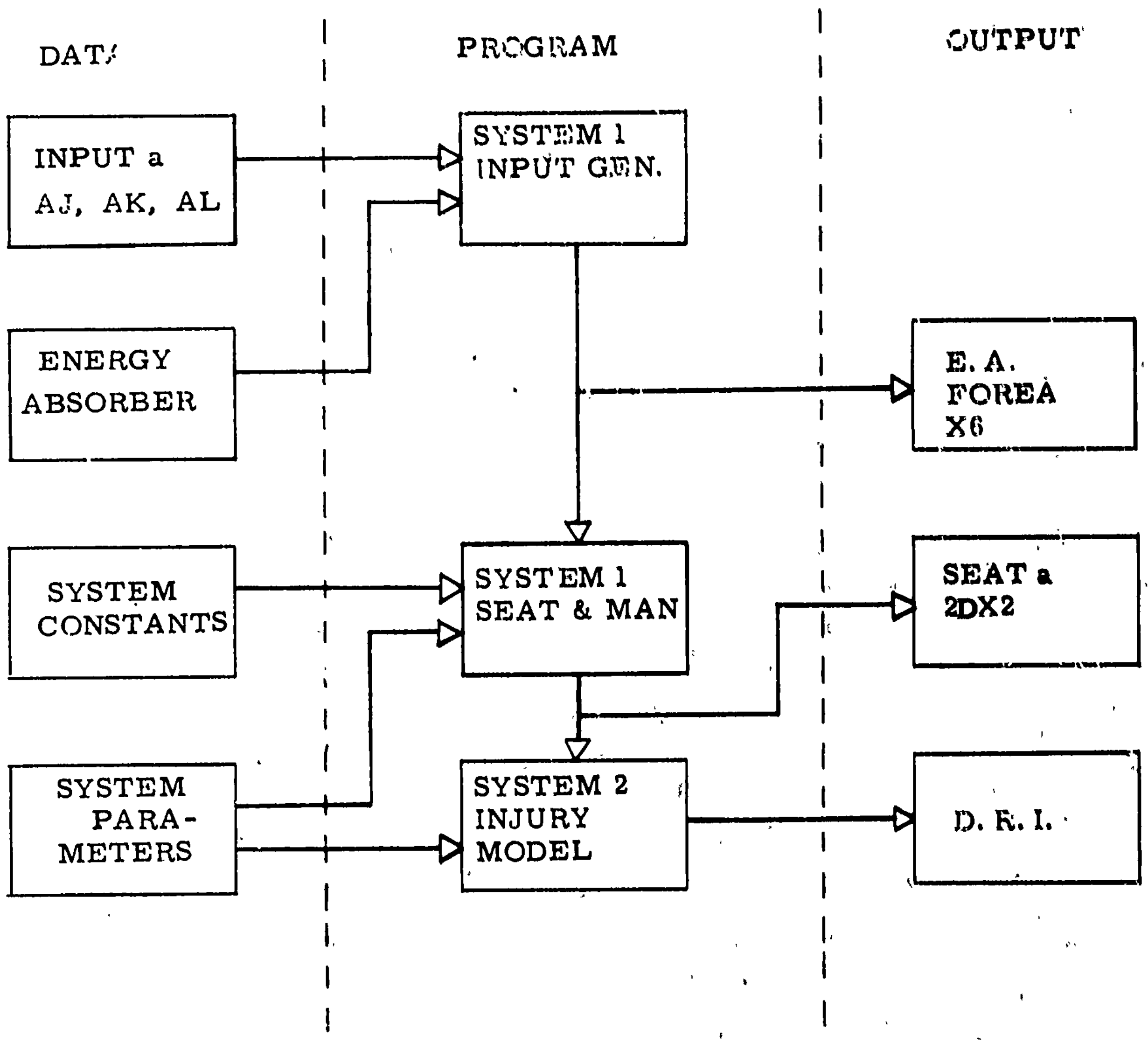


FIGURE 1 COMPUTER PROGRAM FLOW DIAGRAM

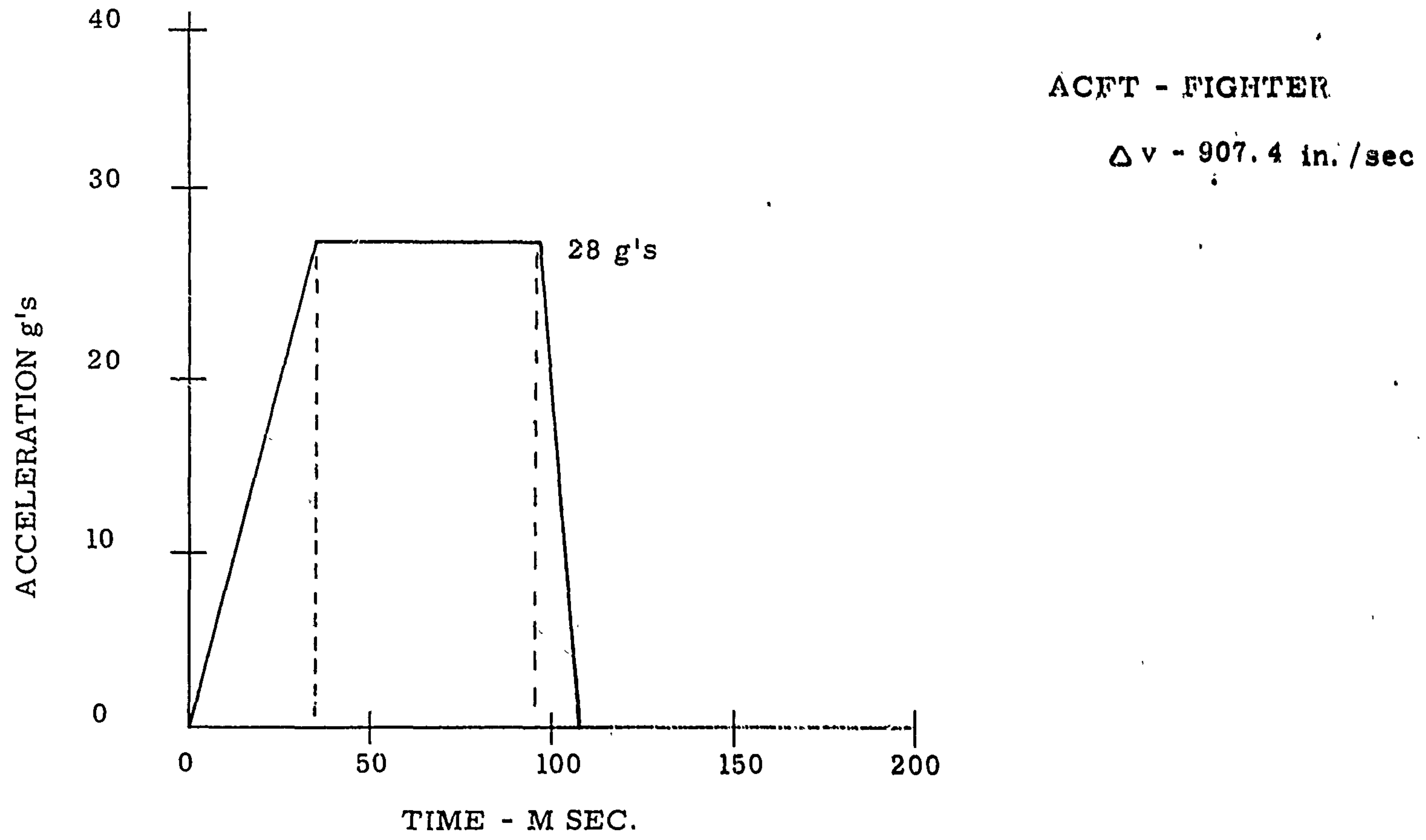


FIGURE 2 FIGHTER INPUT ACCELERATION

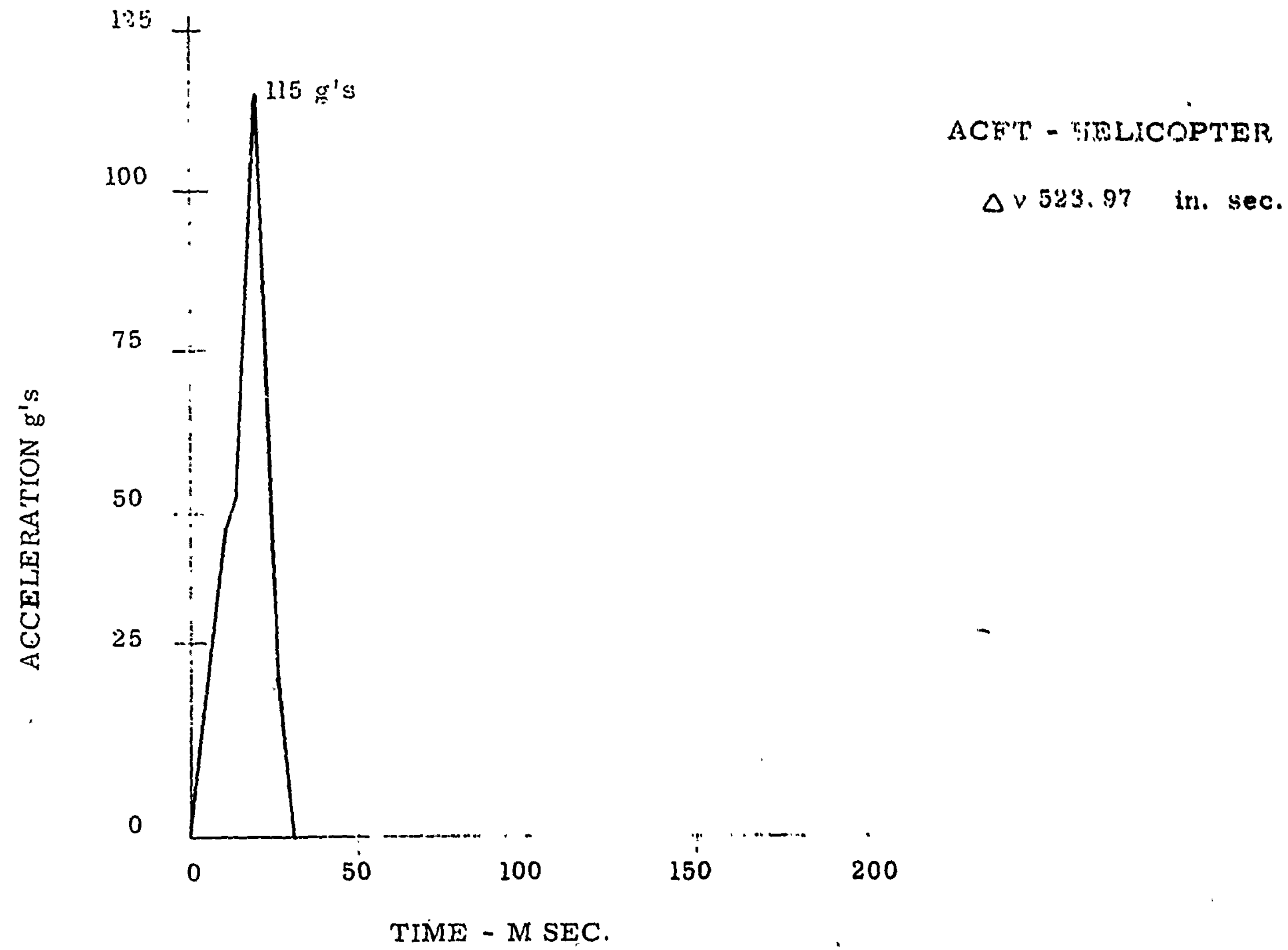


FIGURE 3 HELICOPTER INPUT ACCELERATION

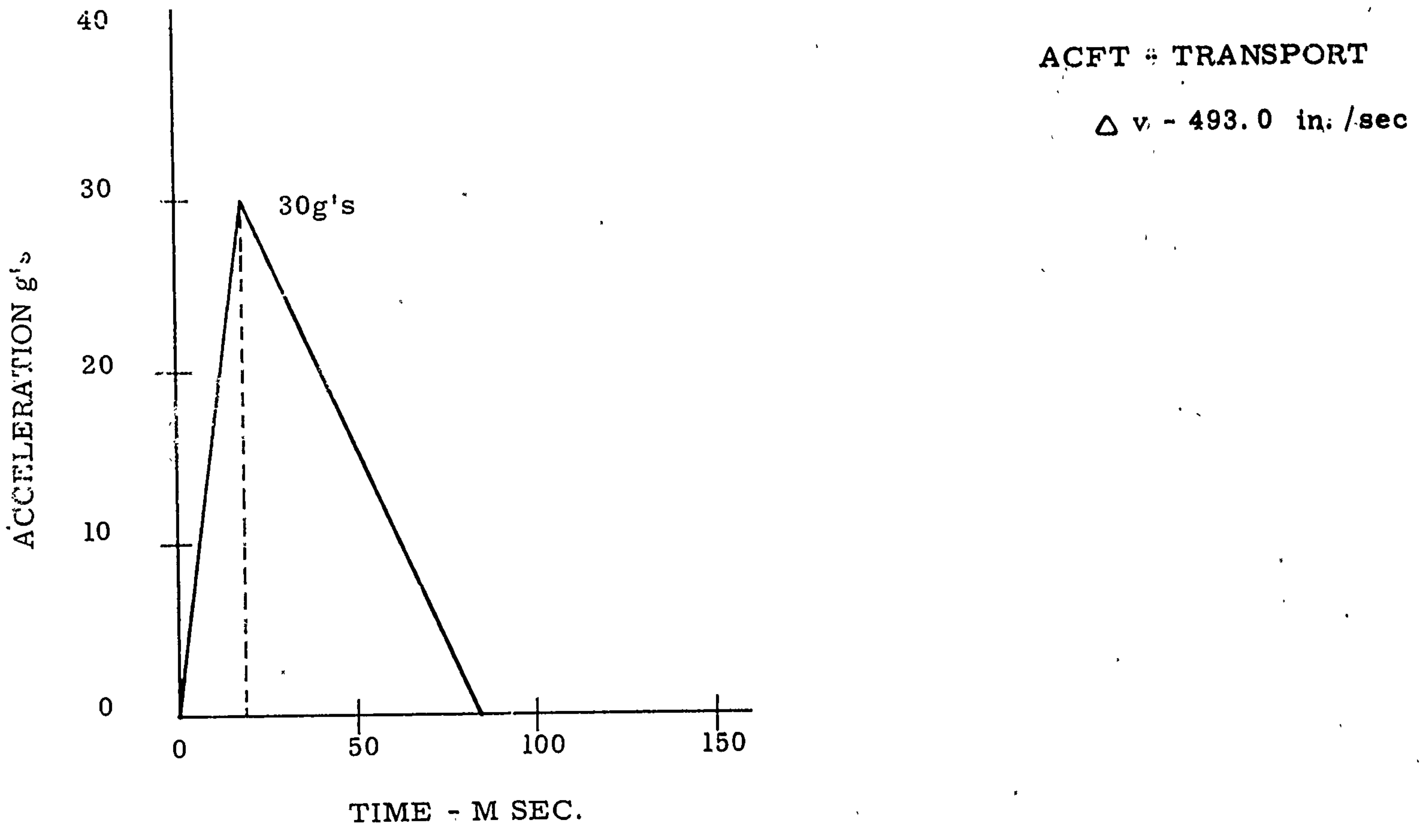


FIGURE 4 TRANSPORT INPUT ACCELERATION

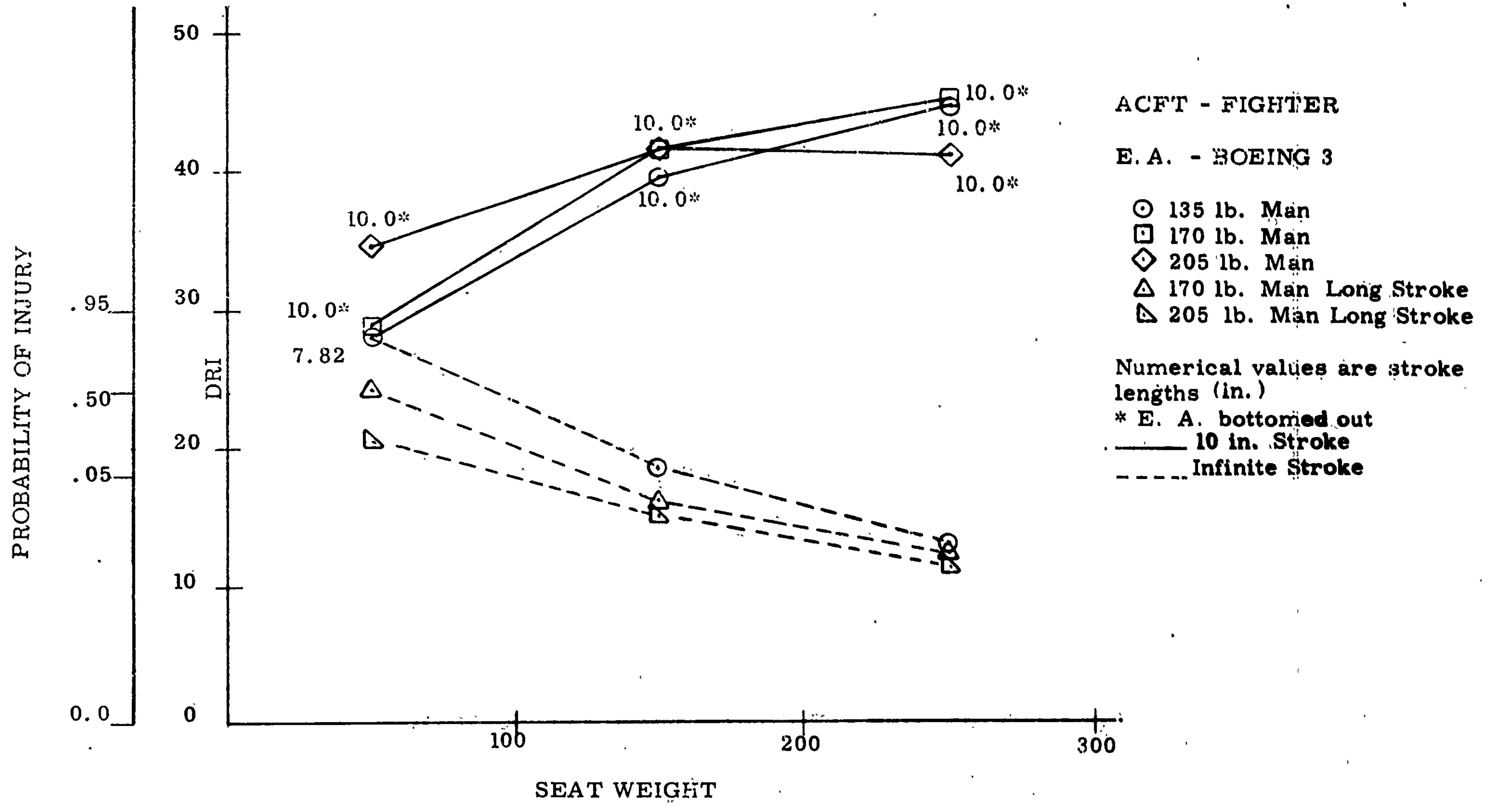


FIGURE 5 PRELIMINARY FIGHTER SEAT WEIGHT CURVES

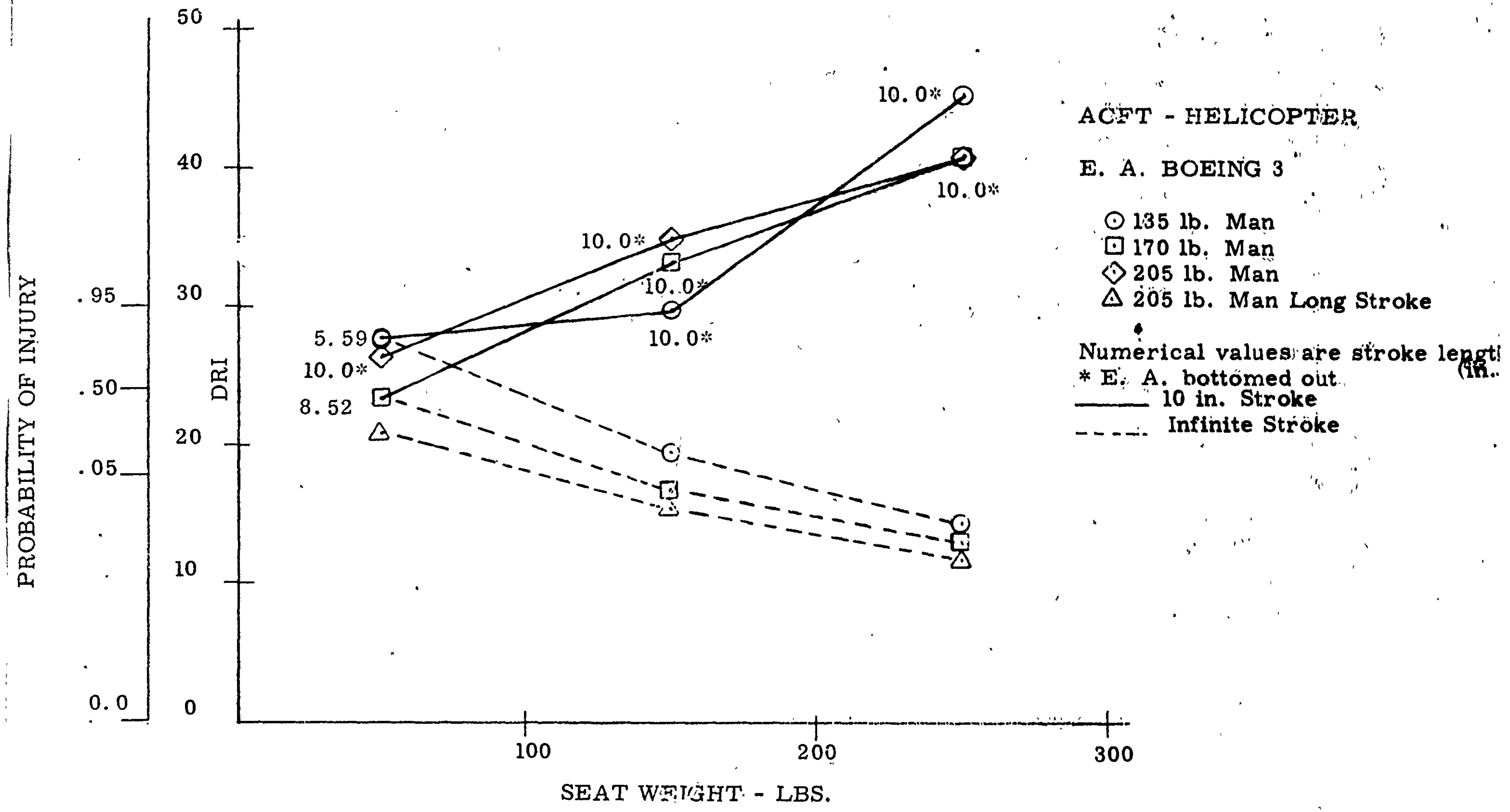


FIGURE 6 PRELIMINARY HELICOPTER SEAT WEIGHT CURVES

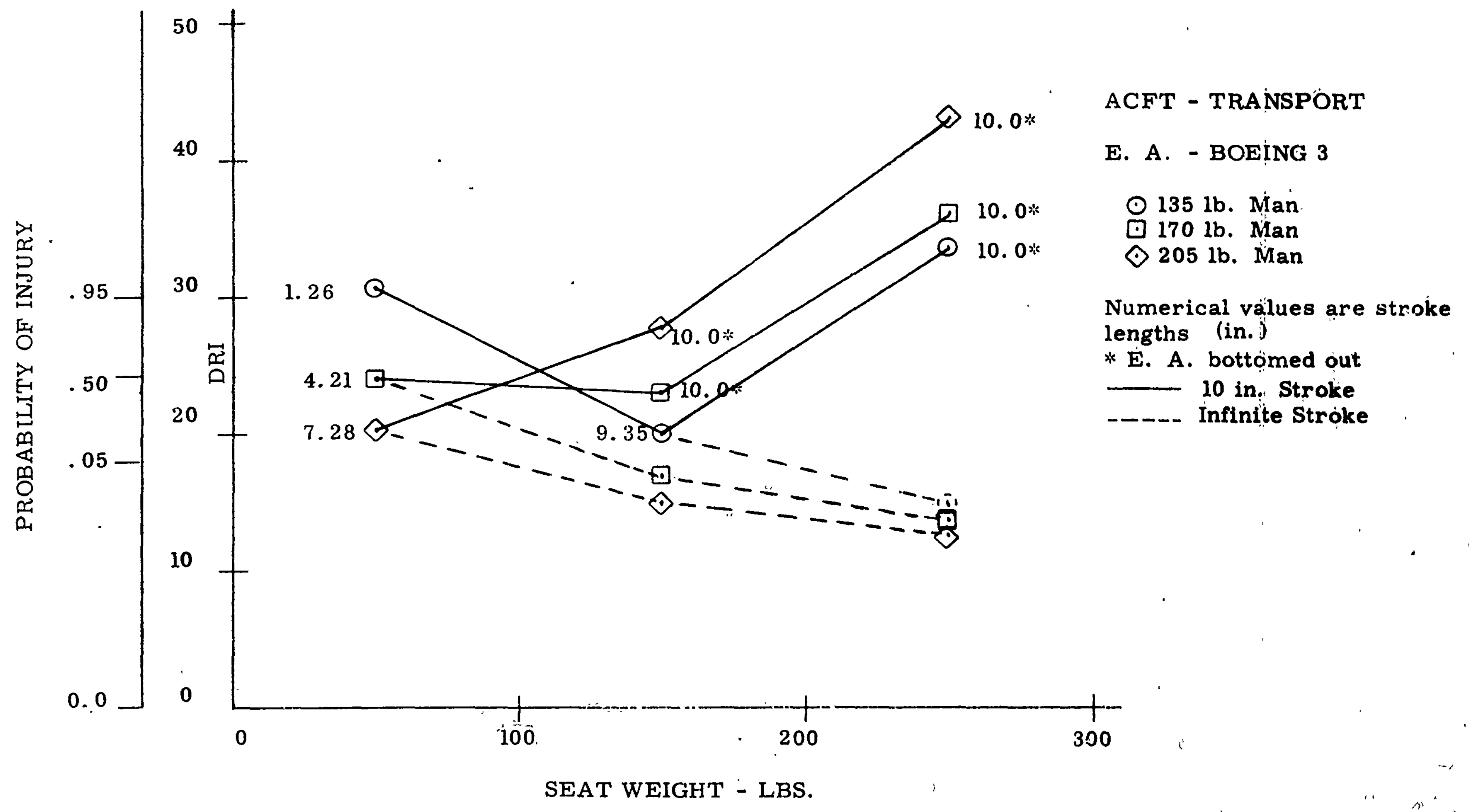


FIGURE 7 PRELIMINARY TRANSPORT SEAT WEIGHT CURVES

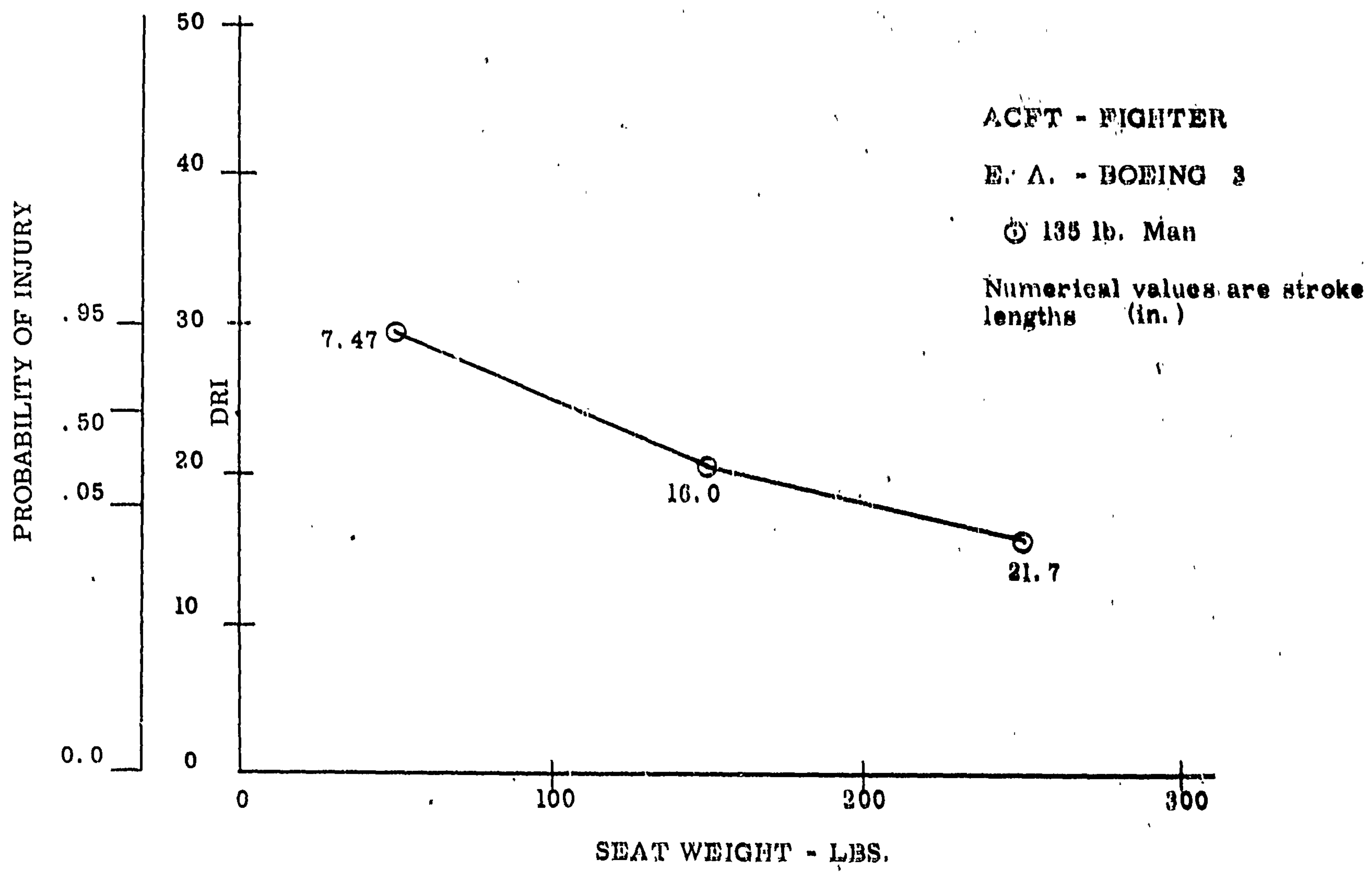


FIGURE 8 FIGHTER SEAT WEIGHT CURVE

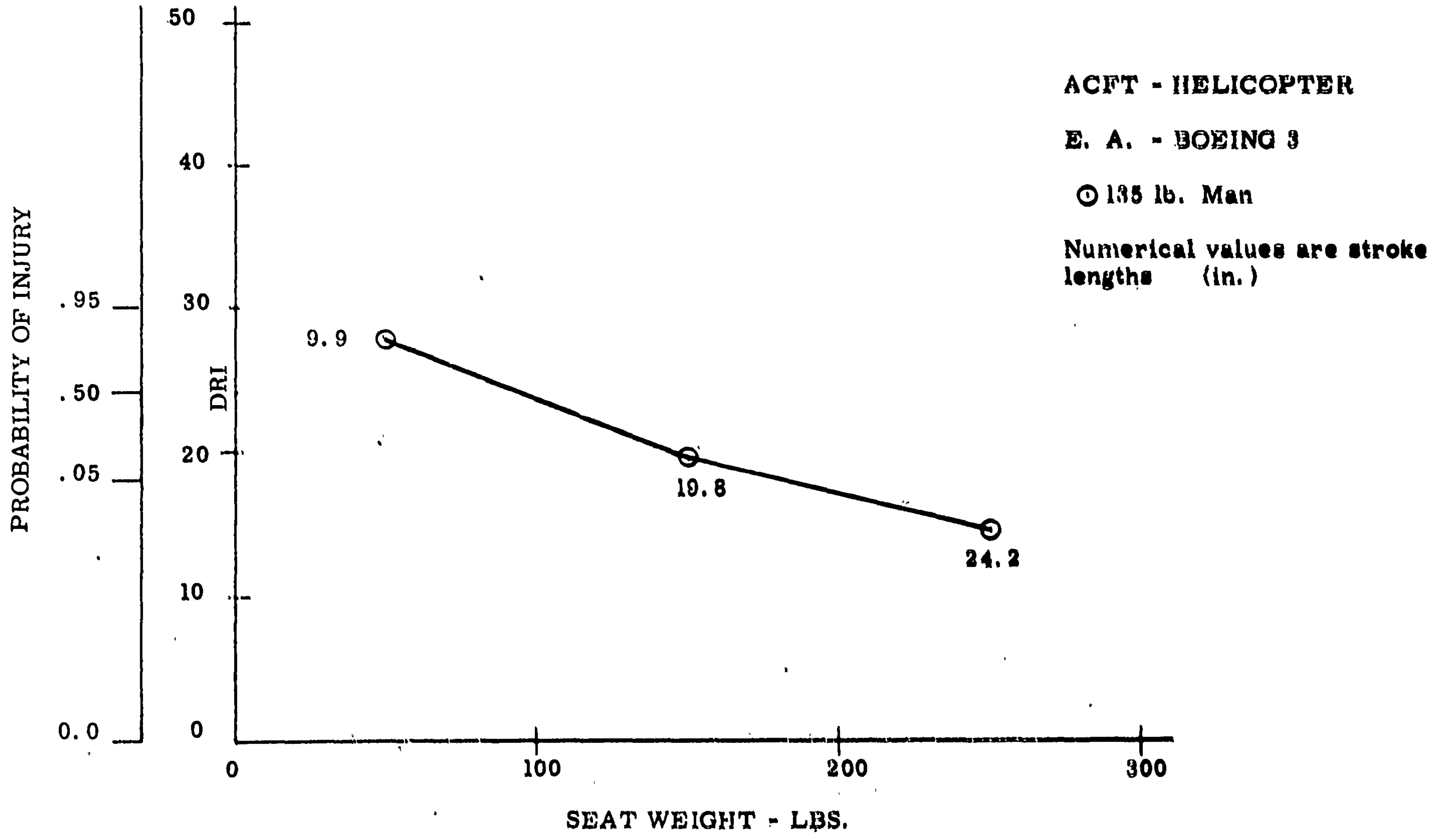


FIGURE 9 HELICOPTER SEAT WEIGHT CURVE

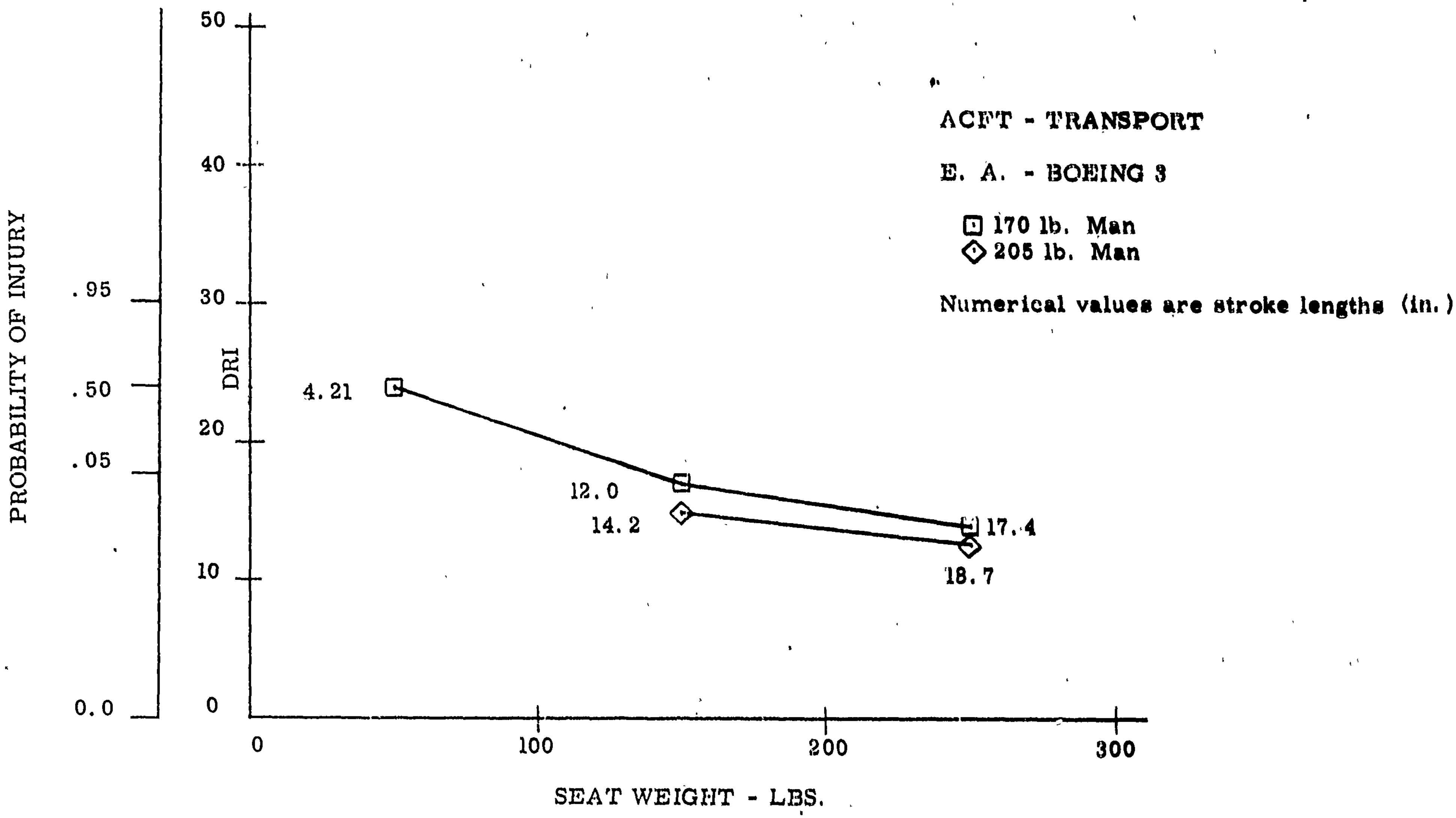


FIGURE 10 TRANSPORT SEAT WEIGHT CURVES

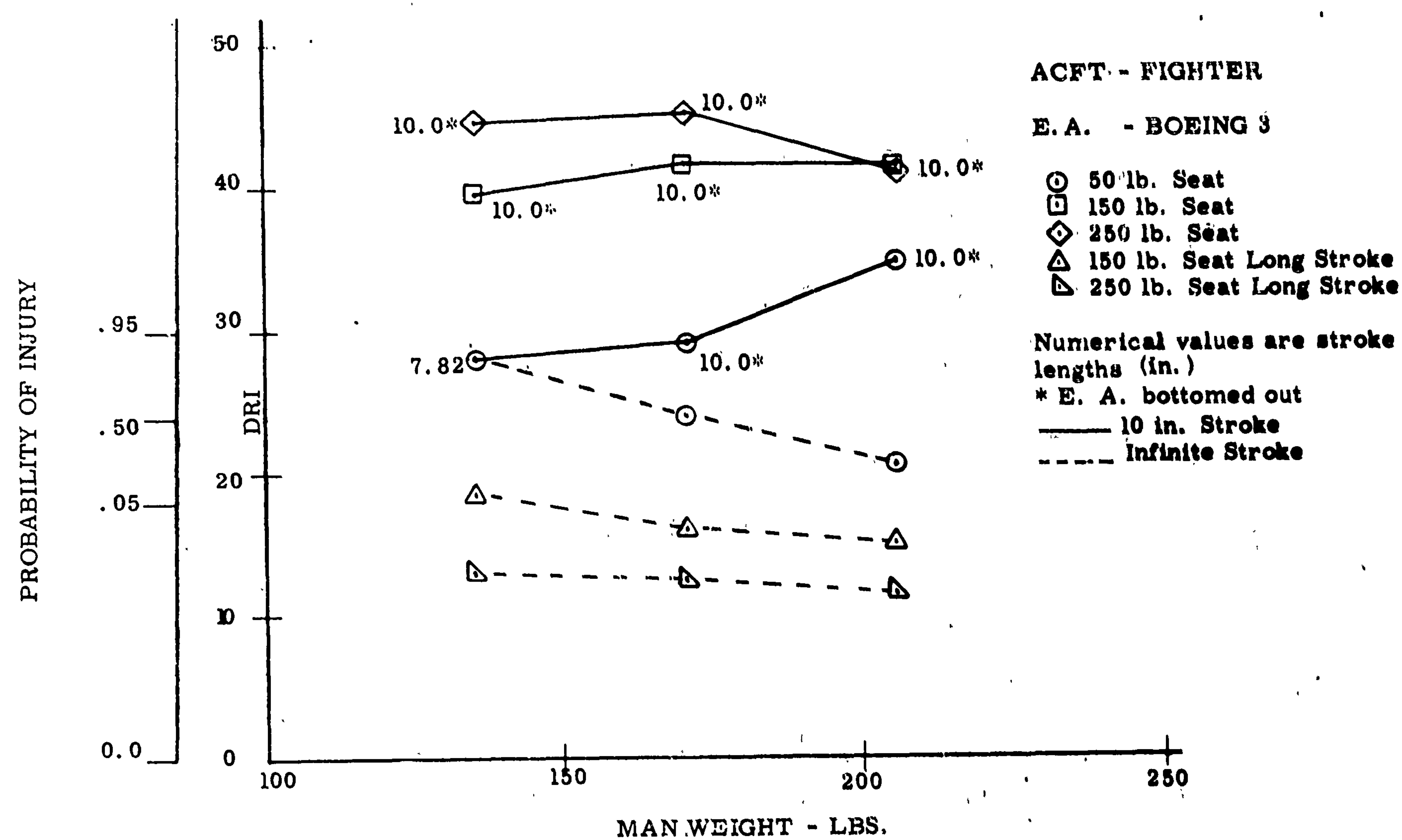


FIGURE 11 PRELIMINARY FIGHTER MAN WEIGHT CURVES

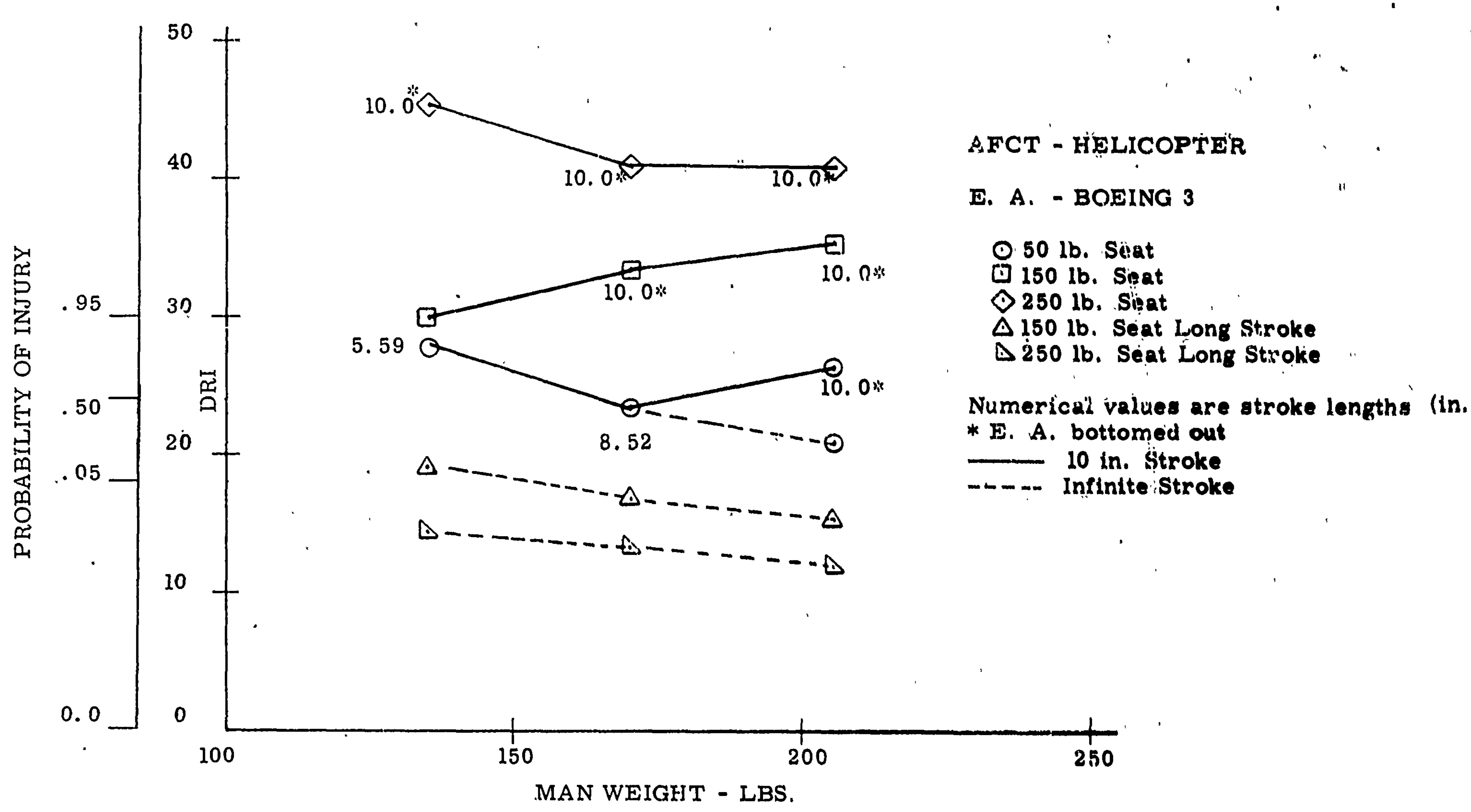


FIGURE 12 PRELIMINARY HELICOPTER MAN WEIGHT CURVES

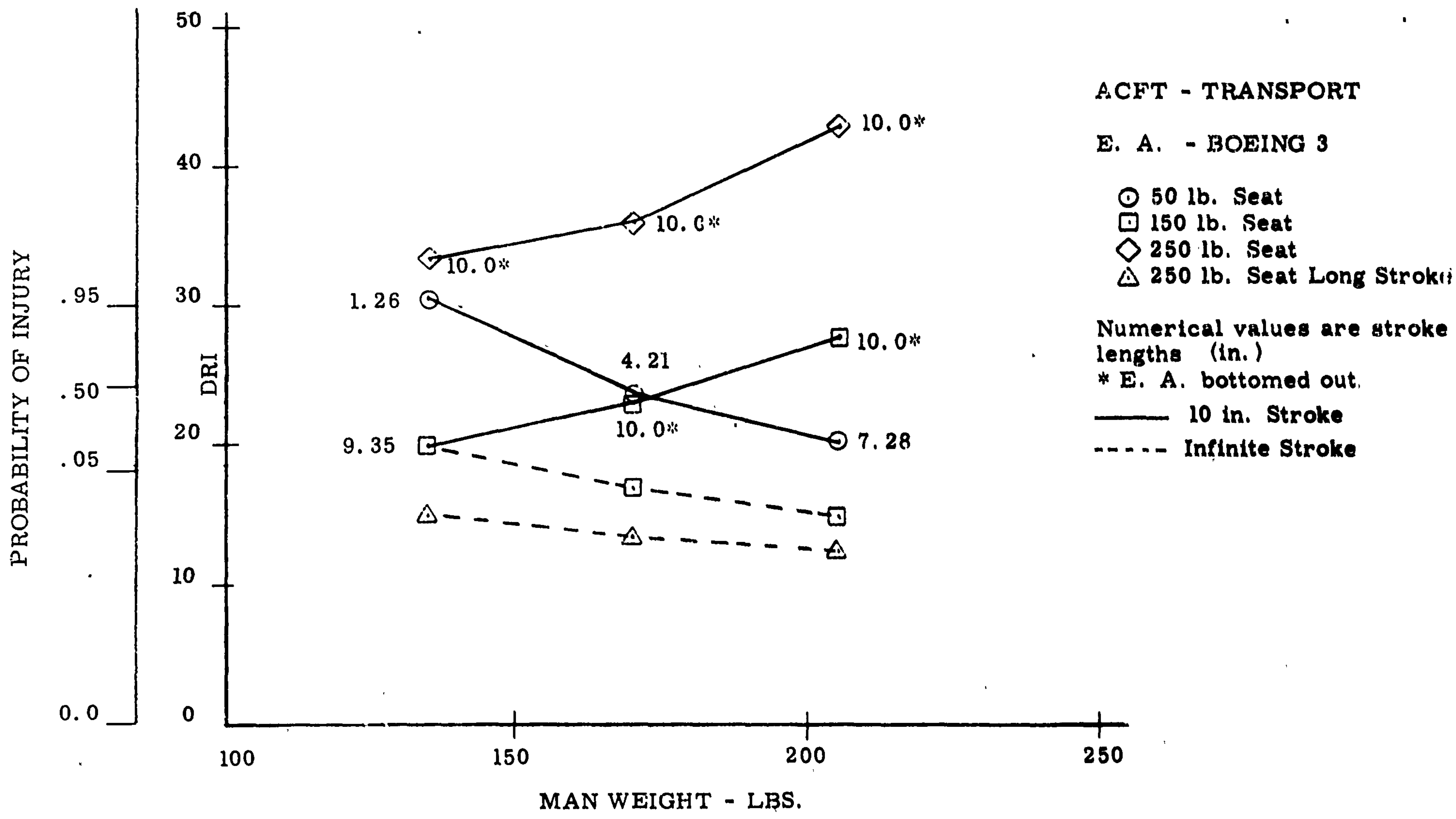


FIGURE 13 PRELIMINARY TRANSPORT MAN WEIGHT CURVES

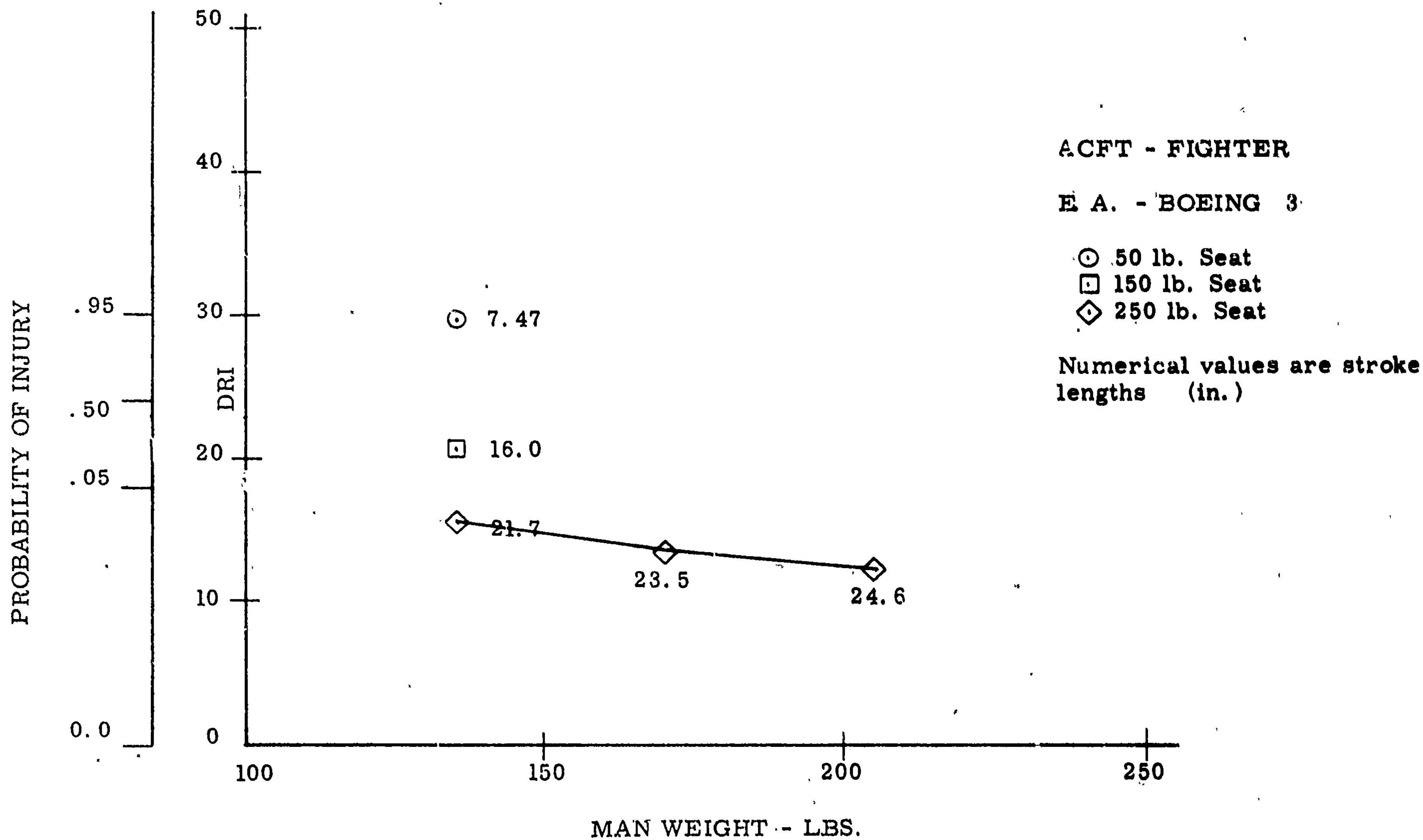


FIGURE 14 FIGHTER MAN WEIGHT CURVE

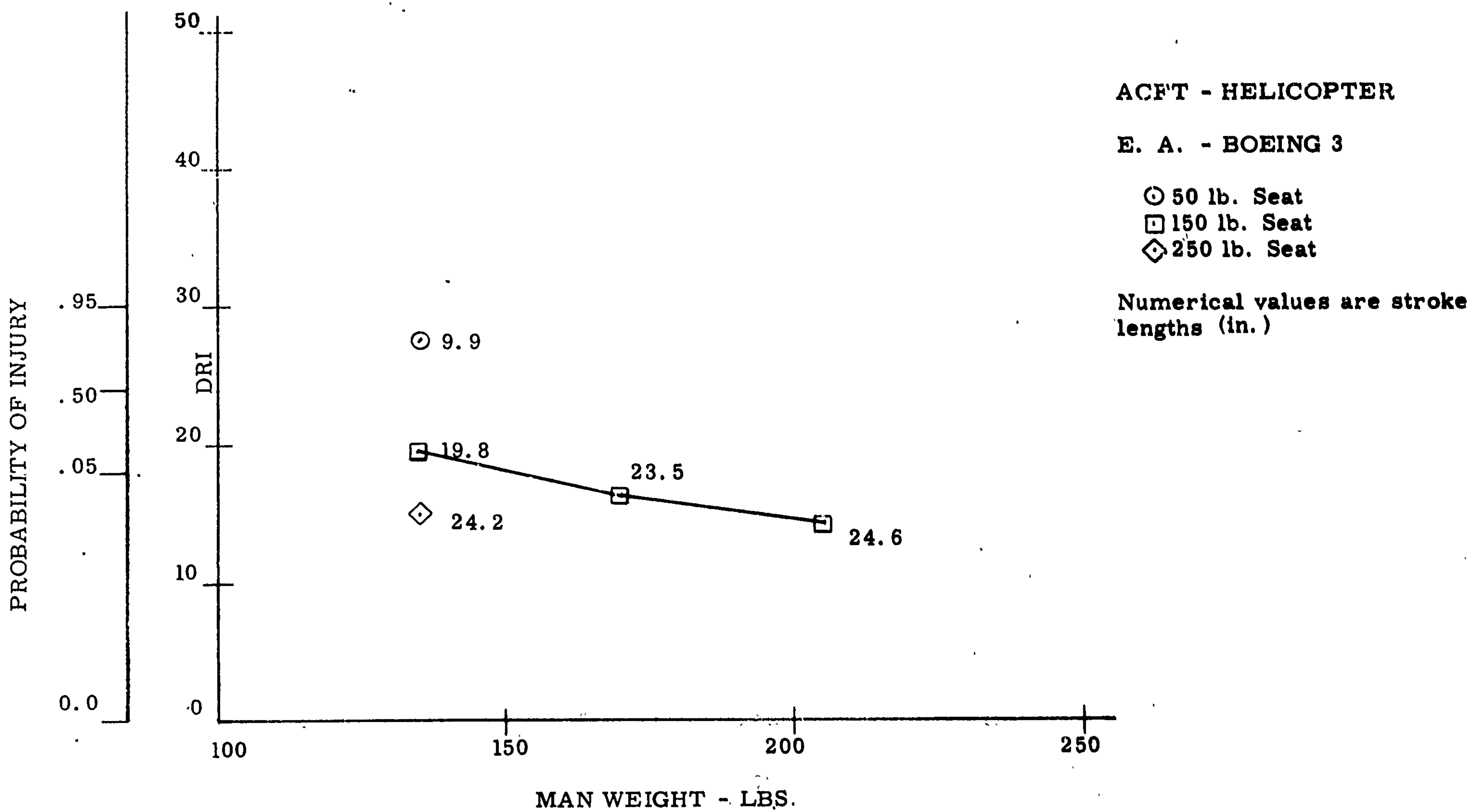


FIGURE 15 HELICOPTER MAN WEIGHT CURVE

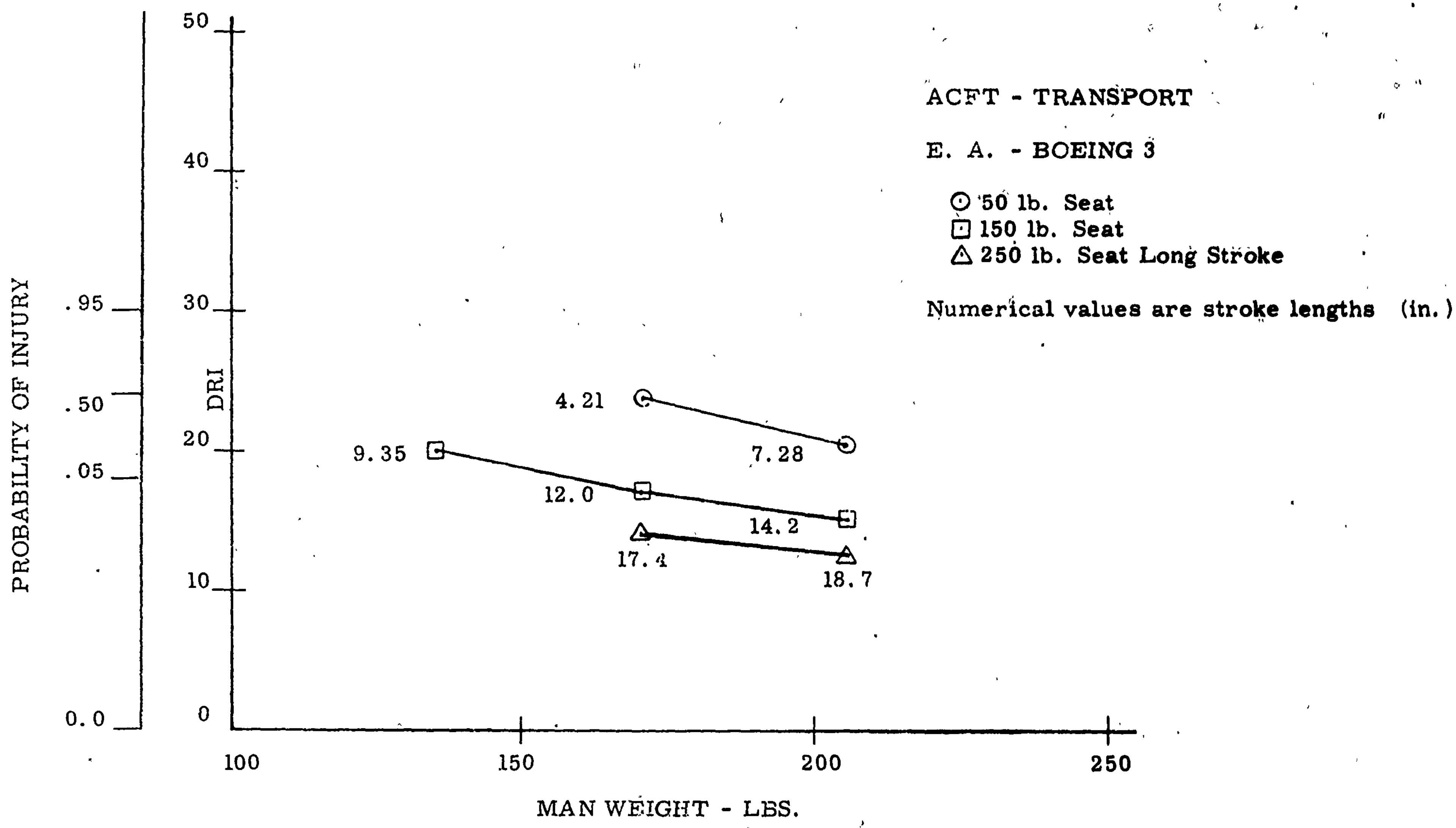


FIGURE 16 TRANSPORT MAN WEIGHT CURVES

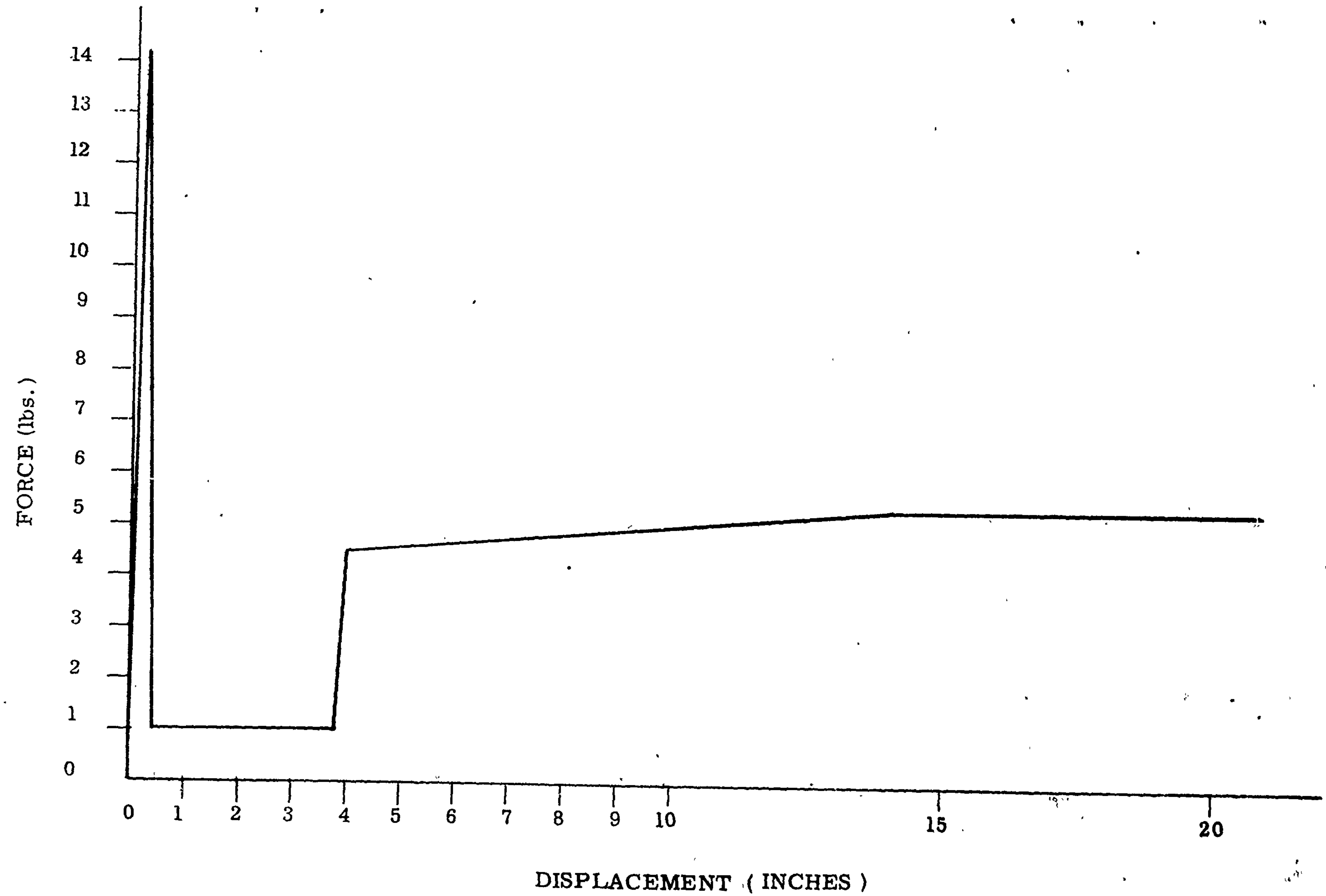


FIGURE 17 - PRELIMINARY OPTIMUM ENERGY ABSORBER - HELICOPTER

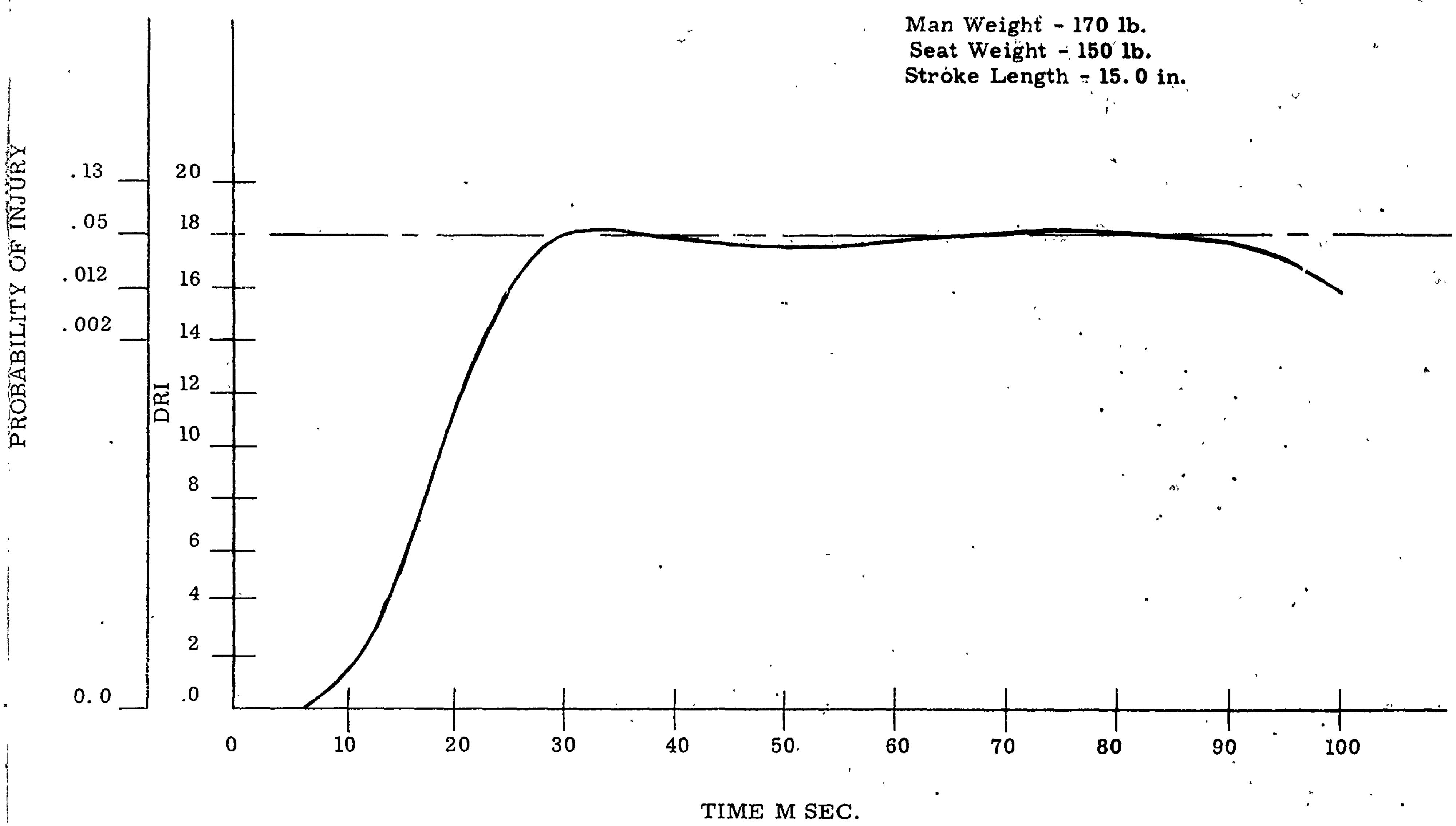


FIGURE 18 - PRELIMINARY ENERGY ABSORBER RESPONSE - HELICOPTER

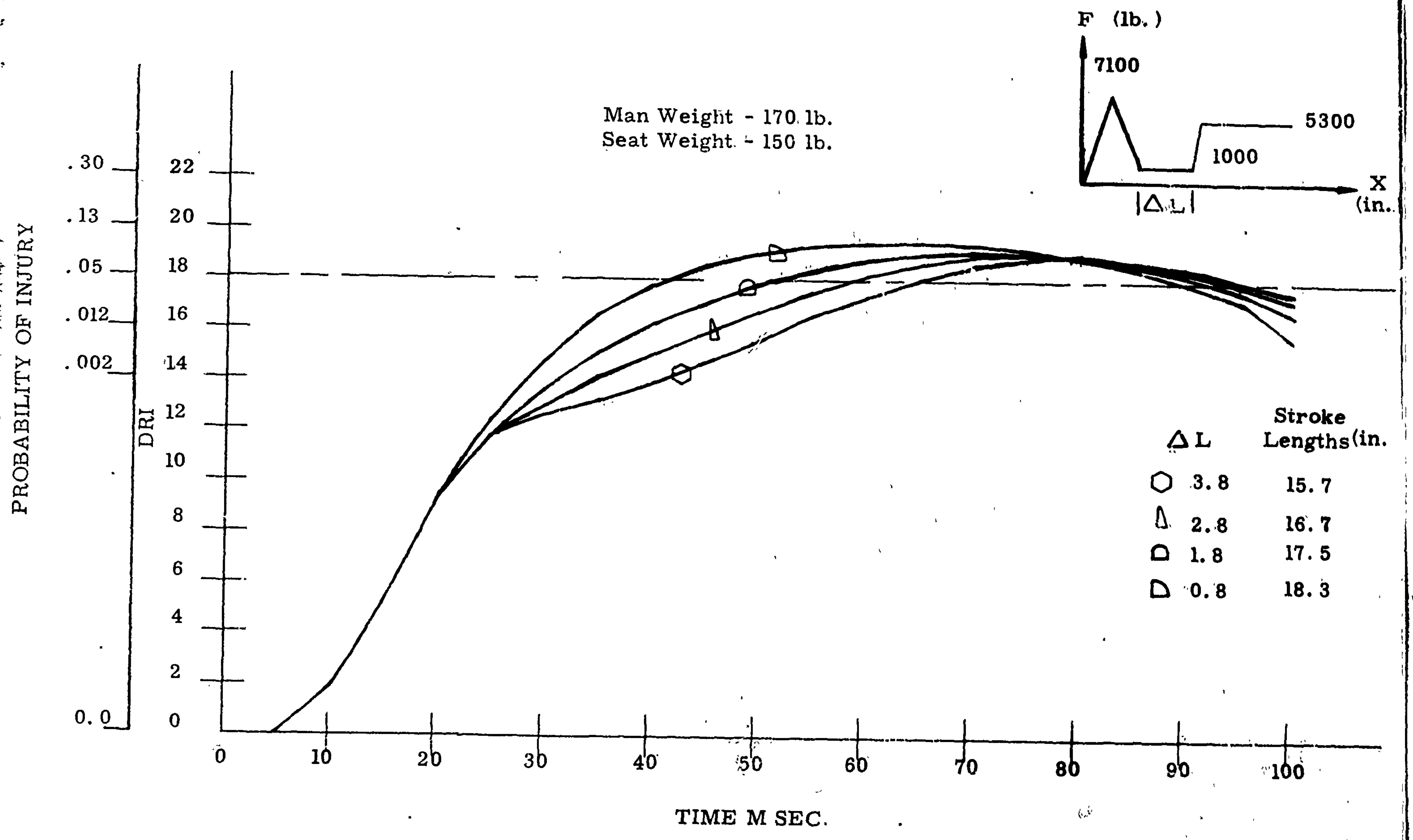


FIGURE 19 - REDUCED ENERGY ABSORBER WAVEFORM RESPONSES - HELICOPTER

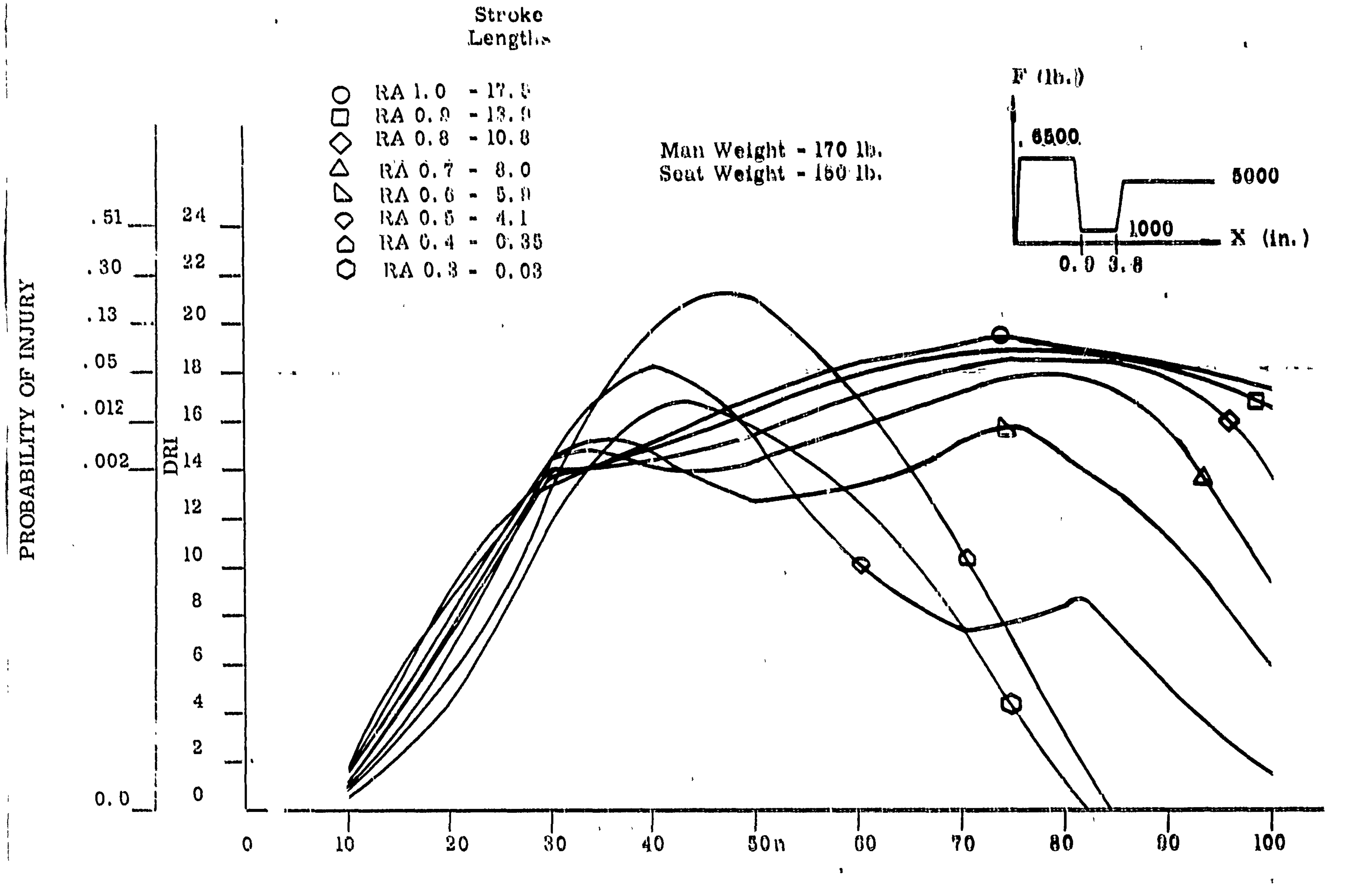


FIGURE 20 - REDUCED INPUT RESPONSE #1 - HELICOPTER

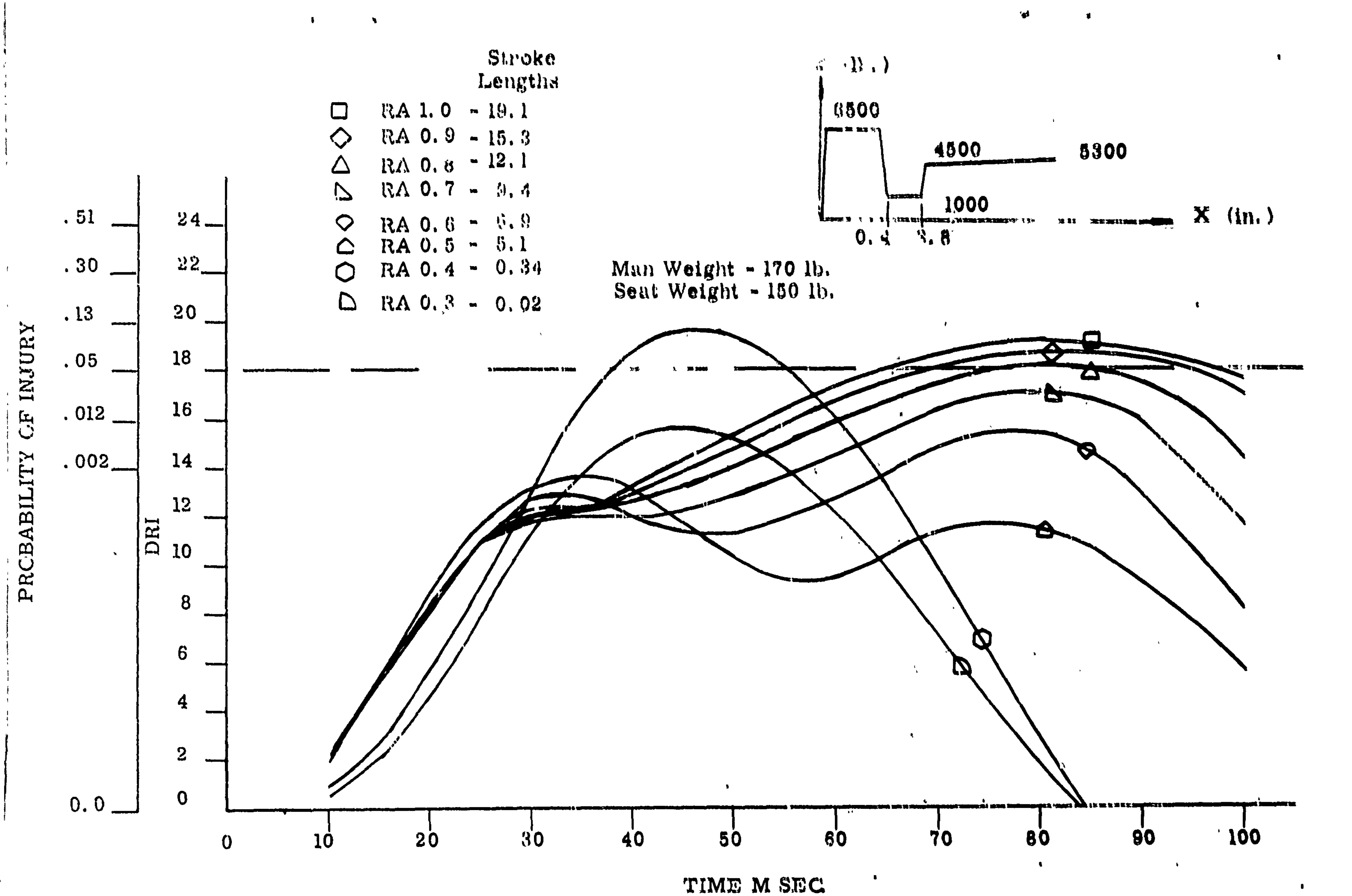


FIGURE 21 - REDUCED INPUT RESPONSE NO. 2 - HELICOPTER

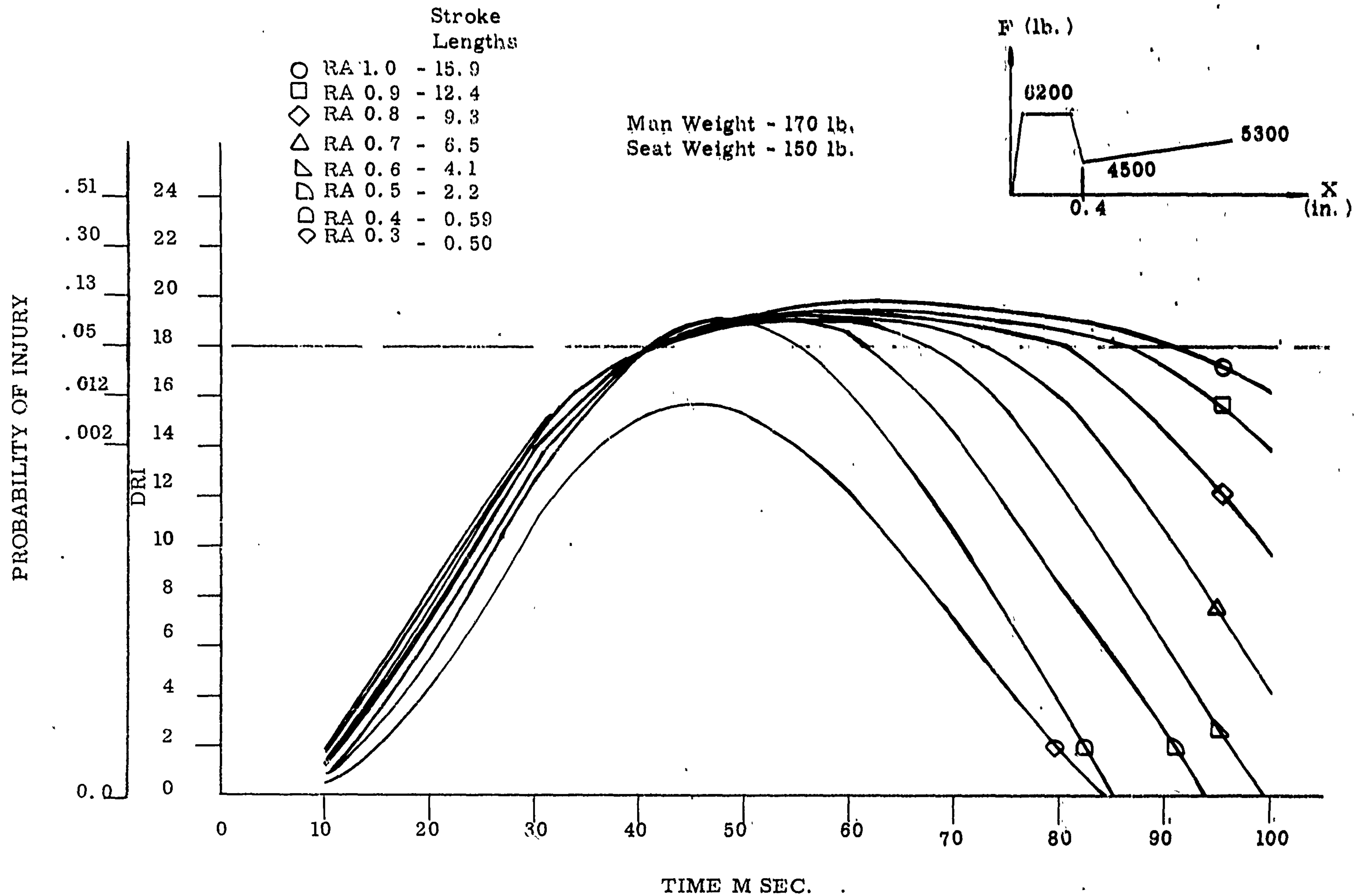


FIGURE 22 - REDUCDED INPUT RESPONSE NO. 3 - HELICOPTER

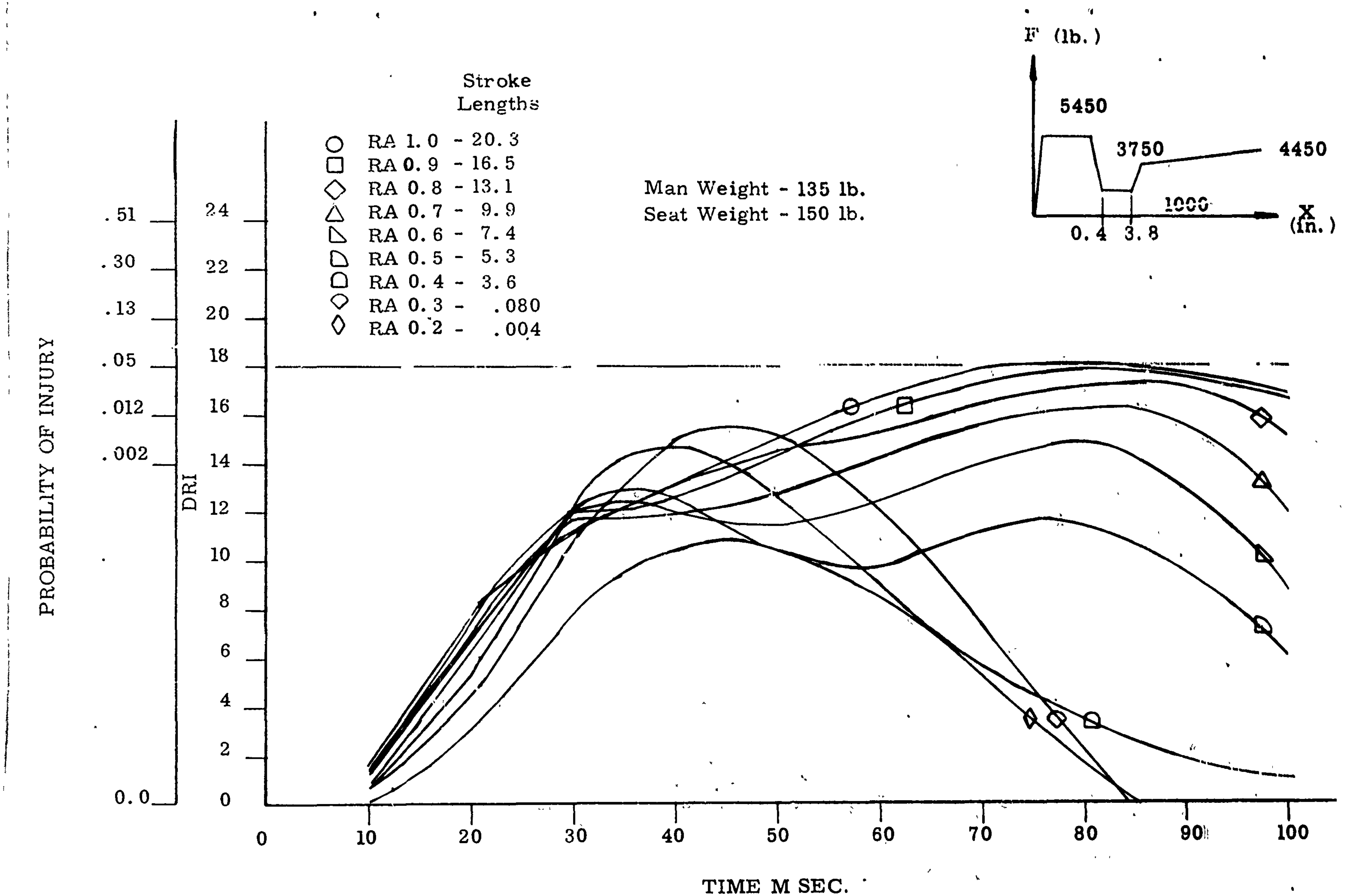


FIGURE 23 - REDUCED INPUT RESPONSE NO. 4 - HELICOPTER

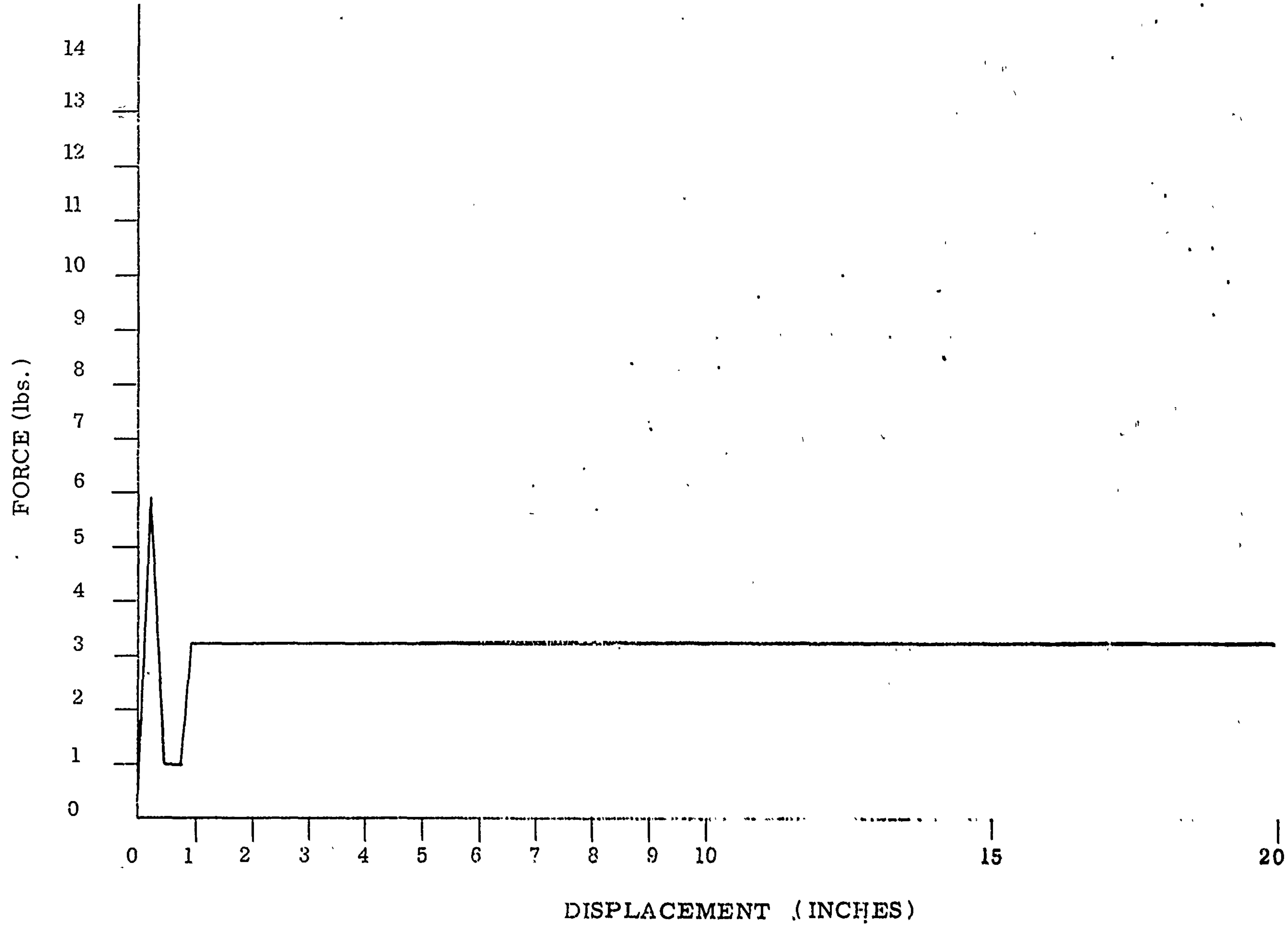


FIGURE 24 - PRELIMINARY OPTIMUM ENERGY ABSORBER - TRANSPORT

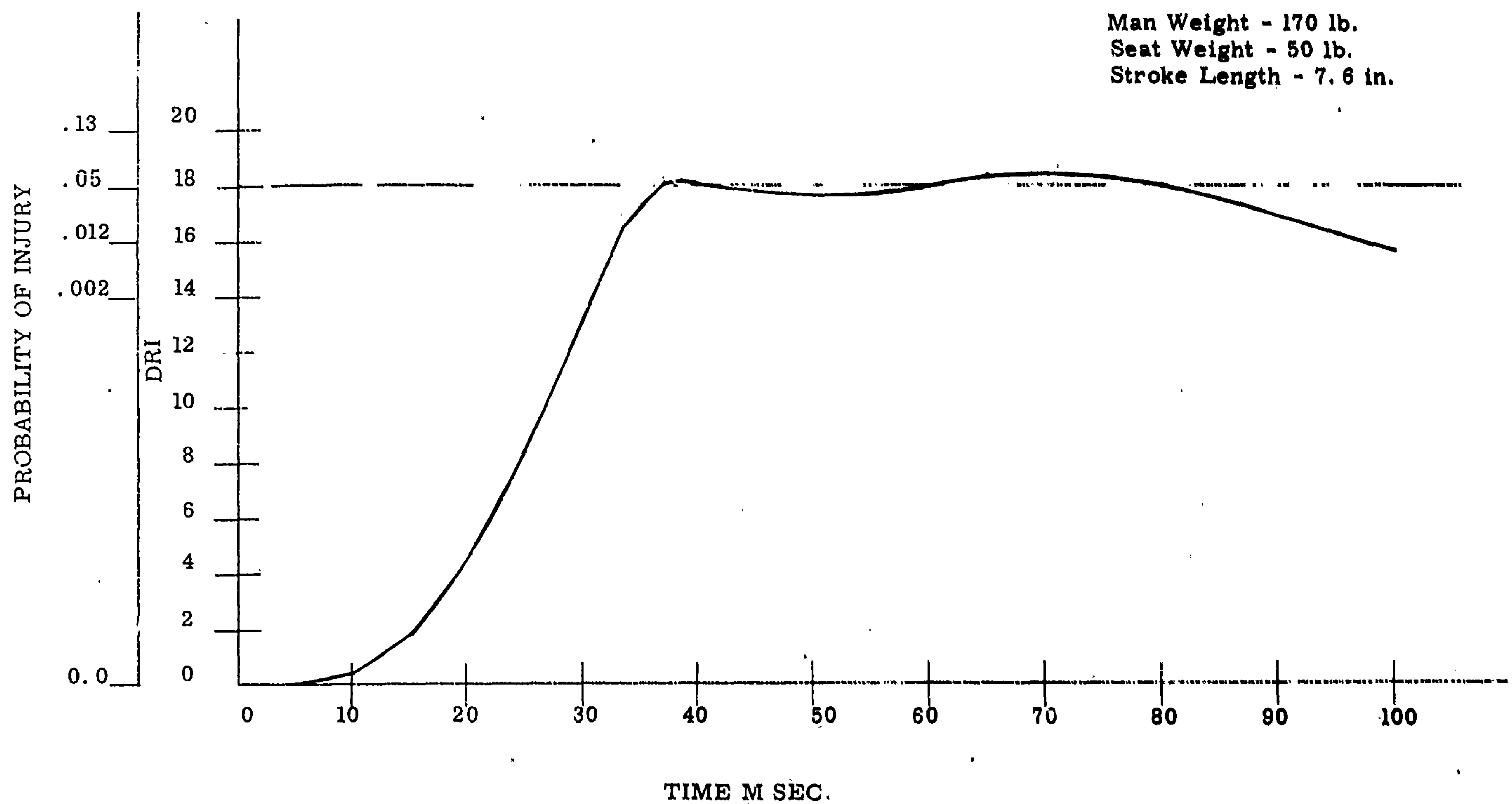


FIGURE 25 - PRELIMINARY ENERGY RESPONSE - TRANSPORT

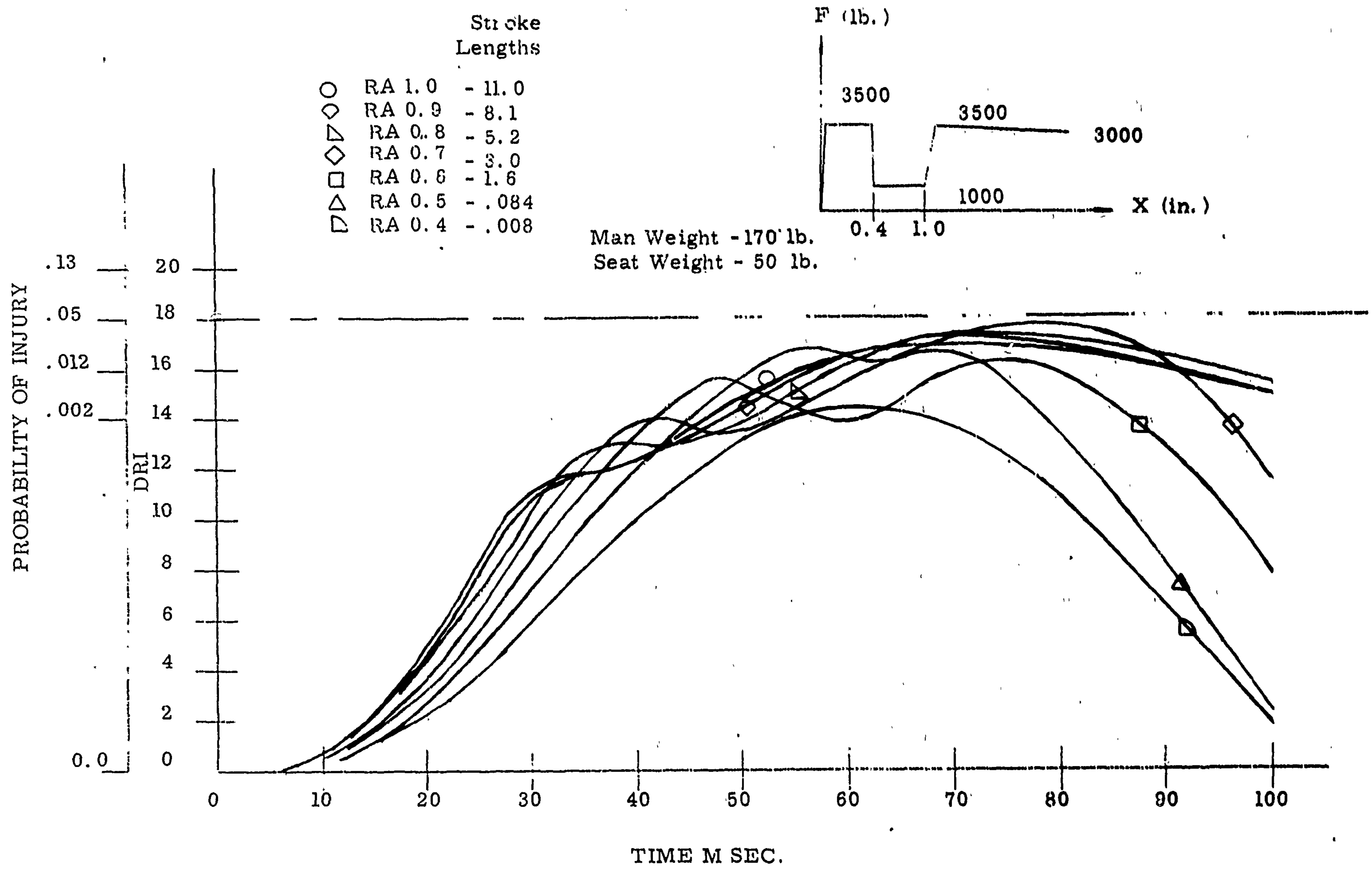


FIGURE 26 - REDUCED INPUT RESPONSES NO. 1 - TRANSPORT

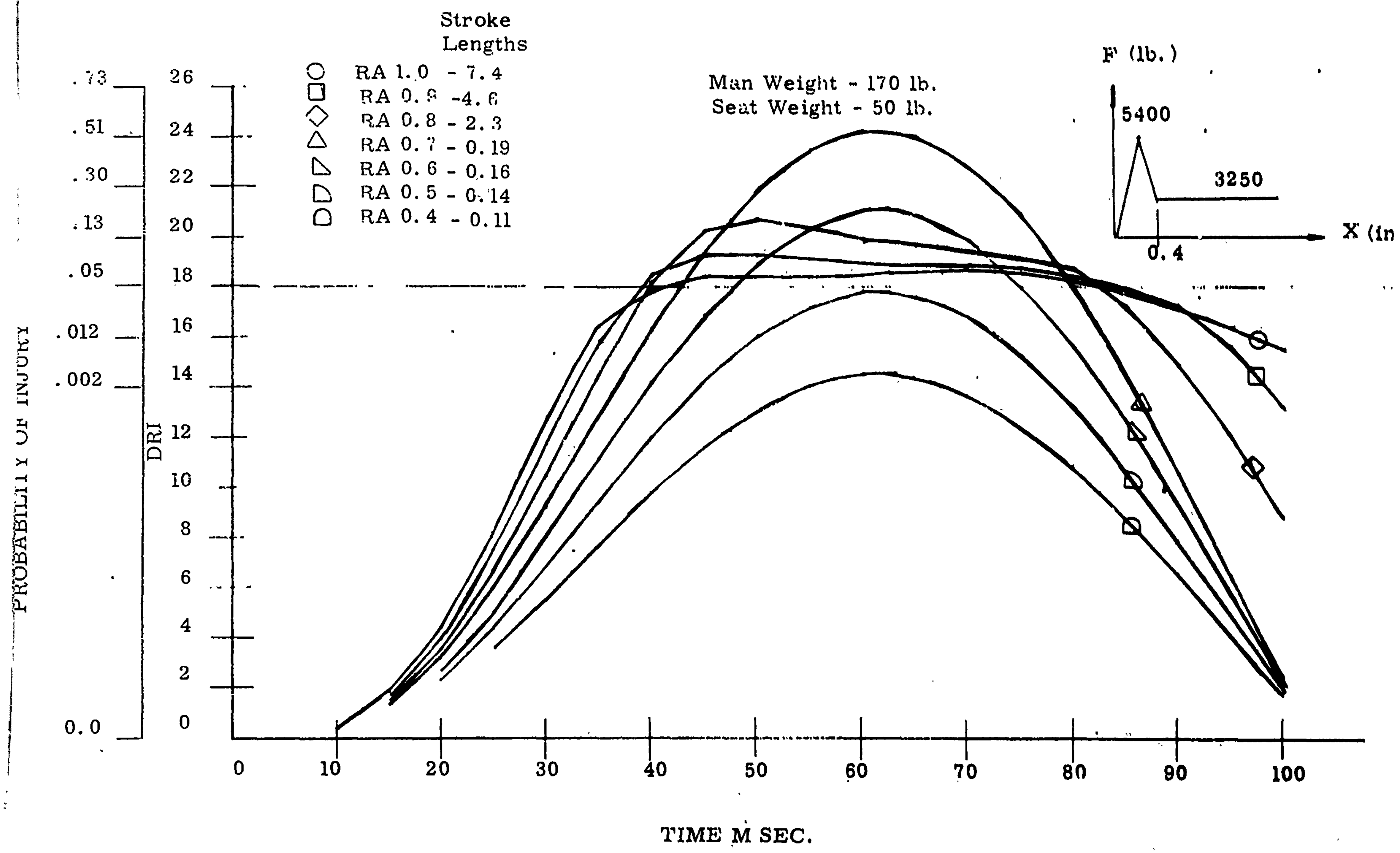


FIGURE 27 - REDUCED INPUT RESPONSES NO. 2 - TRANSPORT

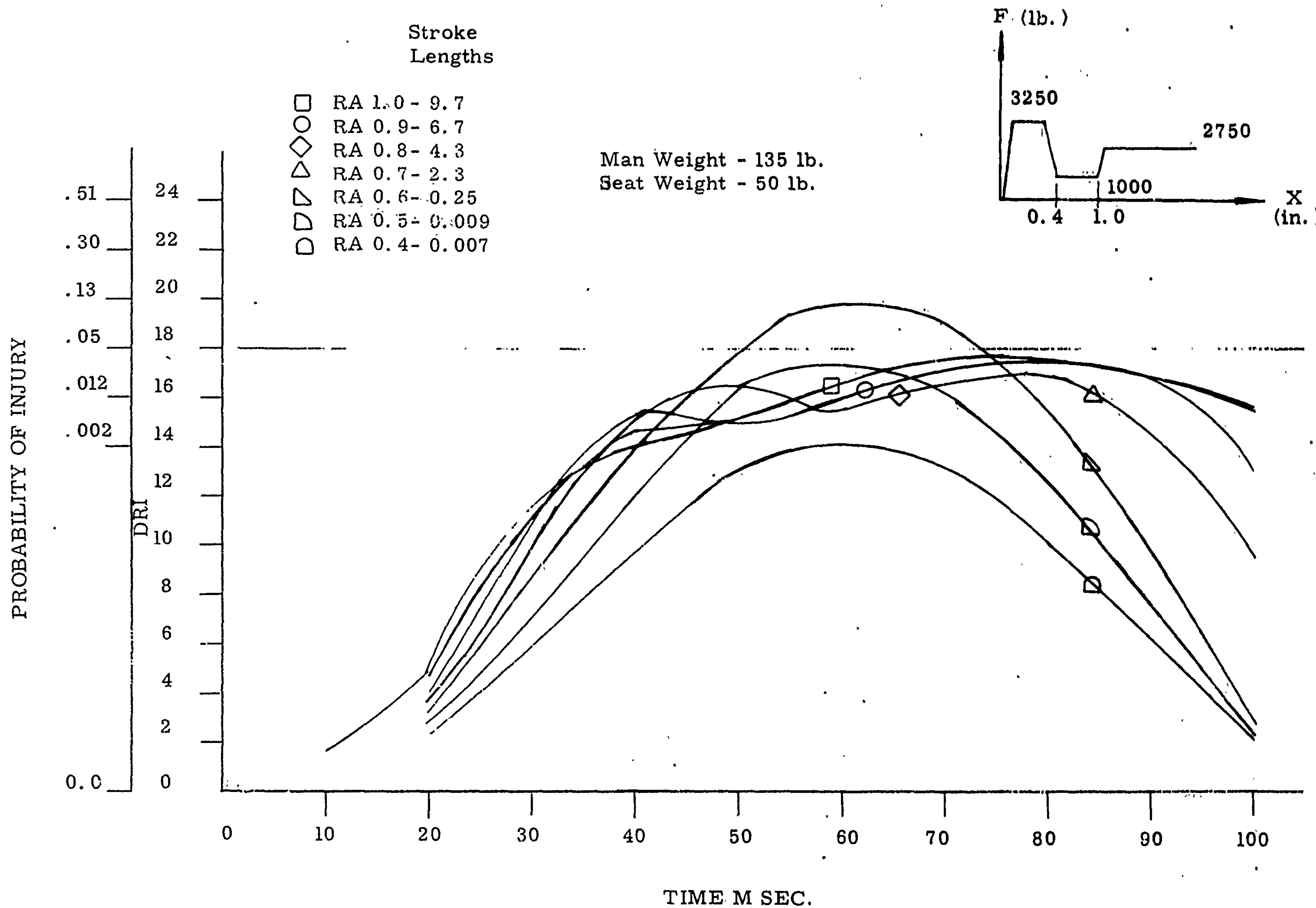


FIGURE 28 - REDUCED INPUT RESPONSES NO. 3 - TRANSPORT

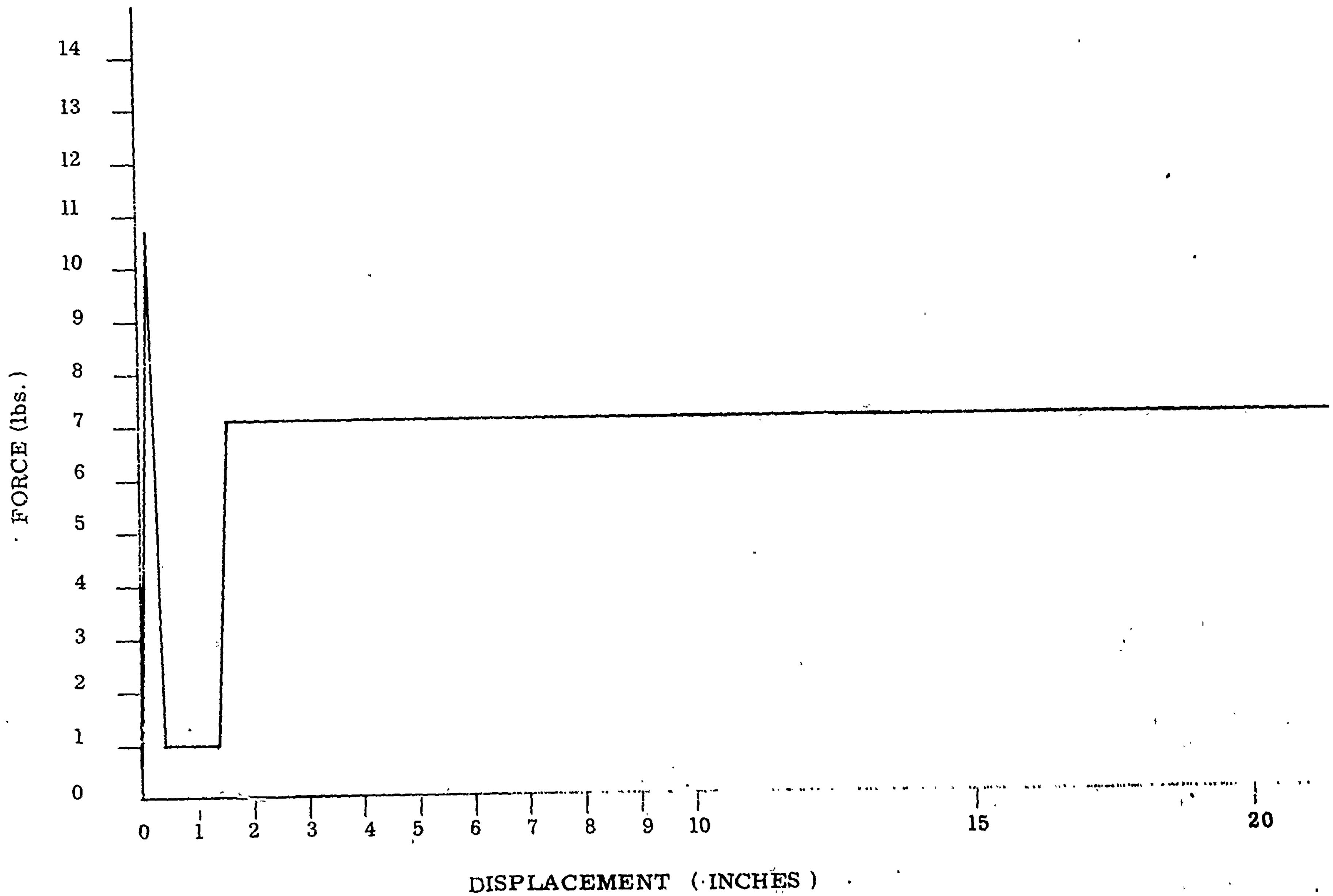


FIGURE 29 - PRELIMINARY OPTIMUM ENERGY ABSORBER - FIGHTER

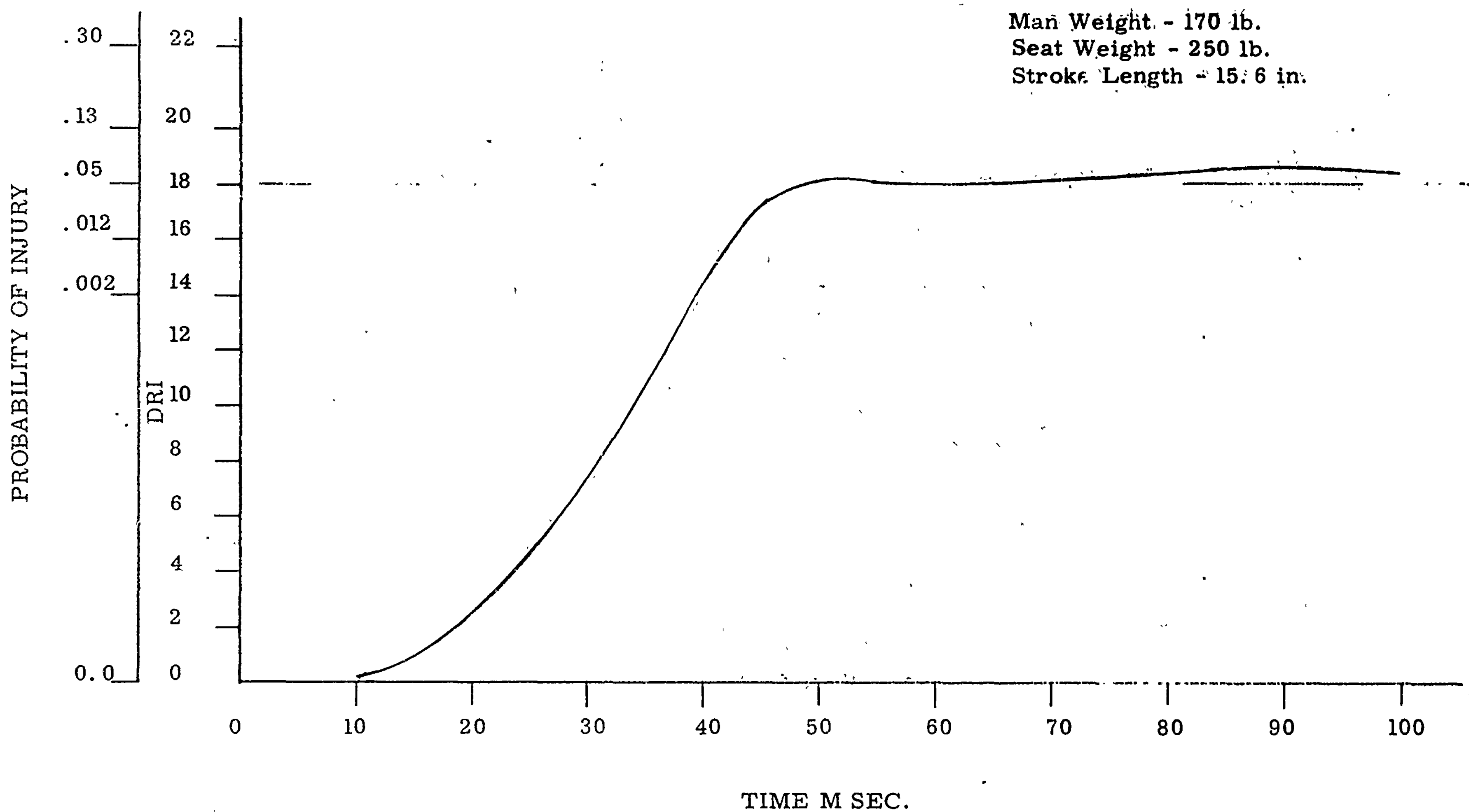


FIGURE 30 - PRELIMINARY ENERGY ABSORBER RESPONSE - FIGHTER

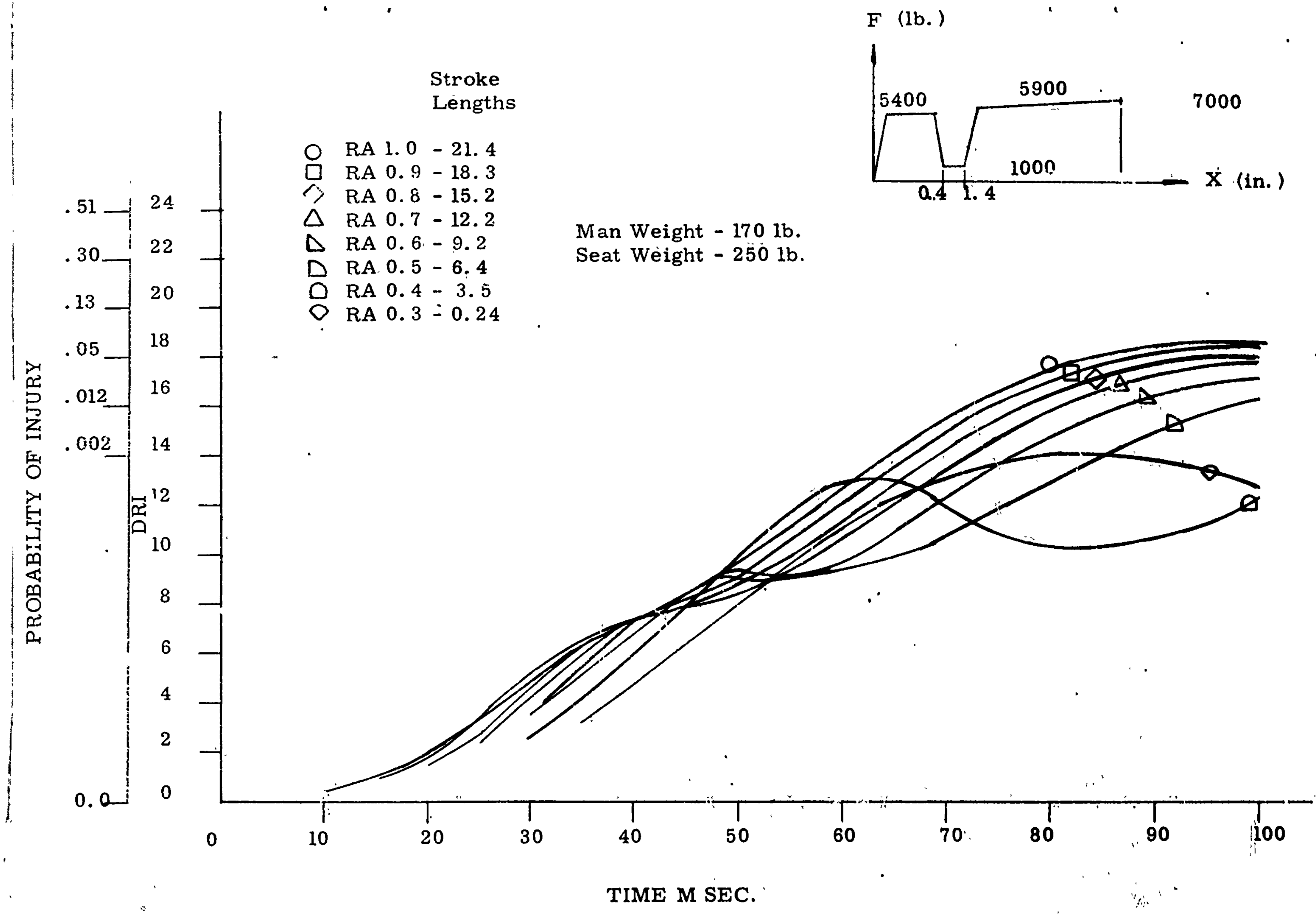


FIGURE 31 - REDUCED INPUT RESPONSES NO. 1 - FIGHTER

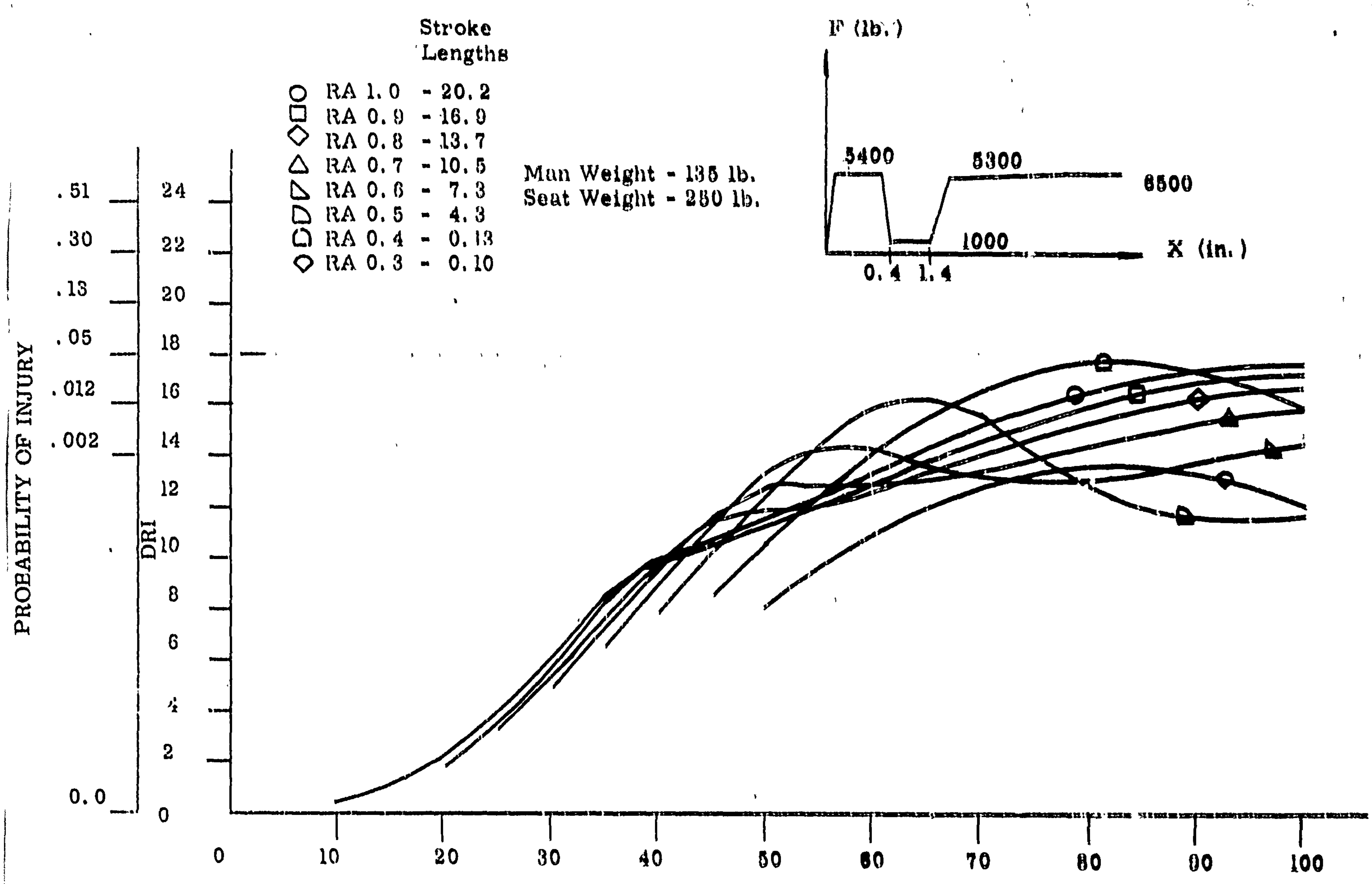


FIGURE 32 - REDUCED INPUT RESPONSES NO. 2 - FIGHTER

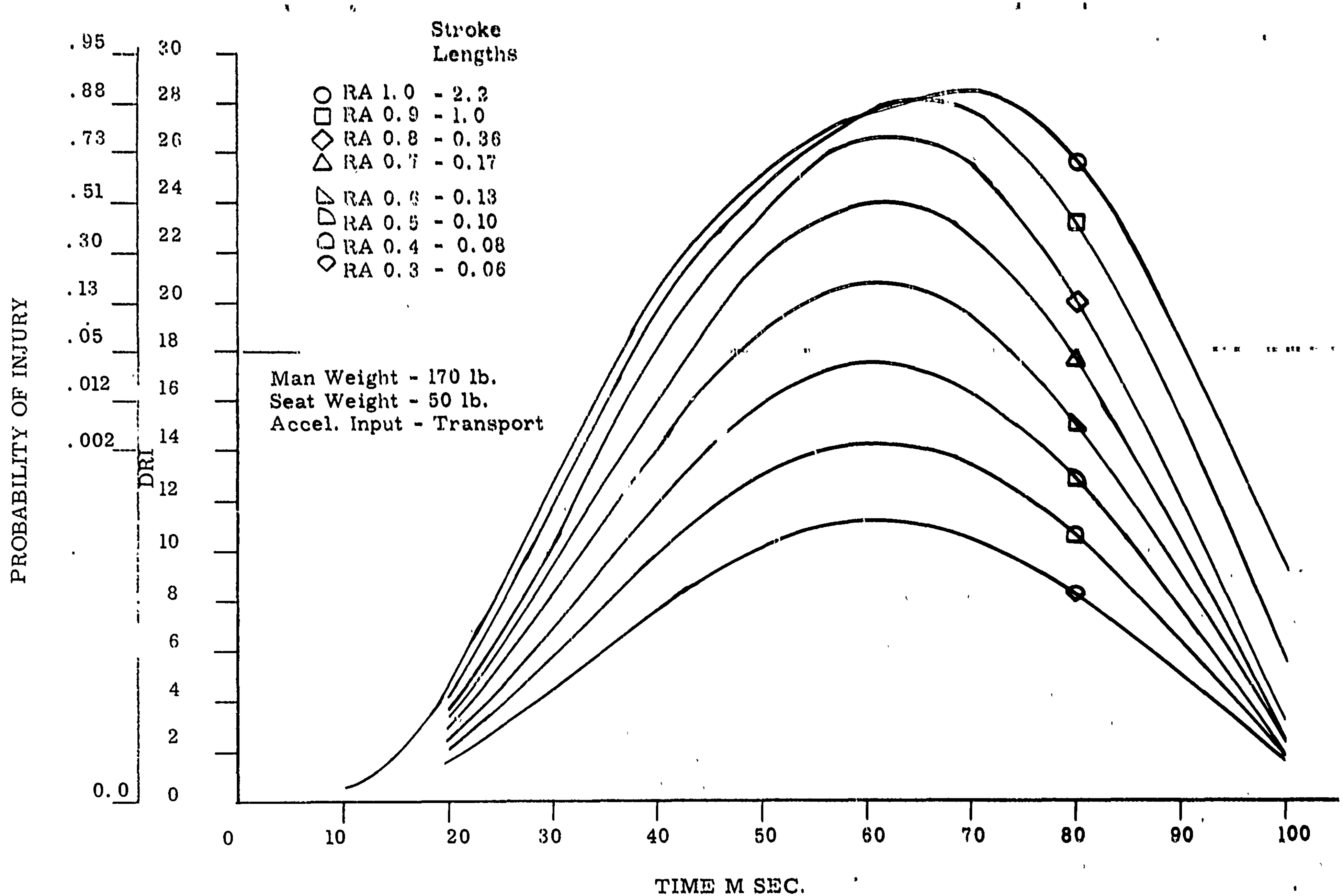


FIGURE 33 - ARA INC. NO. 3 - EVALUATION CURVES

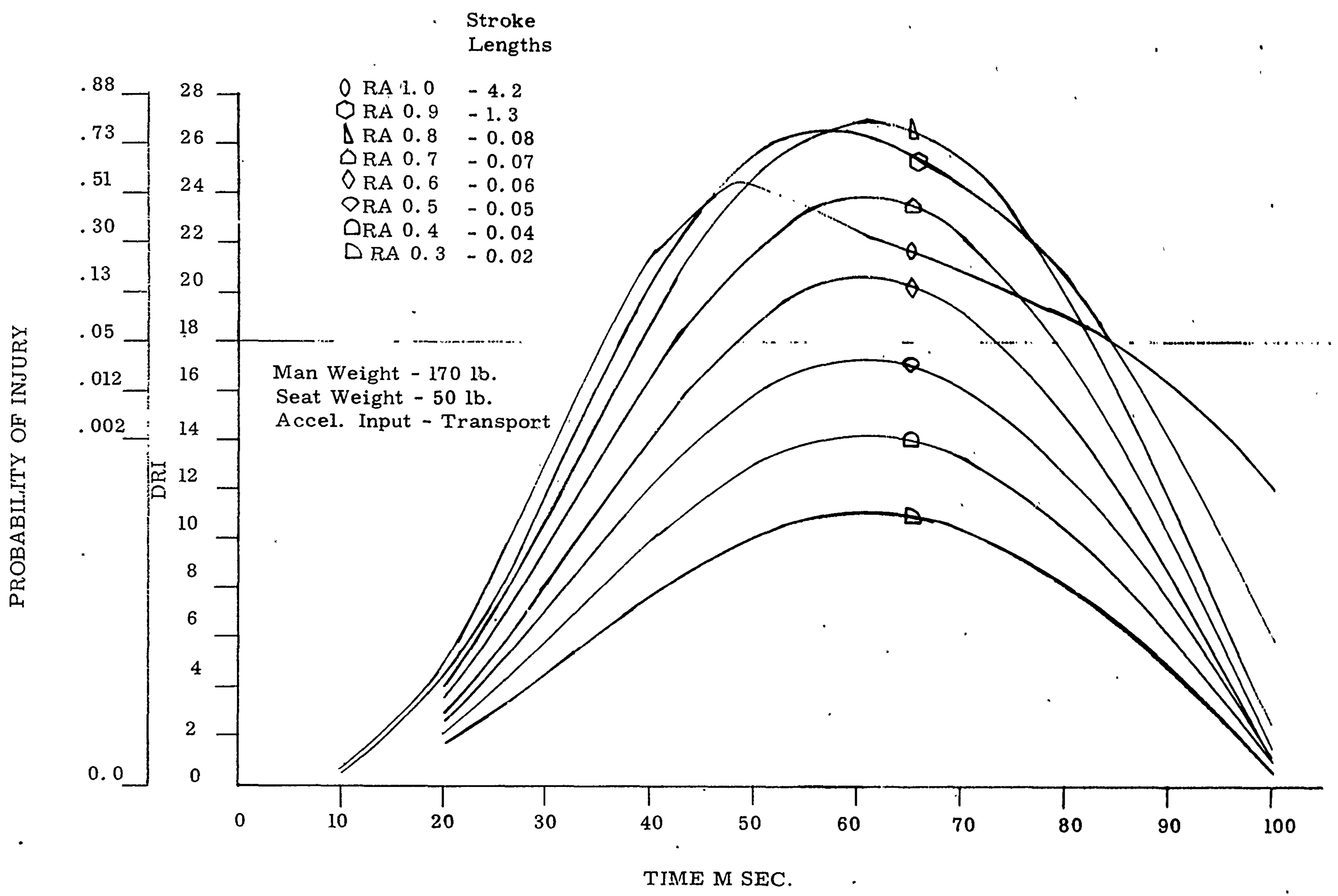


FIGURE 34 - ARDE NO. 2 - EVALUATION CURVE

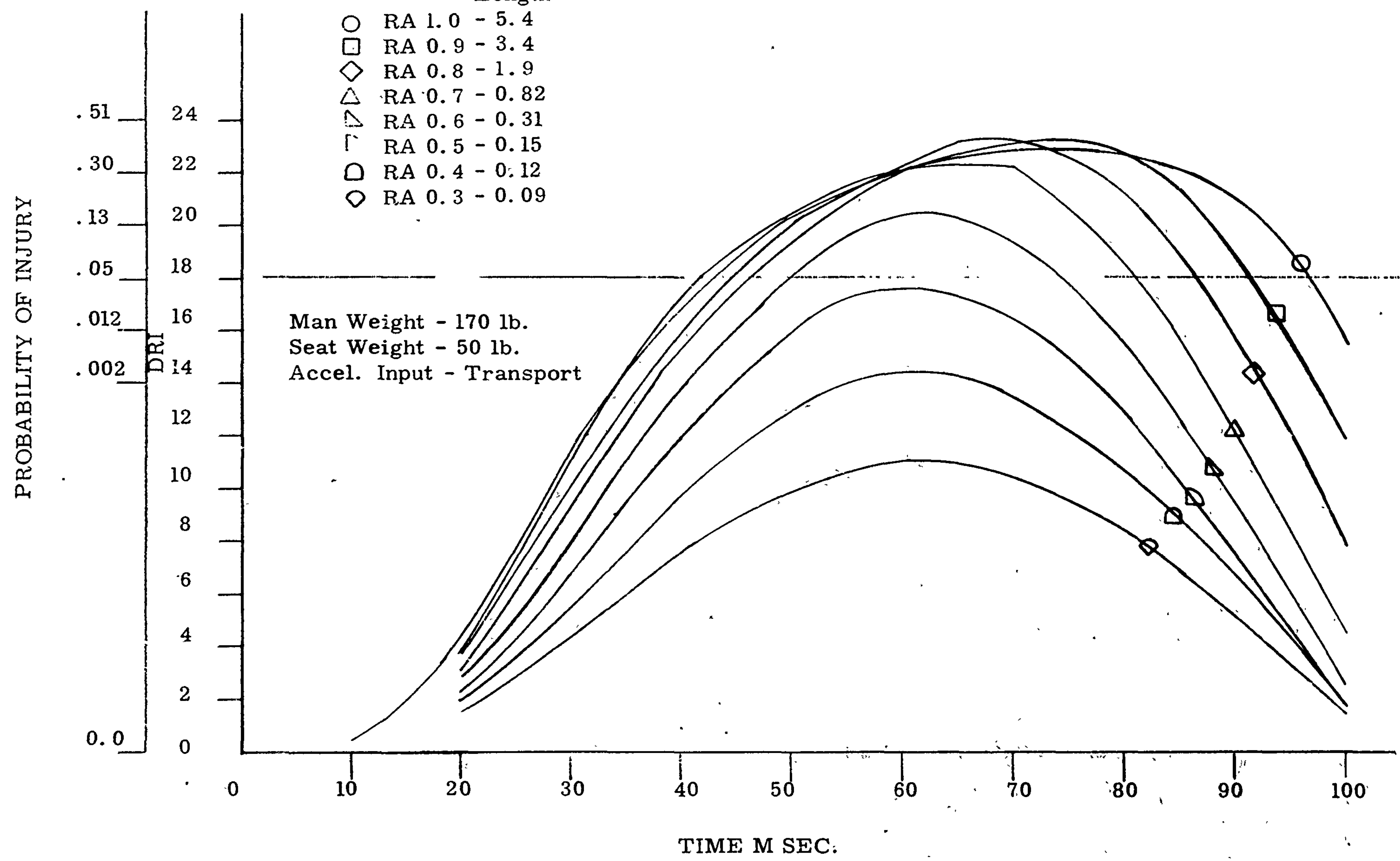


FIGURE 35 - ALL AMERICAN EVALUATION CURVES

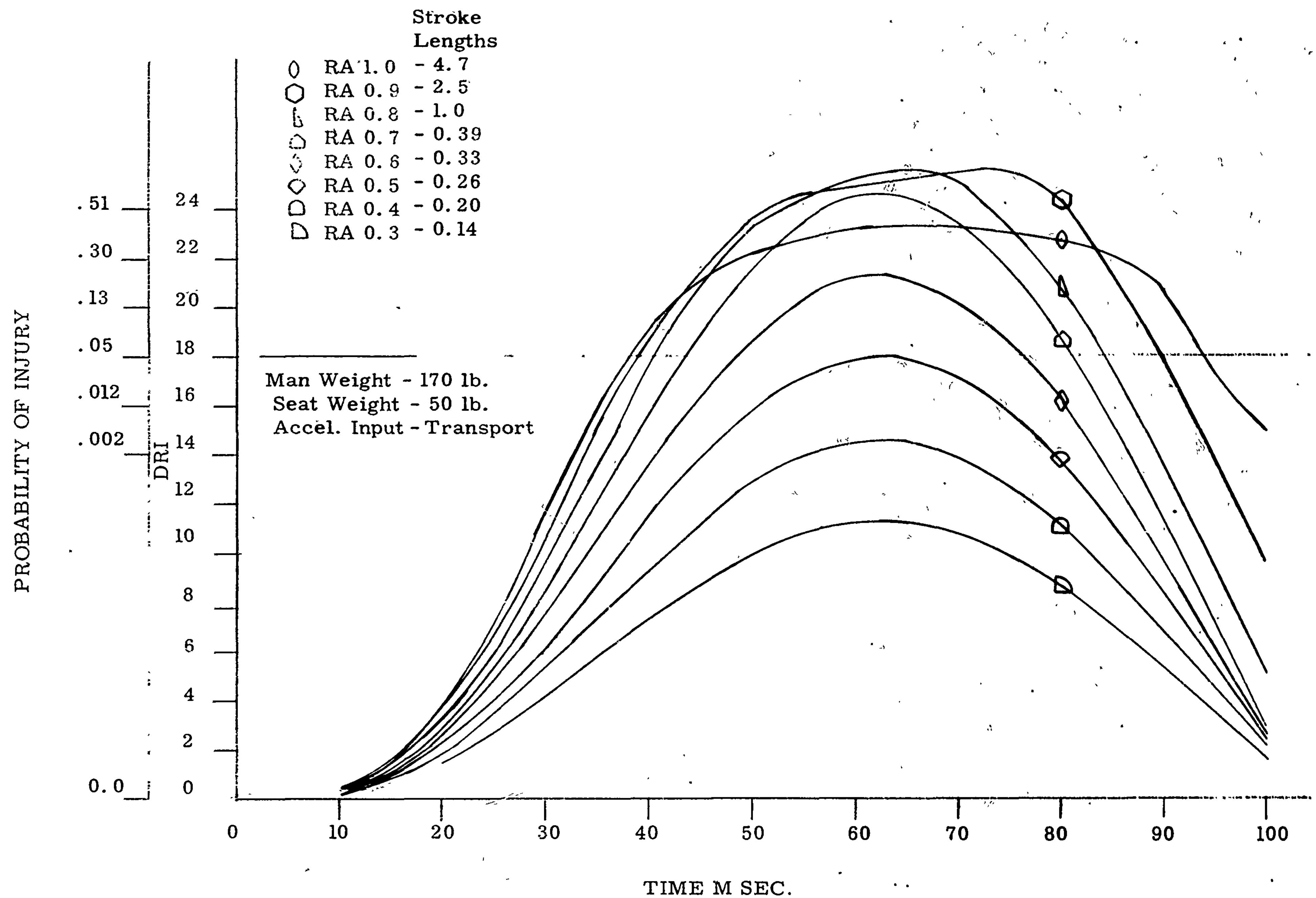


FIGURE 36 - BOEING NO. 3 - EVALUATION CURVES

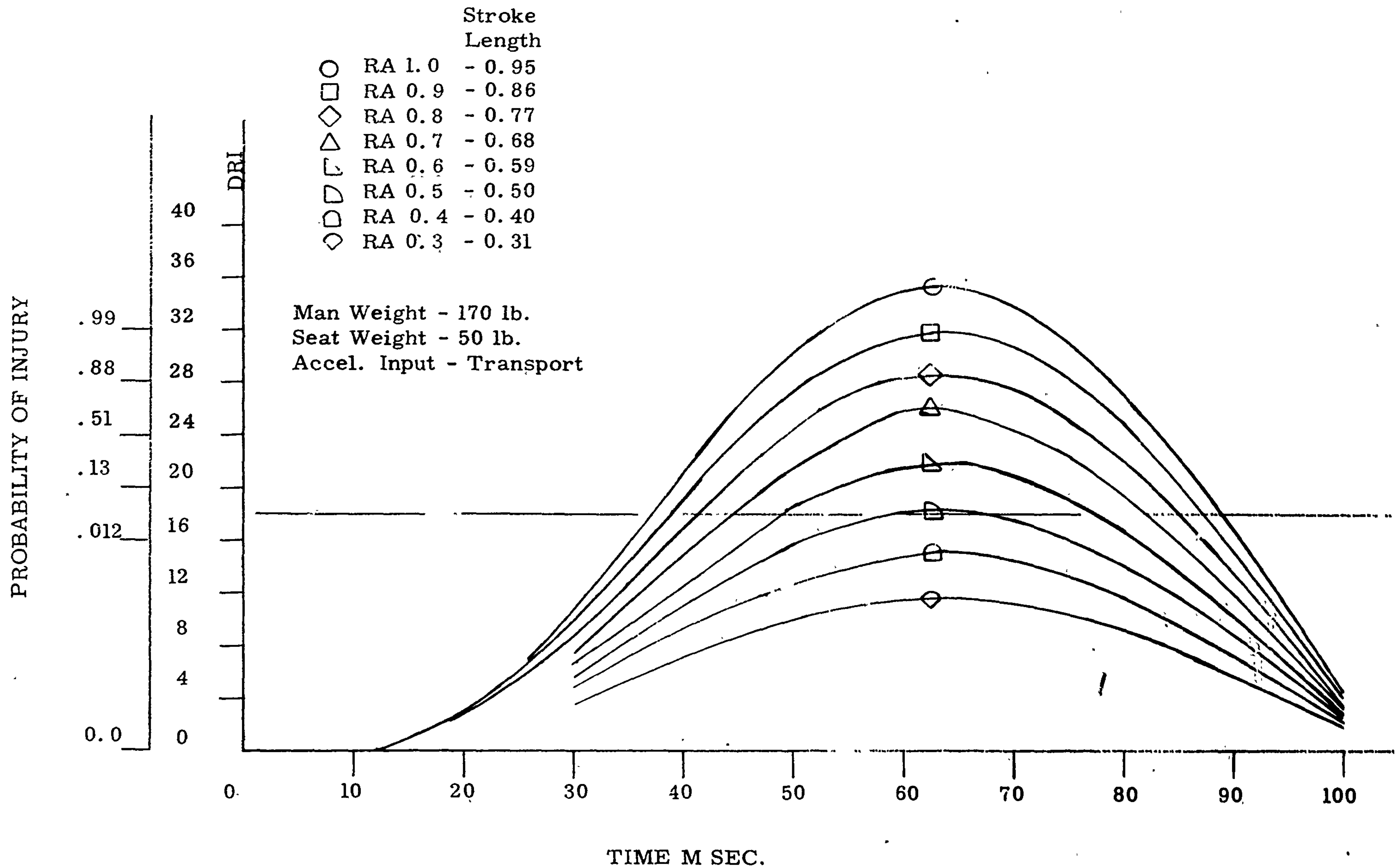


FIGURE 37 - MRI - EVALUATION CURVES

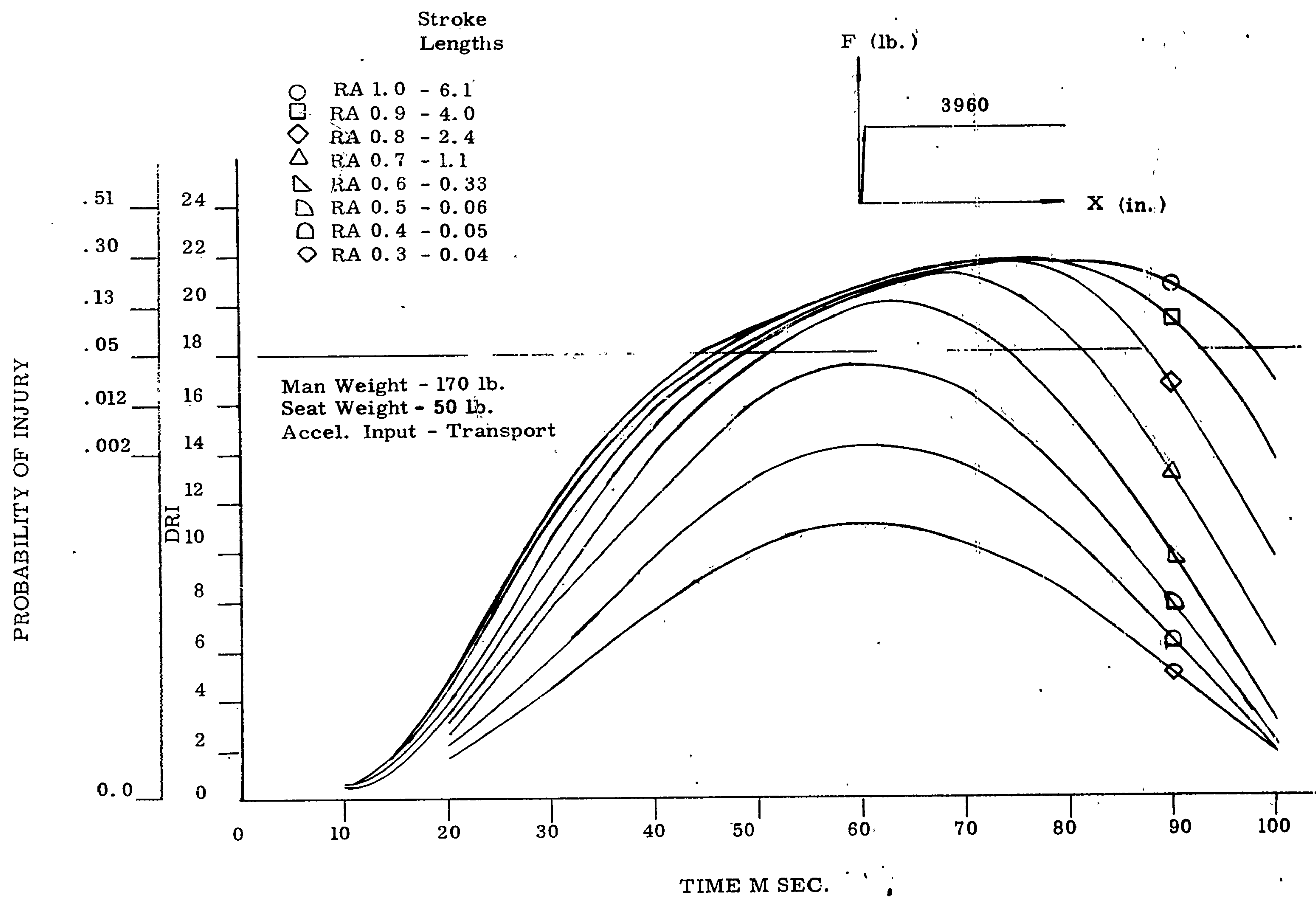


FIGURE 38 - SQUARE WAVE EVALUATION CURVES

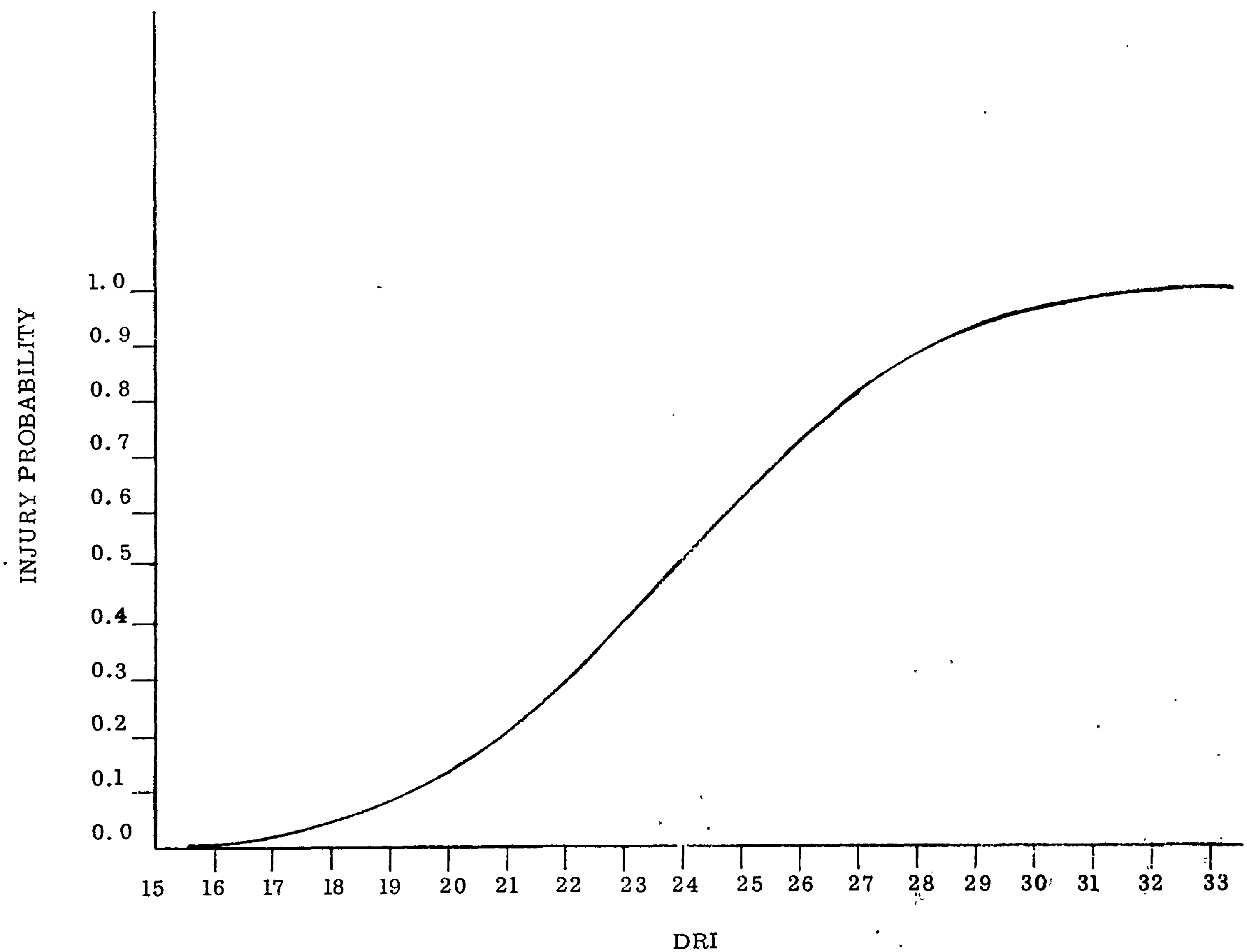


FIGURE 39 - INJURY PROBABILITY CURVE

AIRCRAFT TYPE - GENERAL

REPORT NO.	REPORT TITLE & SUMMARY	COMMENTS
USAAVLABS TR 67-22	Turnbow, J. W., et. al. Crash Survival Design Guide, Jul 67 A design guide to provide the engineer with an understanding of the basic problems associated with developing crashworthy aircraft.	1967
AD 695 648	Turnbow, J. W., et. al. Crash Survival Design Guide, Aug 69 This report consists of a consolidation of data on design criteria by the Flight Safety Foundation which was accumulated from 1961 to 1969.	1969 No Crash Waveform Data
AD 637 132	Avser., United States Army Aviation Crash Survival Research, Jun 66 Project concerned with improving structural crash-worthiness, improving crash survival capability in seats, and retention systems and improving fuel containment.	No Crash Waveform Data
AD 623 575	Greer, D. L., et. al., Crashworthy Design Principles, Sep 64 Study to provide crashworthy design in order to retain an inhabitable shell around occupants, retain occupants in seats and the seats in the aircraft, and to prevent injury due to local impact, and insure rapid evaluation.	No Crash Waveform Data

TABLE I

AIRCRAFT TYPE - GENERAL

REPORT NO.	REPORT TITLE & SUMMARY	COMMENTS
AD 423 188	Campbell, J. A., Analysis of Requirements for a Full Scale Crash Test Facility, May 63 A thorough study of previous aviation crash safety research programs and facilities.	
AD 294 903	Turnbow, J. W., et. al., Military Troop Seat Design Criteria, Nov 62 Strength requirements set forth in military specifications governing the design and fabrication of troop seats currently used in Army aircraft were analyzed.	No Crash Waveform Data
AD 404 561	Avser., Crew Seat Design Criteria for Army Aircraft, Feb 63 This report analyzed specifications covering design and fabrication of non-ejection crew seats.	No Crash Waveform Data

TABLE I

AIRCRAFT TYPE - FIGHTER

REPORT NO.	REPORT TITLE & SUMMARY	COMMENTS
NACA RM E57G11	Acker, L. W., et. al., Research Memorandum Accelerations in Fighter Airplane Crashes Investigation to determine-magnitude, duration direction of accelerations on airplane structure and pilot in fighter planes during crashes.	Crash Waveform Data FH-1

TABLE II

AIRCRAFT TYPE - HELICOPTER

REPORT NO.	REPORT TITLE & SUMMARY	COMMENTS
Boeing D8-0844	Gonsalves, J. E., A Study of Helicopter Accident Data to Determine the Feasibility of A Survival Escape System, Feb 68 Study to determine the need for helicopter escape and survival systems designed to reduce injury and fatality rate in helicopter accidents.	No Crash Waveform Data
AD 610 587	Thompson, D. F., et. al. Armor Protection for Pilot/Co-Pilot Seat with Crash Safety Features for CH-47A Helicopter, Dec 64 Pilot and co-pilot crash safety seat design and manufactured for CH-47A helicopter with maximum protection for occupants.	CH-47A No Crash Waveform Data Some E. A. curves
AD 664 147	U. S. Army H-25 Helicopter Drop Test, Dec 60 Report describes results of a study to establish methods of conducting tests and data from drop testing of H-25 helicopter.	H-25 Crash Waveform Data
AD 416 298	Weinberg, L. W. T., Dynamic Test of a Commercial Type Passenger Seat Installation in an H-21 Helicopter, Jun 63 Contains an analysis of the crashworthiness of a seat installed in an H-21 helicopter.	H-21 Crash Waveform Data
AD 276 210	Spencer, L. E., Breakaway Fuel Cell, May 62 Report on the Crash testing of an H-13G helicopter with an experimental breakaway fuel cell.	H-13G No Crash Waveform Data

TABLE III

AIRCRAFT TYPE - HELICOPTER

REPORT NO.	REPORT TITLE & SUMMARY	COMMENTS
AD 275 184	Final Report U. S. Army Aviation Crash Injury Research, Sep 61 This report covers full scale dynamic testing of aircraft and statistical analysis. It also covers training of crash injury investigators and field investigation of Army aircraft accidents.	No Crash Waveform Data
AD 420 129	Turnbow, J. W., et. al. Dynamic Test of an Experimental Troop Seat Installation in an H-21 Helicopter, Nov 63 A report of an energy absorbing troop seat dynamically tested by being subjected to an actual aircraft crash.	Crash Waveform Data

TABLE III

AIRCRAFT TYPE - TRANSPORT

REPORT NO.	REPORT TITLE & SUMMARY	COMMENTS
USAAVLABS TR 67-16	Haley, J. L., et. al. Floor Accelerations & Passenger Injuries in Transport Aircraft Accidents, May 67 It consists of a study to establish as closely as possible the crash environment for potentially survivable accidents.	DC-7 & L-1649 Crash Waveform Data
USAAVLABS TR 67-17	Turnbow, J. W., et. al., Aircraft Passenger-Seat System Response to Impulsive Loads, Aug 67 It consists of an investigation of the dynamic response of seat passenger system to crash induced floot accelerations through a computer analysis of the problem; an investigation of seat strength and load deformation characteristics and an investigation of conceptual seat-systems designs.	No Crash Waveform Data
AD 613 300	Bigham, J. P., Jr., et. al., Theoretical Determination of Crash Loads for a Lockheed 1649 Aircraft in a Crash Test Program, Jul 64 This report presents the results of an analytical study to theoretically determine the loads to be experienced by a Lockheed Model 1649. Super Constillation during a controlled crash.	No Crash Waveform Data
AD 624 051	Reed, W. H., et. al., Full Scale Dynamic Crash Test of a Douglas DC-7 Aircraft, Apr 65 The purpose of the report is to collect data on fuel containment of crashed DC-7 aircraft:	DC-7 Crash Waveform Data - Ver. Seat

TABLE IV

AIRCRAFT TYPE - TRANSPORT

REPORT NO.	REPORT TITLE & SUMMARY	COMMENTS
AD 654 538	Reed, W. H., et. al., Full Scale Dynamic Crash Test of a Lockheed Constellation Model 1649 Aircraft, Oct 65 Report contains details of a full scale crash of a Lockheed 1649.	L-1649 Crash Waveform Data
AD 687 410	Garner, J. D., Blethrow, J. G., Emergency Evacuation of a Crashed L-1649, Aug 66 Evacuation Test of a Lockheed 1649.	L-1649 No Crash Waveform Data
AD 651 219	Avery, J. P., et. al. Analysis of Army Fixed Wing Cargo Restraint Design Criteria, Jan 67 Computer study of cargo restraint on CU-2 & CU-7 aircraft.	No Crash Waveform Data

TABLE IV

ENERGY ABSORBER	MAN WT lb.	FIGHTER DRI	FIGHTER STROKE in.	HELICOPTER DRI	HELICOPTER STROKE in.	TRANSPORT DRI	TRANSPORT STROKE in.
COMMERCIAL							
ARA INC #1	135	18.2	18.2	23.0	14.7		
ARA INC #1	170	16.5	19.8	20.0	17.5		
ARA INC #1	205	14.8	21.2	17.5	20.2	24.0	4.3
ARA INC #2	135	21.5	15.8	25.5	12.6	34.0	0.1
ARA INC#2	170	18.5	17.6	22.5	15.1	31.8	0.8
ARA INC #2	205	16.5	19.2	19.6	17.6	26.9	2.7
ARA INC #3	135	18.4	18.7	21.5	16.1	33.5	0.5
ARA INC #3	170	16.5	20.3	18.9	18.9	28.5	2.2
ARA INC # 3	205	14.8	21.8	16.7	21.7	23.4	4.7
ARDE #2	135	15.8	21.2	15.5	23.0	33.9	0.09
ARDE #2	170	14.4	22.7	13.5	25.0	23.8	4.3
ARDE #2	205	12.8	24.0	11.5	25.1	19.0	8.6
ARDE #3	135	12.9	24.0	15.5	24.0	23.5	4.4
ARDE #3	170	11.4	25.2	13.5	25.0	19.1	8.0
ARDE #3	205	10.3	25.3	12.1	25.1	16.4	11.4
ALL AMER	135	14.9	22.2	18.7	20.5	27.7	2.5
ALL AMER	170	13.3	23.6	16.6	23.2	22.8	5.4
ALL AMER	205	12.1	24.7	14.5	25.1	19.5	8.3
M. R. I.	135	37.5	7.0	44.5	6.3	35.5	0.7
M. R. I.	170	33.3	9.7	38.5	7.8	35.7	1.0
M. R. I.	205	30.0	12.0	35.3	9.3	36.0	1.1

TABLE V

ENERGY ABSORBER	MAN WT. lb.	FIGHTER DRI	FIGHTER STROKE in.	HELICOPTER DRI	HELICOPTER STROKE in.	TRANSPORT DRI	TRANSPORT STROKE in.
COMMERCIAL							
BOEING #1	135	15.8	20.4	19.6	19.5	28.2	1.7
BOEING #1	170	13.8	2[illegible].9	17.1	21.6	23.5	4.2
BOEING #1	205	12.9	23.2	14.9	23.9	21.5	7.3
BOEING #3	135	15.4	21.7	19.3	19.3		
BOEING # 3	170	13.5	23.1	16.8	22.6	23.5	4.2
BOEING #3	205	12.5	24.3	14.6	24.8	21.5	7.3
THEORETICAL							
FIGHTER-OPTIMUM	170	18.5	15.6				
FIGHTER-NOTCHED	135	18.5	41.8*				
FIGHTER-NOTCHED	170	18.6	42.4*				
HELICOPTER-OPTIMUM	170			18.4	15.0		
HELICOPTER-NOTCHED	135			18.1	20.3		
HELICOPTER-NOTCHED	170			19.2	17.5		
HELICOPTER-UNNOTCHED	170			19.7	15.9		
TRANSPORT-OPTIMUM	170					18.4	7.6
TRANSPORT-NOTCHED	135					17.7	9.7
TRANSPORT-NOTCHED	170					16.9	11.1
TRANSPORT-UNNOTCHED	170					18.7	7.5
SQUARE WAVE	170	23.6	12.9	22.9	14.7	21.7	6.1

* CALCULATION TIME - 200 M SEC. (OTHERS - 100 M SEC.)

TABLE V

REFERENCES

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Stanley Aviation Corporation, Denver, Colorado, A Study of the Dynamic Model Technique in the Analysis of Human Tolerance to Acceleration. NASA TN 2645, Mar 65

Stech, Ernest L and Payne, Peter R., Dynamic Models of the Human Body, AMRL-TR-66-157, Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio, Nov 69

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Webb, Paul (ed.) Bioastronautics Data Book NASA SP 3006 National Aeronautics and Space Administration, Washington, D. C., August 1964.

Wittman, Thomas J., An Analytical Model to Duplicate Human Dynamic Force Response to Impact, AMRL - TR - 66 - 126, Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio

APPENDIX I

COMPUTER PROGRAM USERS GUIDE

APPENDIX I - COMPUTER PROGRAM USERS GUIDE

The computer used for this study program is listed on the following two pages and is discussed in the subsequent paragraphs with a complete listing of the terms following the discussion.

The initial cards establish the constants to be used in specifying the structural constants. The aircraft floor stiffness is (K6) and damping is (C6). The impact velocities for each acceleration waveform are A1, A2, and A3.

The first three constant function cards, CFN, represent the acceleration waveforms used as inputs. The number within the field indicates the number of time data points within the field. If it takes 10 points to describe the acceleration input, CFN (10. 0) would be required. The last CFN card represents the energy absorber as a function of displacement and a series of ten points. The parameter cards are those inputs that are used to study the variations of response with input parameters. The user has the capability to put in any variation of subject weight, W1; seat weight, W2; aircraft type, AC; energy absorber stroke, SL; number of energy absorbers, NE; and RA input reduction factor.

The function cards establish the functional relationship between the parameters on the constant function cards. That is, FUN (AJ, T) indicates that the data on the CFN card AJ is a function of time, T.

MIMIC SOURCE-LANGUAGE PROGRAM

```
*                     IMPACT RESPONSE OF SEATED MAN
                      CON(K6,C6,K7)
                      CON(A1,A2,A3)
* AF - FIGHTER
            AF        CFN(4.0)
* AH - HELICOPTER
            AH        CFN(6.0)
* AT - TRANSPORT
            AT        CFN(3.0)
            EA        CFN(8.0)
            FA        FUN(AF,T)
            HA        FUN(AH,T)
            TA        FUN(AT,T)
                      PAR(W1,W2,AC,SL,NE,RA)
            M1        W1/386.
            K1        M1*3950.
            C1        0.6*M1*62.8
            M2        W2/386.
            M3        M1
            K3        M3*2500.
            C3        0.44*M3*50.
            FOREA     FUN(EA,X6)
            AD        AC-2.
            ARR       FSW(AD,A1,A2,A3)
            AR        RA*ARR
            2DX1      (-C1*1DX1-K1*X1+C1*1DX2+K1*X2-W1)/M1
            1DX1      INT(2DX1,AR)
            X1        INT(1DX1,0.)
            2DX2      (C1*1DX1+K1*X1-C1*1DX2-K1*X2+ENAB+STR-W2)/M2
            1DX2      INT(2DX2,AR)
            X2        INT(1DX2,0.)
            2DX3      (C3*1DX2+K3*X2-C3*1DX3-K3*X3-W1)/M3
            1DX3      INT(2DX3,AR)
            X3        INT(1DX3,0.)
            BRI       (K3*(X2-X3))/(M3*386.)
            ARS       FSW(AD,FA,HA,TA)
            2DX4      RA*ARS
            1DX4      INT(2DX4,AR)
            X4        INT(1DX4,0.)
            X6        X4-X2
            1DX6      1DX4-1DX2
            1DX7      AP*1DX6
            X7        INT(1DX7,0.)
            AM        FSW(T-.005,1.,1.,0.)
            AN        FSW(AM+1DX6,FALSE,FALSE,TRUE)
            AB        FSW(AM+1DX6,TRUE,TRUE,FALSE)
            DISP      TAS(X6,AN,0.)
            FORED     TAS(ENAC,AN,0.)
            DIS2      TAS(X6,AB,0.)
            FOR2      TAS(ENAC,AB,0.)
            STR       K6*X8+C6*1DX8
            AY        FSW(X6-SL,FALSE,FALSE,TRUE)
            AZ        LSW(AY,1.,0.)
            1DX8      AZ*1DX6
            X8        INT(1DX8,0.,TRUE,AY)
            ENAB      NE*ENAC
            ENAC      FSW(1DX6,FOREB,FOREB,FOREF)
            FOREF     FOREA*BN+FOREB*AP
            BN        LSW(DIS2,0.,1.)
            AP        LSW(DIS2,1.,0.)
```

```
B3        FSW(1DX7,TRUE,TRUE,FALSE)
B1        LSW(B3,1.,0.)
B4        FSW(1DX7,FALSE,TRUE,TRUE)
B2        LSW(B4,1.,0.)
FORS      FOR2*B2+FORED*B1
FOREB     FORS+REBD
1DX9      B1*1DX7
X9        INT(1DX9,0.,TRUE,B3)
1DX10     B2*1DX7
X10       INT(1DX10,0.,TRUE,B4)
REB1      K7*X9
REB2      K7*X10
REBD      REB1*B1+REB2*B2
DT        .001
DTMAX     DT
DTMIN     DTMAX
          FIN(T,.1)
          HDR(TIME,2DX2,2DX4,X6,ENAB,DRI)
          OUT(T,2DX2,2DX4,X6,ENAB,DRI)
          PLO(T,2DX4,2DX2,X6,DRI)
          SCA(.001,200.,200.,.15,1.)
          ZER(0.,0.,0.,0.,50.)
          END
```

The computer will establish linear relations between the points given and interpolate as required.

The next series of cards merely evaluate the stiffness and damping coefficients for the models. Since the man models are fixed, 10 HZ and ζ = 0.3 for the force model; 8 HZ and ζ = 0.22 for the injury model; the coefficients are calculated by inserting the given body weight.

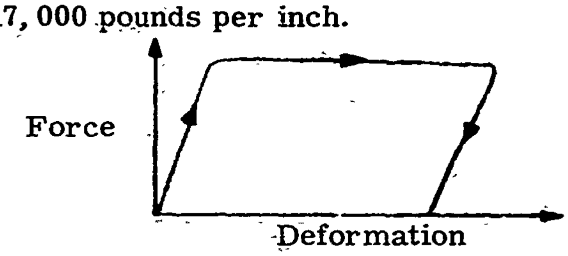
The remainder of the program is the coding of the differential equations of motion previously mentioned. For example, the differential equation for the seat is written:

$$M_2\ddot{X}_2 = C_1\dot{X}_1 + K_1X_1 - C_1\dot{X}_2 - K_1X_2 + F_{ea} + F_{st} - W_2$$

The first terms are directly from a summation for forces. The last three are the forces due to the energy absorber, forces due to structural response, and the inertial term. As the energy absorber compresses, the force generated changes with increasing relative displacement. However, it cannot displace an unlimited amount. If an energy absorber is not sufficient to absorb the input energy, it would attempt to travel a distance greater than practically available. Therefore, the stroke limit, SL, is specified. If the device attempts to exceed this limit it is assumed that the seat impacts on a very rigid structure having stiffness K6.

This caused large magnitude and high frequency "ringing" to occur and structural damping C6 is included to limit the ringing.

The other condition is that of seat rebound. If the absorber dissipates the energy properly, a point is reached where the relative velocity between the floor and seat goes to zero. If the seat and man want to rebound, the energy absorber does not necessarily respond as a continuous element. Since rebound data is not available for all types of absorbers, it is assumed the device deforms elastically back to zero force with the same stiffness as the original elastic deformation of the curve. This is shown below. The value used at present is 17, 000 pounds per inch.



The remainder of the program contains the logic required to properly control the energy absorber "rebound" and the structural bottoming. The structural response is the easiest to explain. When the absorber deformation, X6, exceeds the selected stroke, SL, the displacement of the "rigid" link is calculated by integrating the relative velocity starting at the time when X6-SL is greater than zero. This creates a force STR which is added into the differential equation.

When the deformation becomes less than the limiting stroke, the integration stops and the force goes to zero. The seat is free to rebound.

The energy absorber action is more complicated. As the displacement, X6, increases; the relative velocity, IDX6, eventually slows to zero. At this point the absorber wants to rebound, but not along the original path. Instead, it wants to unload along a line parallel to the initial elastic portion of the force-displacement curve. There the last value of force and displacement attained at zero relative velocity must be stored as the initial value of the rebound or relaxation portion of the curve. This is the purpose of the "track and store" operations such as:

DISP = TAS (X6, AN, O.)

FORED = TAS (ENAC, AN, O.)

From these initial conditions we must backtrack along the stiffness curve K7. Therefore, the force in the energy absorber is the stored value minus the product of K7 and X9. When the absorber reaches another zero relative velocity, expands as far as it will go, the deformation may again increase along the elastic curve from the stored values:

DIS2 = TAS (X6, AB, O.)

FOR2 = TAS (ENAC, AB, O.)

The occurrence of elastic rebound within the elastic range, even though IDX6 goes positive, is recognized by having the logical test placed upon IDX7 which detects the first change in relative velocity. When the absorber initially compresses, the relative velocity is positive but the maximum displacement has not occurred to initiate IDX7. After the peak displacement is once reached, IDX7 has some value and enables the computer to calculate the relaxation effect rather than return to the original force displacement curve.

The output of the program can be selected by use of header and outs cards in the formats shown. As written, the program prints out and plots the input acceleration, the seat acceleration, the energy absorber crush and the D. R. I. These provide in one plot the input, the seat response, energy absorber response, and the human physiological response.

It is necessary that the program cards be placed in a particular order and with a particular number of cards sequenced properly. The proper order is explained below.

The first card is a job card having the maximum number of minutes and lines of output anticipated along with an identifying problem number and name.

```
$JOB      S546    0,5,5000        69-568,N S PHIL, BETA IND. INC.
```

The second card is an execute card that identifies the routine to be used.

175220 0 $EXECUTE MIMIC

This is followed by a comment card which is the printout to be placed at the top of computer program listing. The program deck follows the comment card and the last card of the program is the End card to be followed by data.

The cards following the program are those called out within the program in the order they are listed. The constants K6, C6, and K7 are on the first card and the velocities A1, A2, and A3 are on the second.

K6	C6	K7
1.00000E 06	2.00000E 02	7.00000E 05

A1	A2	A3
-9.07400E 02	-5.23570E 02	-4.93000E 02

Crash acceleration waveforms are the next sets required. The number of points for each must match the number within the constant function field of the identifying card. That is, for the fighter, AF=CFN (4.0) must have four data cards. The acceleration cards are as shown.

4.	AF
0.	0.
3.50000E-02	1.080C0E 04
9.60000E-02	1.08000E 04
1.07000E-01	0.

6.	AH
0.	0.
10.00000E-03	1.830C0E 04
1.30000E-02	2.030C0E 04
1.80000E-02	4.43000E 04
2.50000E-02	9.67000E 03
3.00000E-02	0.

3.	AT
0.	0.
1.80000E-02	1.16000E 04
8.50000E-02	0.

The next set of cards described the energy absorber force-deflecting characteristics. A sample is shown below for EA=CFN (7.0).

7.	EA
0.	0.
10.00000E-03	6.20000E 03
3.90000E-01	6.20000E 03
4.00000E-01	4.50000E 03
1.40000E 00	5.30000E 03
5.00000E 00	5.30000E 03
5.00000E 01	5.30000E 03

The deck is completed by adding the parameter cards required. These are the variations to be run with one deck. For each set of parameter cards a complete set of data are computed and printed out.

The first parameter card identifies the weight of the man, the weight of the seat, the aircraft selected, the stroke length, the number of energy absorbers, and input reduction ratio. These are shown below.

W1	W2	AC
1.70000E 02	1.50000E 02	2.00000E 00
SL	NE	RA
5.00000E 01	1.00000E 00	1.00000E 00

The last card is the end of the file card and completes the deck.

AC	Aircraft control parameter. This is input to the program to select either the fighter, helicopter or transport acceleration input depending upon whether or not the value is 1, 2, or 3 respectively.
AF, AH, AT	Symbols identifying the acceleration data points for the fighter, helicopter, and transport.
DISP	The displacement of the absorber as long as the relative velocity is positive. The track and store operation causes DISP to track X6 until 1DX6 goes negative and stores that value. When 1DX6 goes positive again, DISP tracks until another velocity reversal. In this manner DISP always contains the initial conditions for displacement when the seat attempts to compress the absorber.
DRI	The Dynamic Response Index which is a measure of vertebral fracture.
EA	Symbol identifying the data points obtained from the energy absorber curve. The number in parenthese establishes the number of points to be used as input. (Force in pounds versus time in second.)
ENAB	Total force for all absorbers. (pounds)
ENAC	The force developed by one absorber at any time. (pounds)
FA, HA, TA	Symbols identifying the time function generated by the data points AF, AH, and AT
FOREA	Symbol establishes the relation between the energy absorber curve and calculated relative displacement.
FORED	The force the absorber develops as long as the relative velocity is positive. This duplicates the actions of DISP.
FORS	A stored force at the beginning of expansion or compression.
NE	Number of energy absorbers, also an input.
SL	Stroke limit is included as input (inches)
STR	The force developed by the structure at impact of the seat when the stroke limit is exceeded.
A1, A2, A3	Velocities of the fighter, helicopter, and transport aircraft respectively. These are used as the initial values of the integrators of the program.

C1	The damping factor of the 10 HZ man model (#/inch/sec.)
C3	The damping factor of the 8 HZ injury model (#/inch/sec.)
C6	Damping coefficient of structural element that is impacted when seat impacts. (#/inch/sec.)
DISC2	The displacement of the absorber as long as the relative velocity is negative. The track and store operation is reversed so that DIS2 will always contain the value of absorber displacement as the absorber attempts to elongate. This provides the initial conditions for absorber displacement during expansion.
FOR2	The value of the force in the energy absorber during expansion. The value is held during compression
K1	The stiffness of the 10 HZ man model (#/inch)
K3	The stiffness of the 8 HZ injury model (#/inch)
K6	Stiffness of structural element that is impacted when seat impacts after exceeding stroke limit. (#/inch)
K7	Relaxation stiffness of energy absorber. This can be an assumed equal to the initial stiffness of energy absorber force-displacement curve. (#/inch)
M1	The mass of the 10 HZ man model ($\#/inch/sec^2$)
M2	The mass of the seat ($\#/inch/sec^2$)
M3	The mass of the 8 HZ injury model ($\#/inch/sec^2$)
X6	Relative displacement across the energy absorber
2DX1, 1DX1, X1	The acceleration, velocity and displacement of the force model mass, M1.
2DX3, 1DX3, X3	The acceleration, velocity, and displacement of the injury model mass, M3.
2DX4, 1DX4, X4	The acceleration, velocity, and displacement of the crash input.
RA	Input Reduction Ratio

APPENDIX II

WAVEFORM LINEARIZATION

APPENDIX II - WAVEFORM LINEARIZATION

The input acceleration waveforms used in evaluating and optimizing energy absorbers were obtained from measured data taken during controlled crashes of actual aircraft. The waveforms actually measured, however, were complex in nature containing "structural ringing" and other high frequency "hash" and it was necessary to modify the measured data so that the pulses could be handled easier. The data reduction method used is described below as it was applied to crash data measured on a transport. The same technique was also used on fighter and helicopter data.

Particular curves are available for 6-degree and 20-degree impacts of a Lockheed L-1649 Transport and for an 8-degree and 20-degree impact of a Douglas DC-7 Transport. Let us examine the 8-degree impact for the DC-7 Transport. The measured data are shown with an approximate mean drawn through it. How can we realistically develop an acceleration profile from this that can be used? Should we duplicate this curve and establish it as a criteria? To do so would require users to be able to handle complex waveforms. Or is it possible to approximate the waveform and feel assured that the approximation will provide accurate data?

The most approximate "wave analysis" is simply to record the time of "peak" and "valley " accelerations and note their magnitudes. If this is done from 0.65 seconds to 0.80 seconds, the mean time between peak and valley is 0.010 seconds.

The oscillation modulating the "basic" pulse is therefore a 50 HZ vibration. The acceleration essentially passes through a rigid energy absorber and acts upon the man. The man acts as a 10 HZ acceleration is attenuated 28 db or by a factor of 0.04. The mean magnitude of the acceleration is about 12 g. Therefore, the man model would respond by generating 0.48 g, approximately 2.5 per cent of the basic acceleration.

The modulating accelerations were approximately 50 HZ with an amplitude of 12 g. By subtracting this from the peaks and adding to the valleys, a new curve was generated with a peak at 0.73 seconds. A line was drawn through the points and a symmetrical waveform generated. From the plot it is apparent that this does not agree with the rate of onset or rate decay as well as could be hoped for. By extending the waveform a better approximation of the rate of onset can be achieved. The result is a 22 g symmetrical, triangular pulse. The complete description for this case is then,

Peak g	22
Time Duration	200 milleseconds
Velocity Change	71 feet per second
Rate of Onset	220 g/second
Rate of Decay	220 g/second

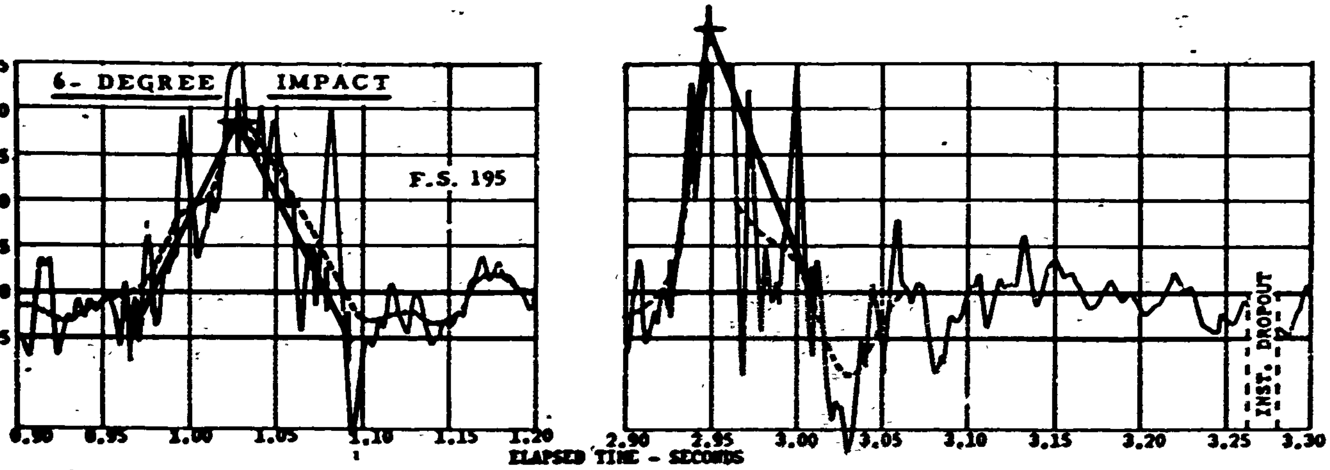
These are representative of the 8-degree impact for a DC-7.

A similar approach was taken for the 20-degree impact. In this case the modulation is not as distinct and it appears that the best approximation to fit the complete pulse is to represent it by a skewed triangle.

Similar results for the L-1649 Transport are shown below,

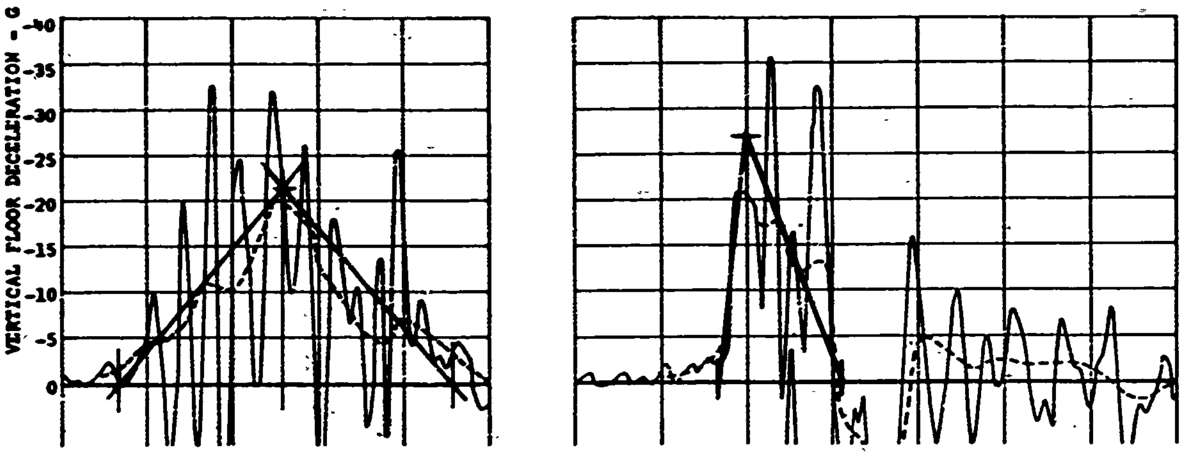
	6 Degree	20 Degree
Peak g	23	30
Pulse Duration	110 milleseconds	85 milleseconds
Velocity Change	40.7 feet/second	41.1 feet/second
Rate of Onset	536 g/second	1650 g/second
Rate of Decay	343 g/second	450 g/second

These four triangle pulses are shown graphically in Figure II-1.



Vertical G Values in a 6-Degree and 20-Degree Impact - Lockheed L-1649 Transport.

——— APPROXIMATING WAVEFORMS

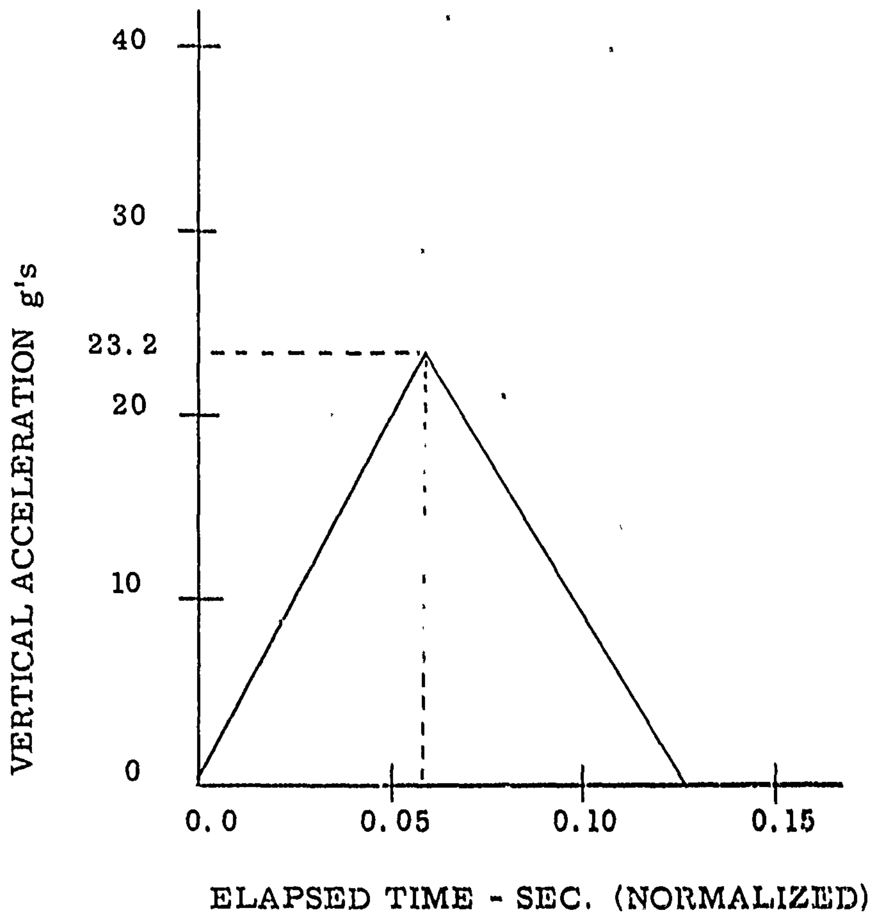


Longitudinal and Vertical G Values in an 8-Degree and 20-Degree Impact - Douglas DC-7 Transport.

FIGURE II-1 INPUT ACCELERATION PULSES

APPENDIX III

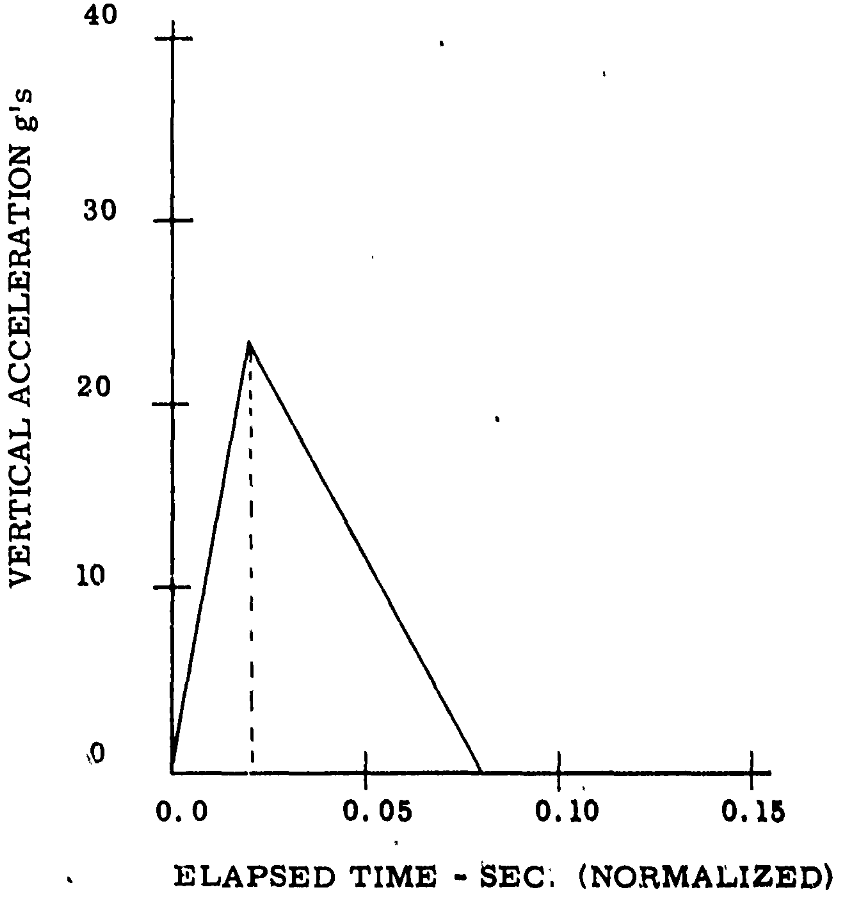
CRASH ACCELERATION WAVEFORMS



ACFT - TRANSPORT

REF - USAAVLABS TR 67-16

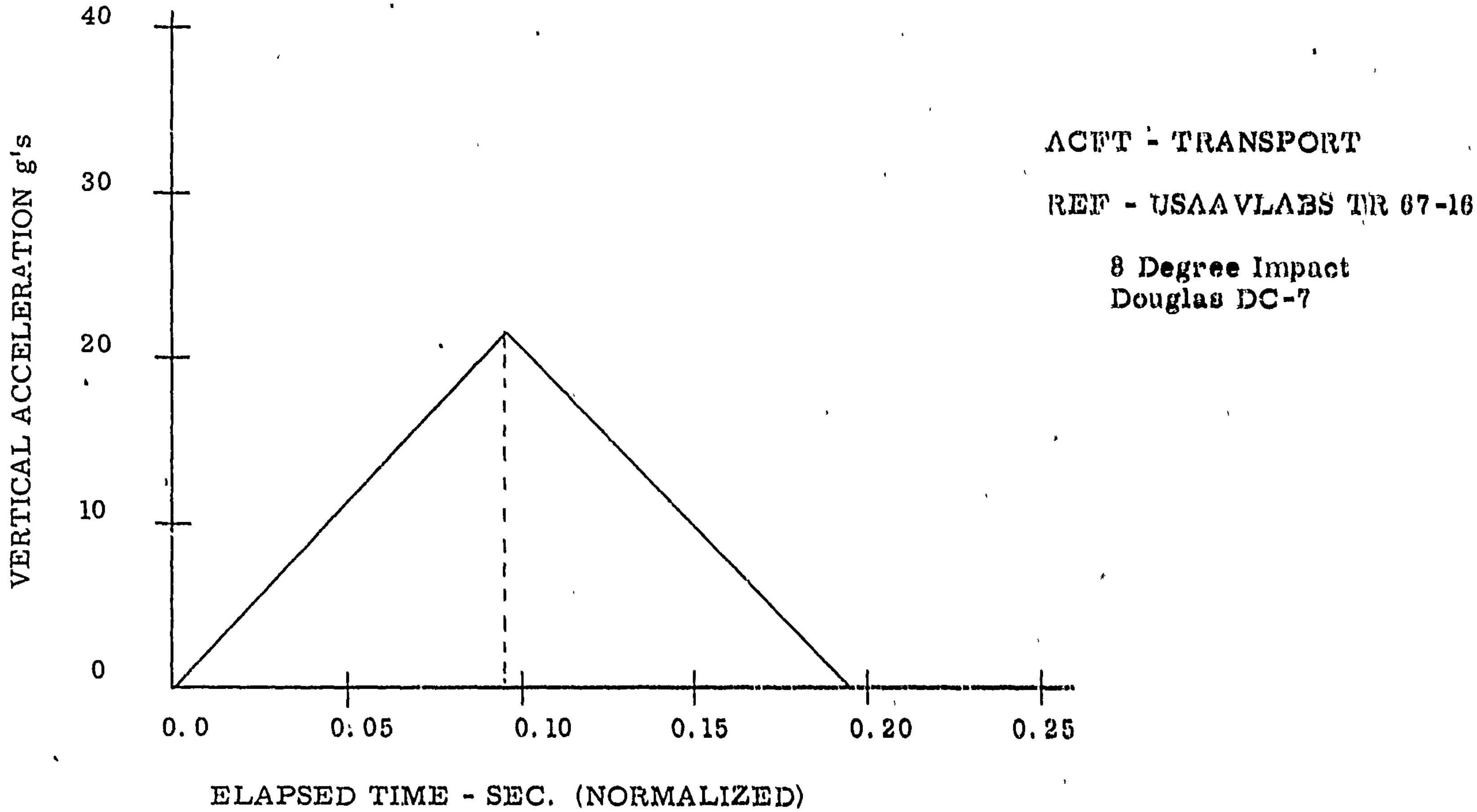
6 Degree Impact
Lockheed L-1649

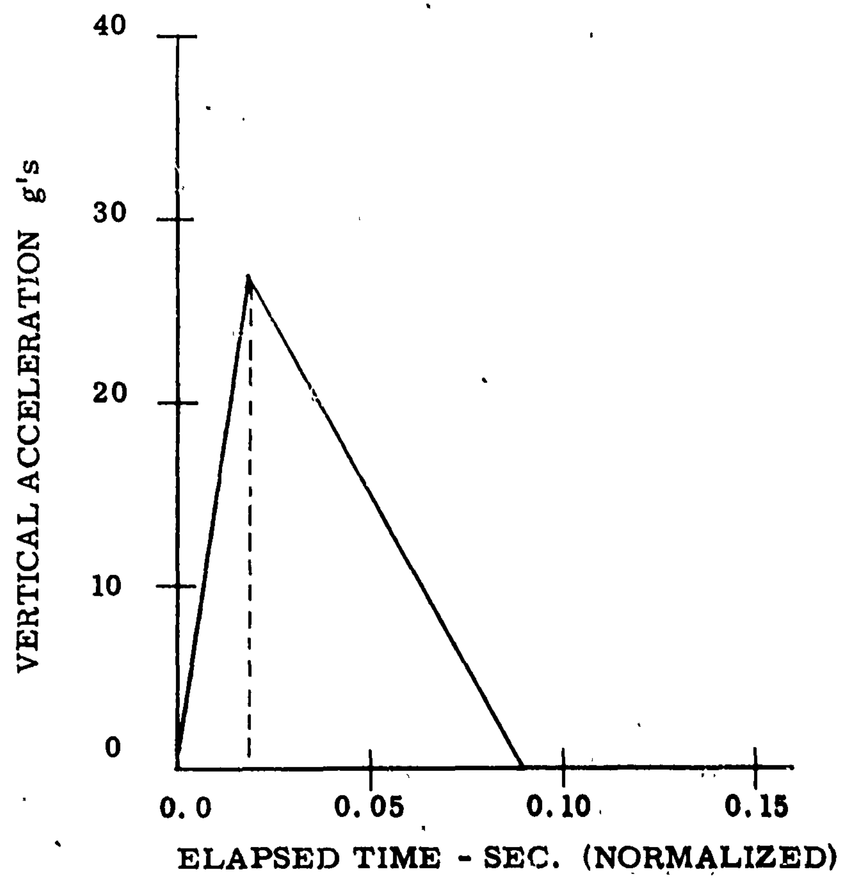


ACFT - TRANSPORT

REF - USAAVLABS TR 67-16

20 Degree Impact
Lockheed L-1649

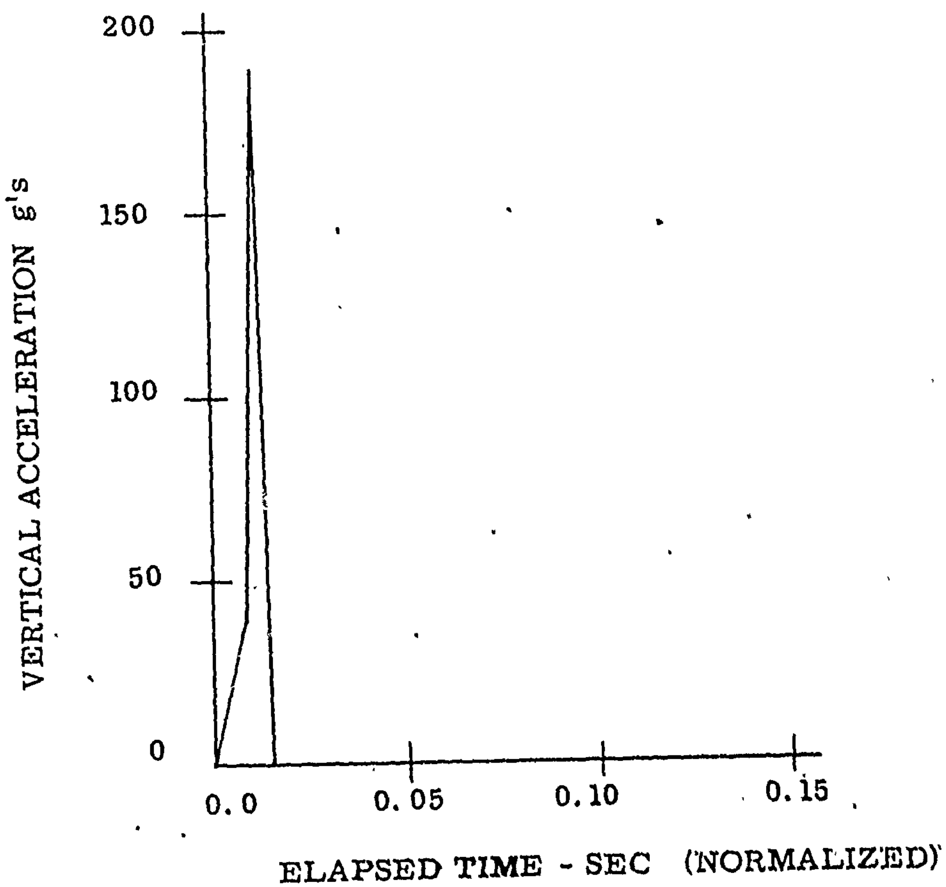

ACFT - TRANSPORT
REF - USAAVLABS TR 67-16
8 Degree Impact
Douglas DC-7
VERTICAL ACCELERATION g's
40
30
20
10
0
0.0
0.05
0.10
0.15
0.20
0.25
ELAPSED TIME - SEC. (NORMALIZED)



ACFT - TRANSPORT

REF - USAAVLABS TR 67-16

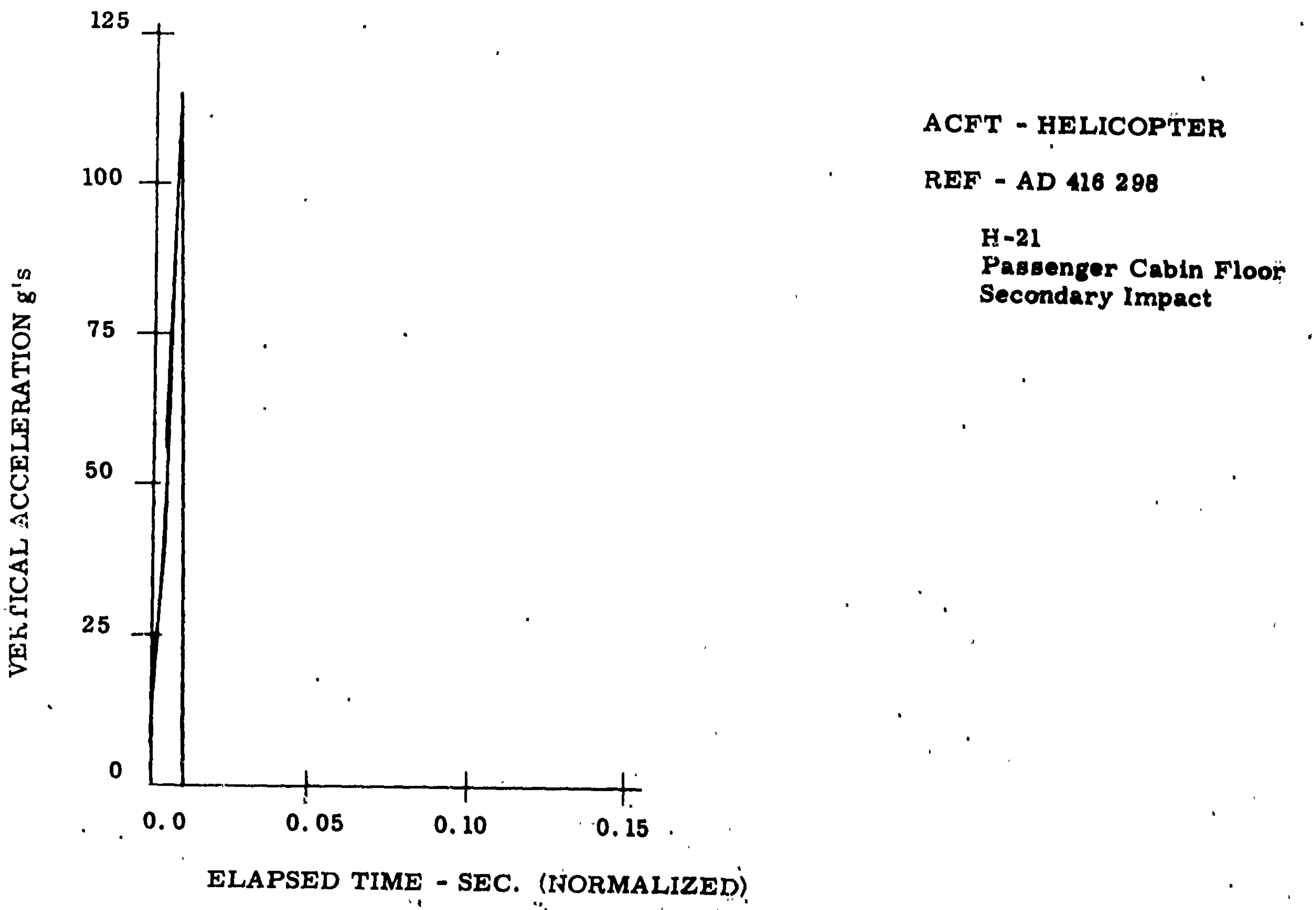
20 Degree Impact
Douglas DC-7

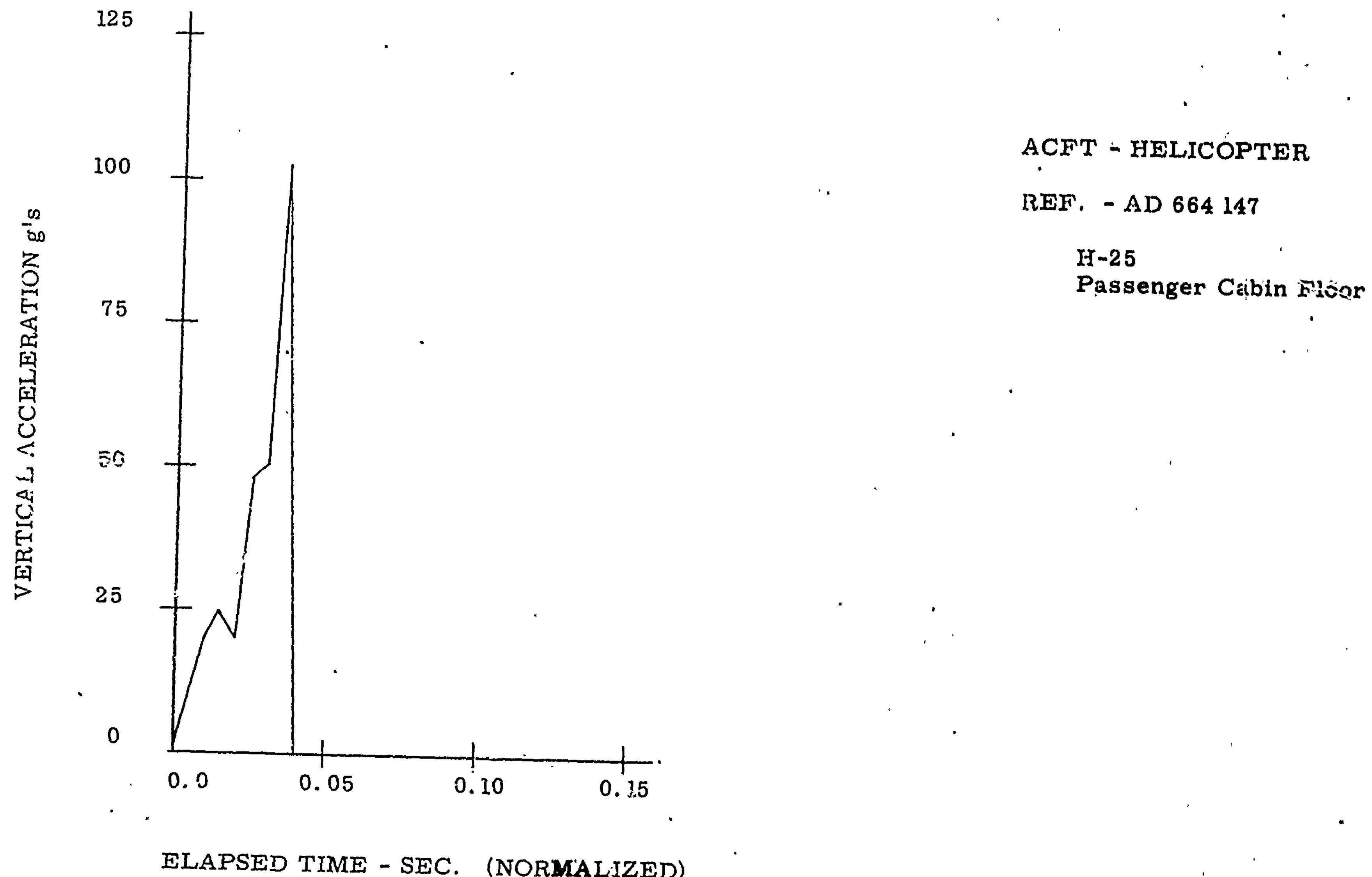


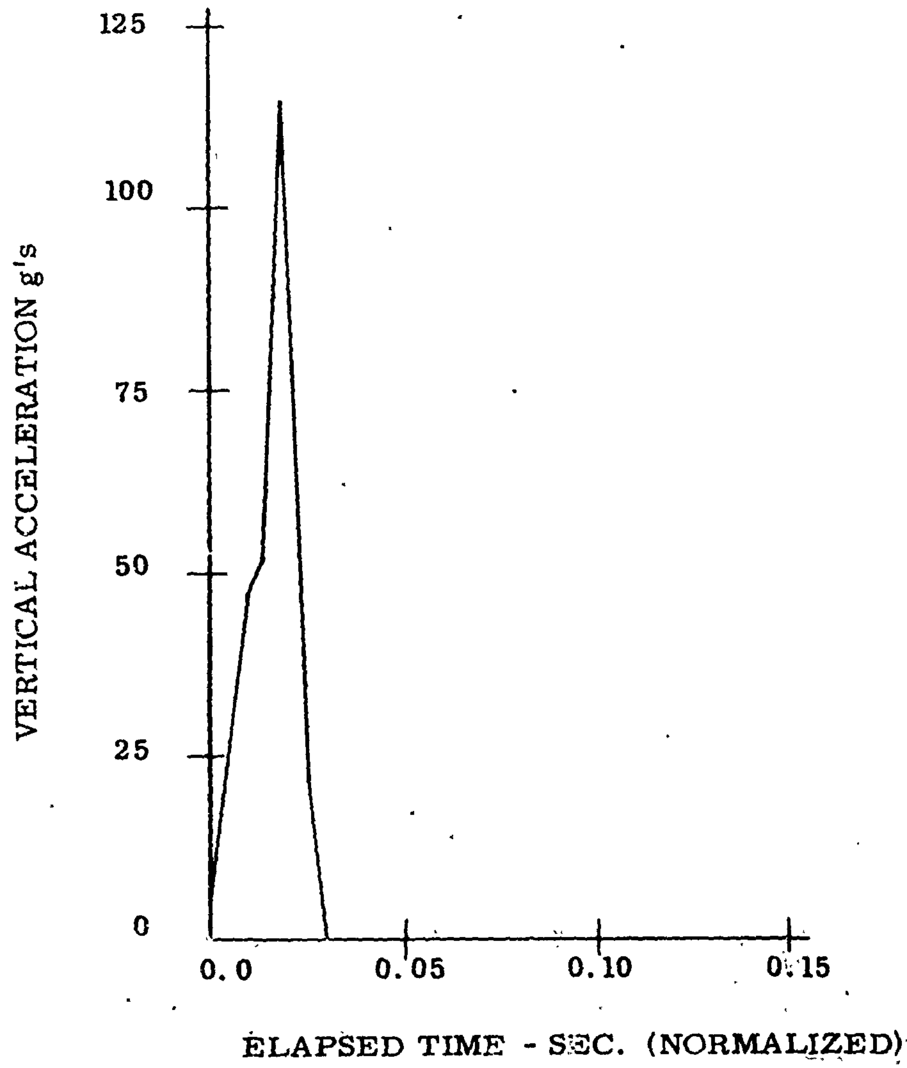
ACFT - HELICOPTER

REF - AD 416 298

H-21
Passenger Cabin Floor
Primary Impact


125
100
75
50
25
0
VERTICAL ACCELERATION g's
0.0
0.05
0.10
0.15
ELAPSED TIME - SEC. (NORMALIZED)
ACFT - HELICOPTER
REF - AD 416 298
H-21
Passenger Cabin Floor
Secondary Impact

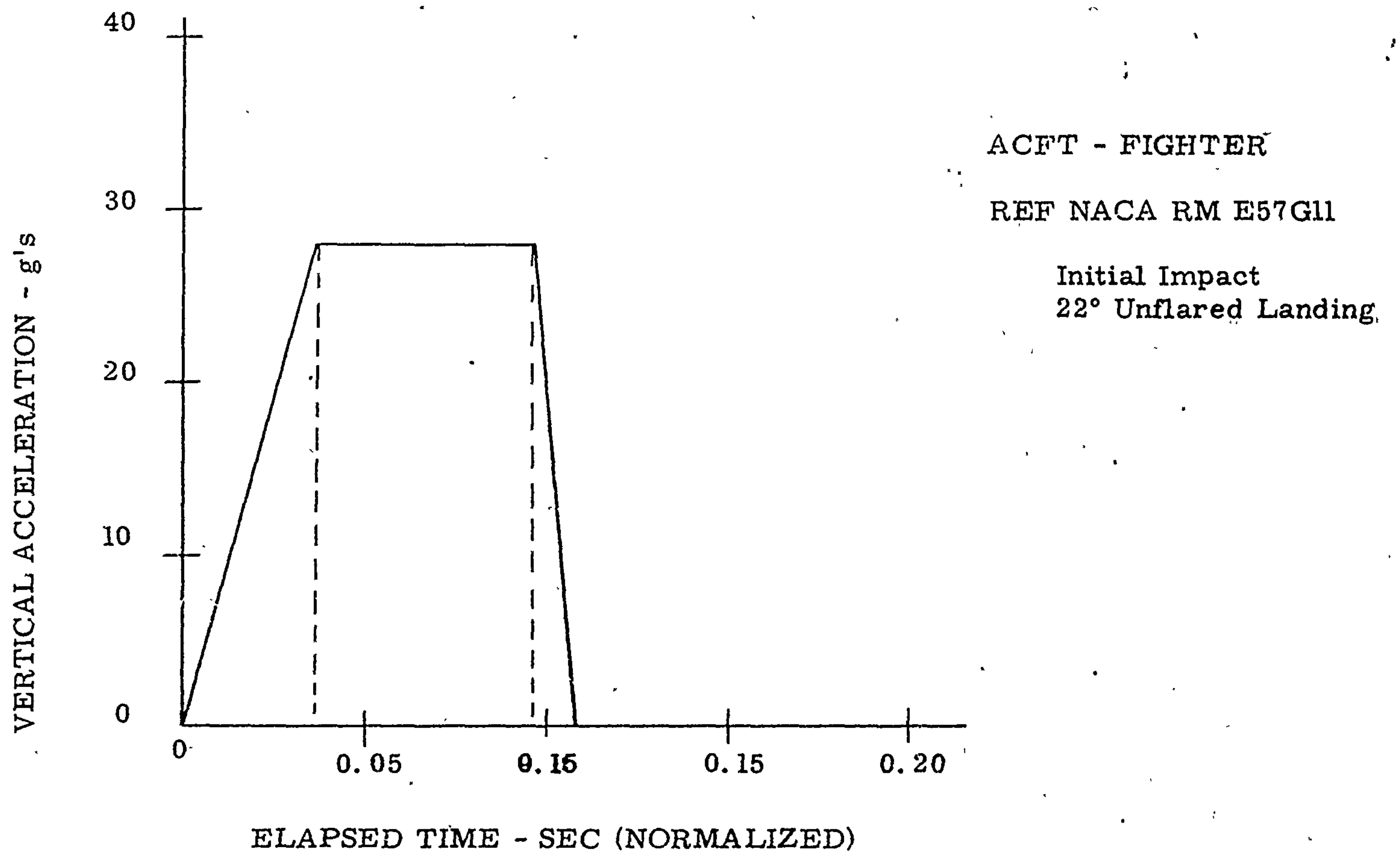

VERTICAL ACCELERATION g's
125
100
75
50
25
0
0.0
0.05
0.10
0.15
ELAPSED TIME - SEC. (NORMALIZED)
ACFT - HELICOPTER
REF. - AD 664 147
H-25
Passenger Cabin Floor



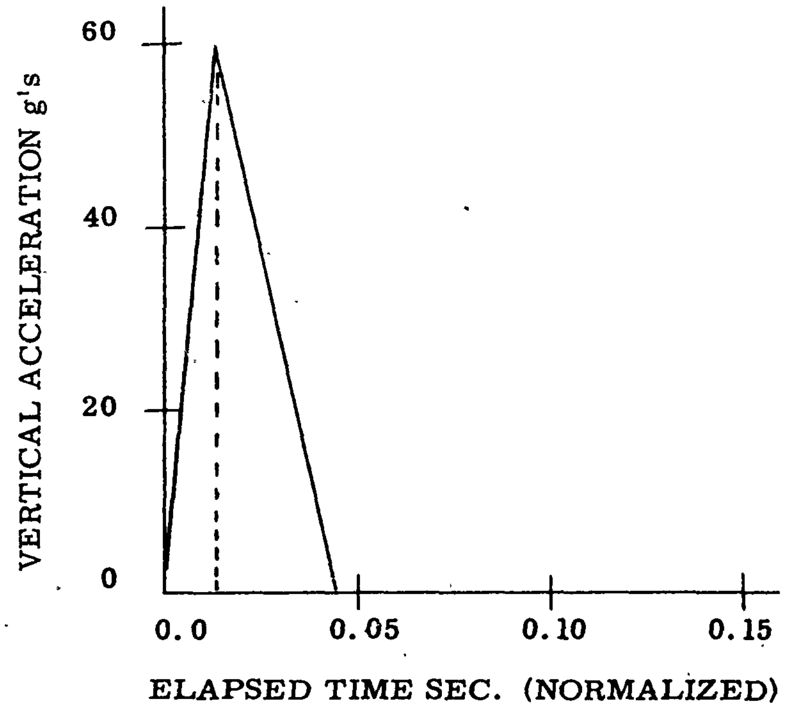
ACFT - HELICOPTER

REF. AD 664 147

H-25
Cockpit Cabin Floor



VERTICAL ACCELERATION - g's
40
30
20
10
0
0
0.05
0.15
0.15
0.20
ELAPSED TIME - SEC (NORMALIZED)
ACFT - FIGHTER
REF NACA RM E57G11
Initial Impact
22° Unflared Landing



ACFT - FIGHTER

REF - NACA RM E57G11

2nd Impact
22° Unflared Landing

APPENDIX IV

ENERGY ABSORBER CHARACTERISTIC CURVES

APPENDIX IV ENERGY ABSORBER CHARACTERISTIC CURVES

Records of nine existing energy absorbers previously tested by ACED were evaluated and formatted for use in the computer program. The records supplied contained input acceleration profiles and force-acceleration-time profiles of the energy absorbers response, generated from experiments in which energy absorbers supported dead weights during impact. However, if energy were to be analytically included into the computer program, the characteristic force-deflection curve is required. The method used to find this characteristic curve for one particular energy absorber is described in the following paragraphs and this technique was used repeatedly to find the force-deflection curves of the other devices, which are shown in Figures IV-6 thru IV-14.

The Boeing-Vertol Load Limiter Strut is a device that attenuates energy by forcing a pre-cut tube over a mandrel and causing the cut sections to curl up along the side of the tube. Three tests were conducted on the device. This data, as well as static and dynamic force-displacement curves, made it a logical first attempt to use the test information. The tests consisted of three drops. The first two bottomed out and generated large overshoots in the load cell. The third resulted in a smooth response for all three data channels and was selected for analysis.

The physical set-up of the test was such that accelerometers measured the input acceleration of the cart above the load cell and the output acceleration at a dead weight directly below the energy absorber. If we assume that the stiffness of all elements between the accelerometers are large in relation to the stiffness of the energy absorber, then the two provide a means of evaluating the relative accelerations across the absorbers.

Overlays were made of the two accelerations and the platform acceleration scaled up to that of the dead weight (Figure IV-1). The difference between the two was found (Figure IV-2) and integrated twice (Figure IV-3). With the displacement versus time and the measured force versus time, a crossplot was made to construct the force-displacement curve of the absorber (Figure IV-4). The displacement calculated was found to be 3.28 inches as compared with the 3.5 inches mentioned in the test discussions.

The force-displacement curve constructed matches very well with the measured curve of dynamic force-displacement found for Boeing test number 2. The correlation between the two indicated that the one curve is a reasonable representation of the dynamic force-displacement curve for the Boeing E/A Strut.

A comparison of the dynamic curve with the static curve (Figure IV-5) indicates that there is a significant difference in the two. We could use the dynamic curve as available for all environments. However, the fact that the static and dynamic do differ is sufficient to indicate that this area should be further pursued. At present we assume that the dynamic force-deflection curve is valid for the environments to be investigated since the peak g and waveform are approximately representative of the of the crash accelerations being examined.

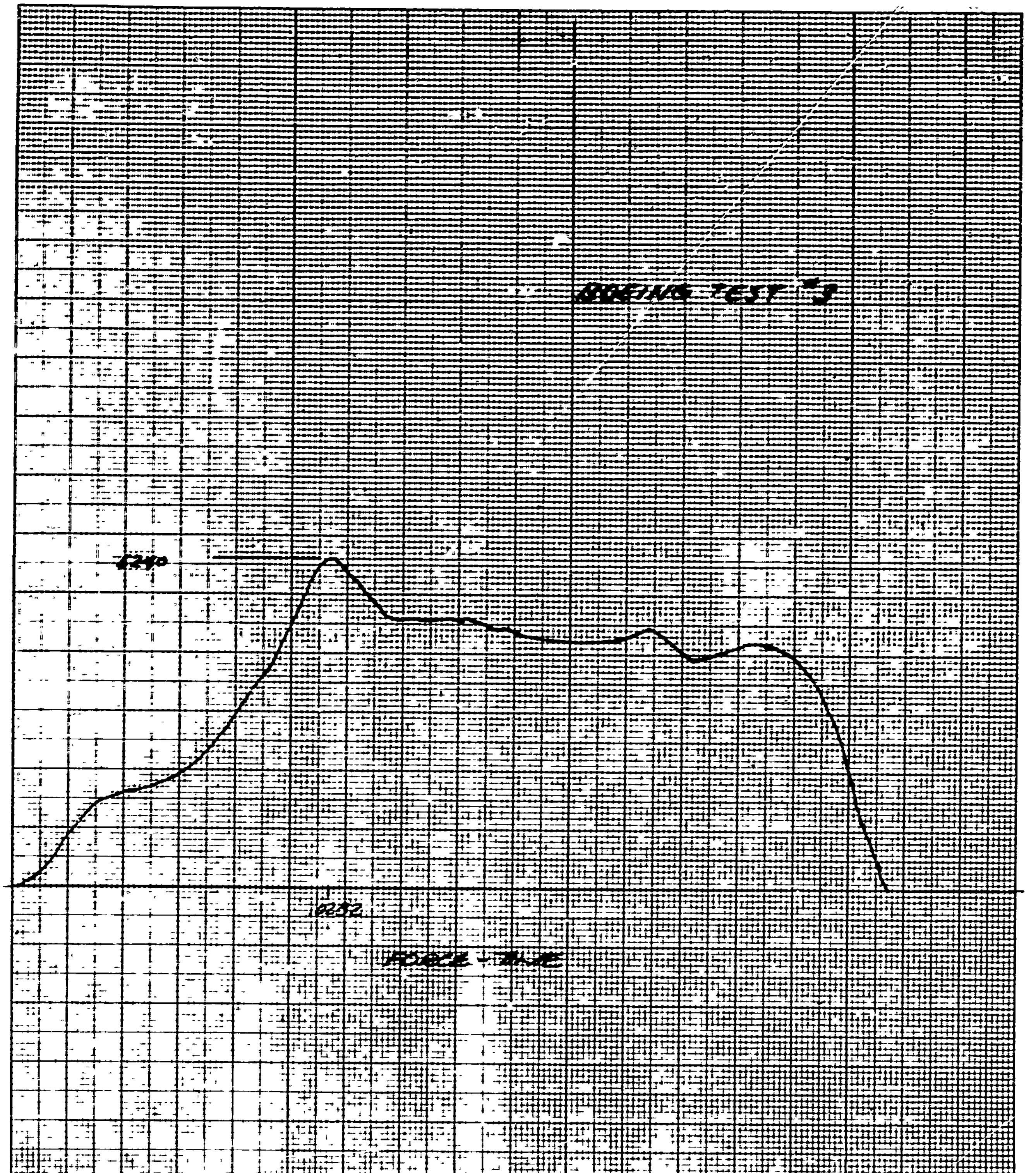
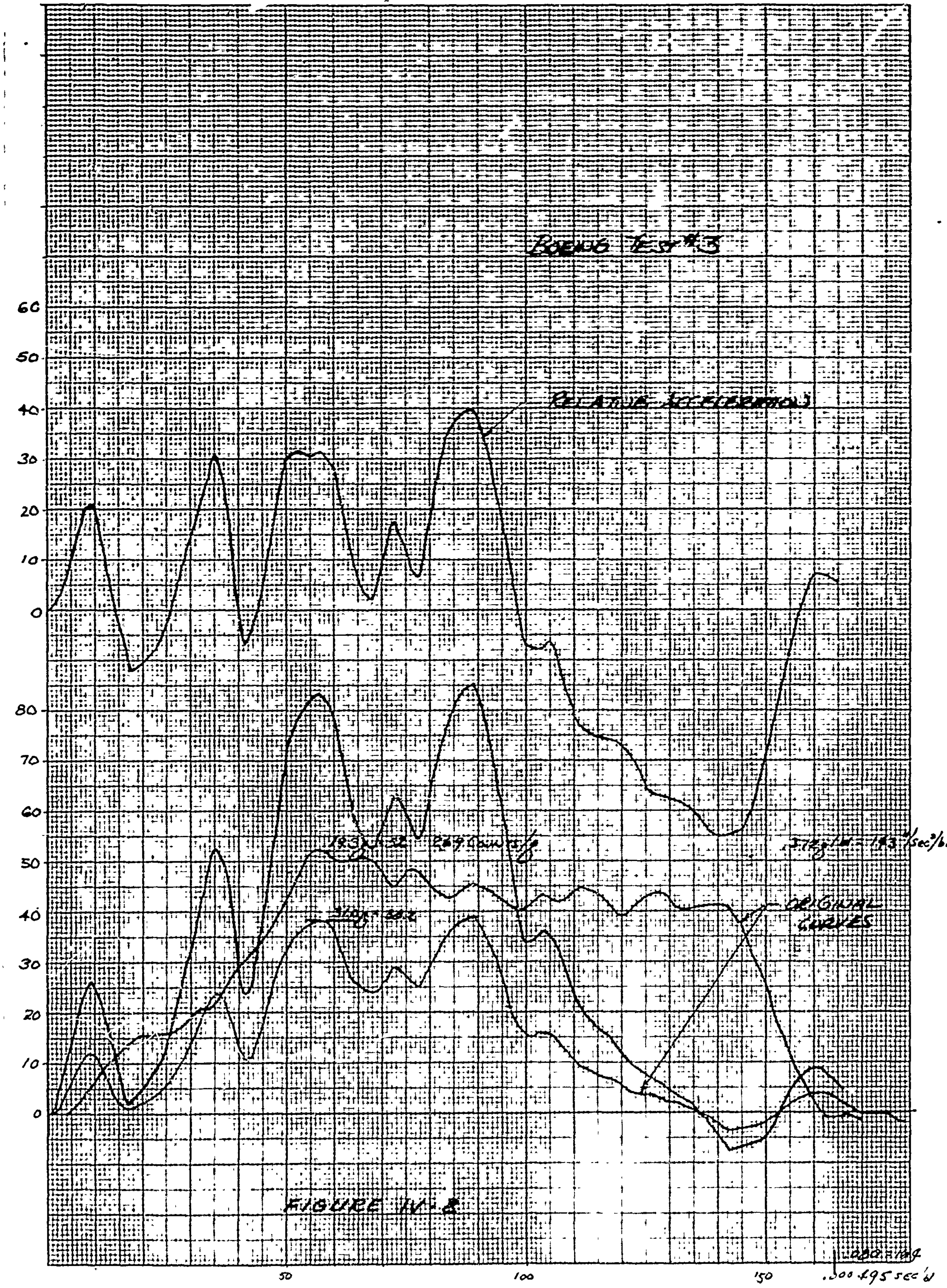


FIGURE IV-1



BOEING TEST #3
RELATIVE ACCELERATION
ORIGINAL
CURVES
60
50
40
30
20
10
0
80
70
60
50
40
30
20
10
0
50
100
150

FIGURE IV-8

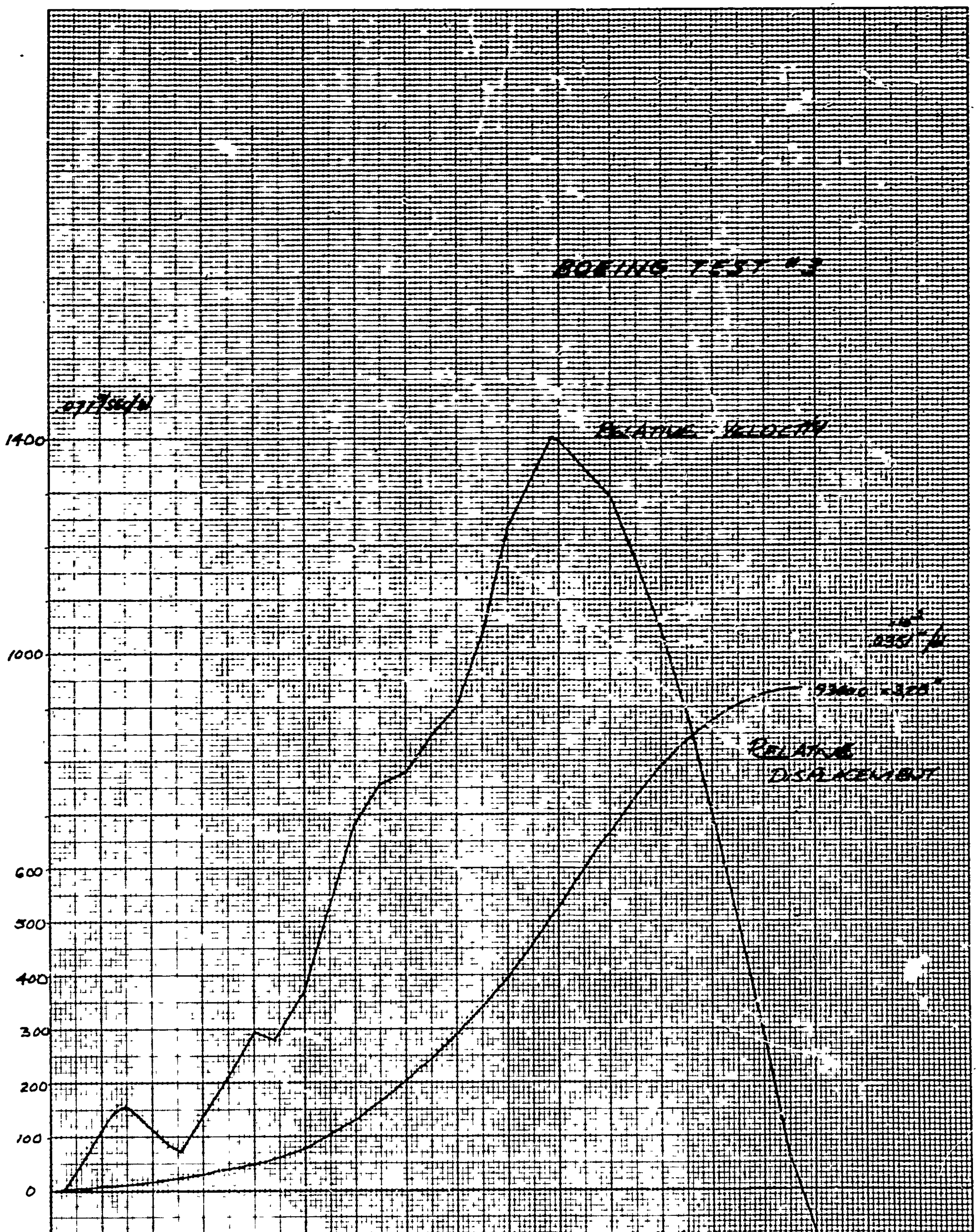

BOEING TEST #3
RELATIVE VELOCITY
RELATIVE DISPLACEMENT
1400
1000
600
500
400
300
200
100
0

FIGURE IV-3

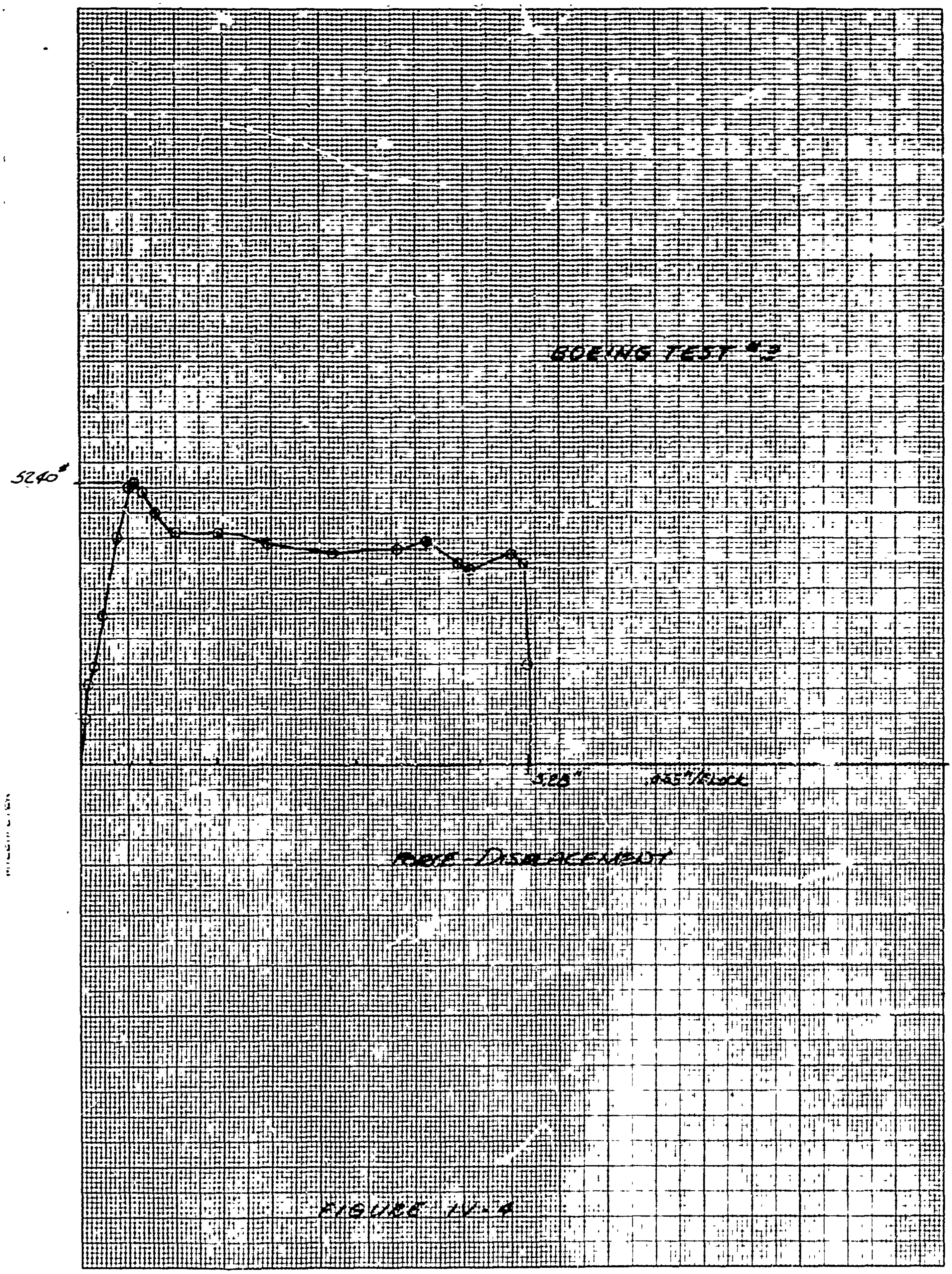


FIGURE IV-4

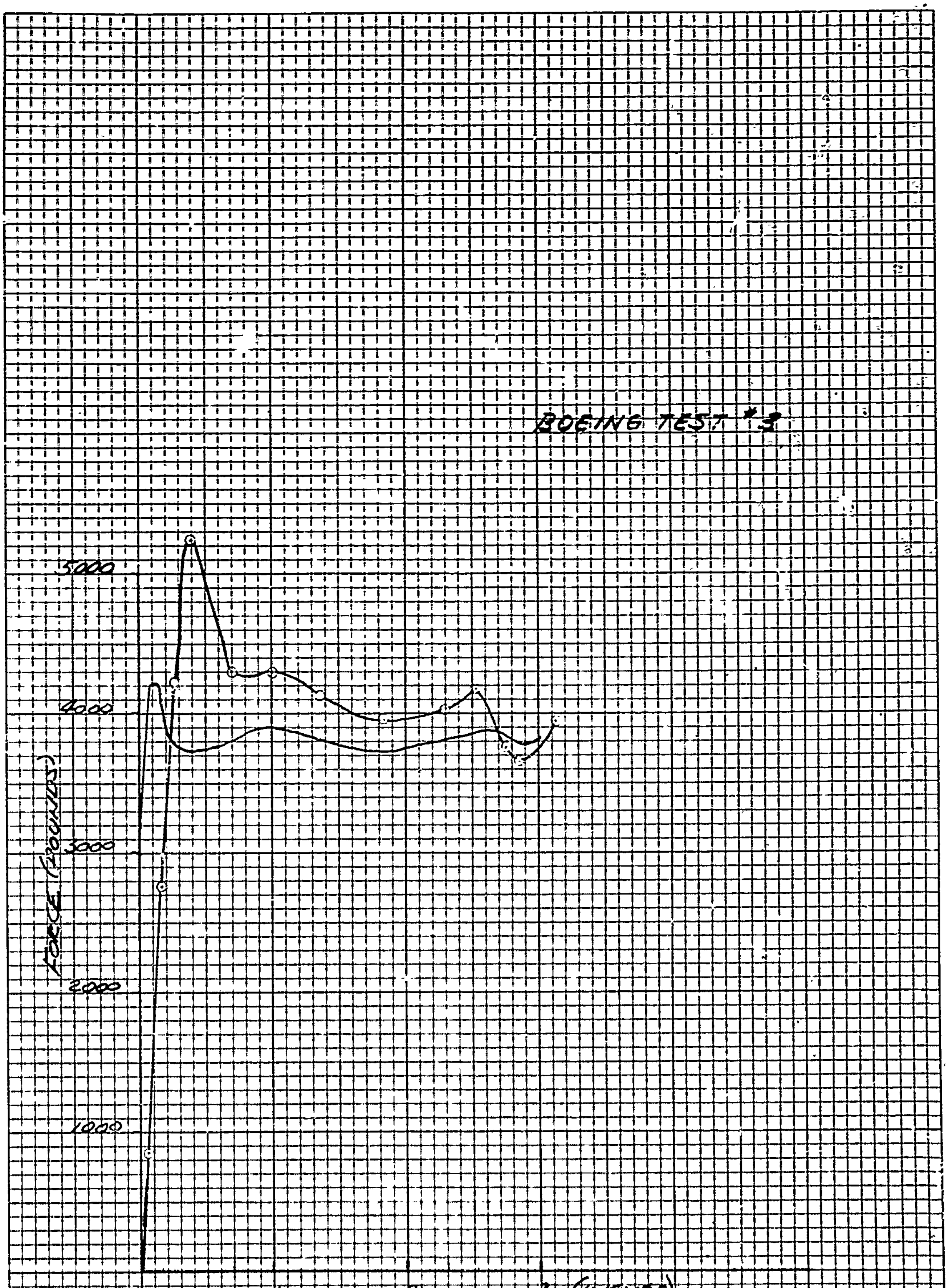

BOEING TEST #3
5000
4000
3000
2000
1000
FORCE (POUNDS)
0
1
2
3 (INCHES)

FIGURE IV-5

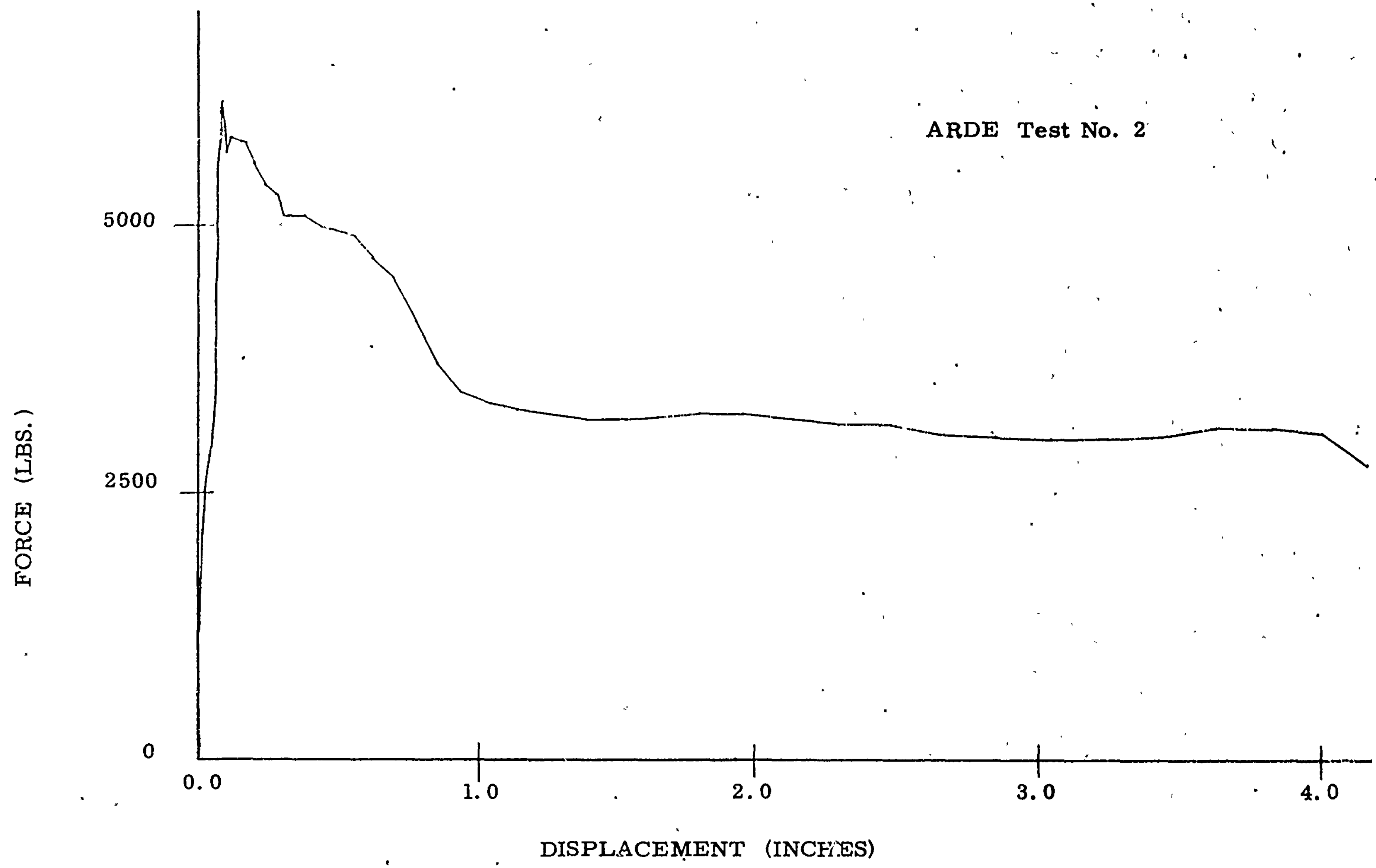

ARDE Test No. 2
FORCE (LBS.)
5000
2500
0
0.0
1.0
2.0
3.0
4.0
DISPLACEMENT (INCHES)

FIGURE IV-6

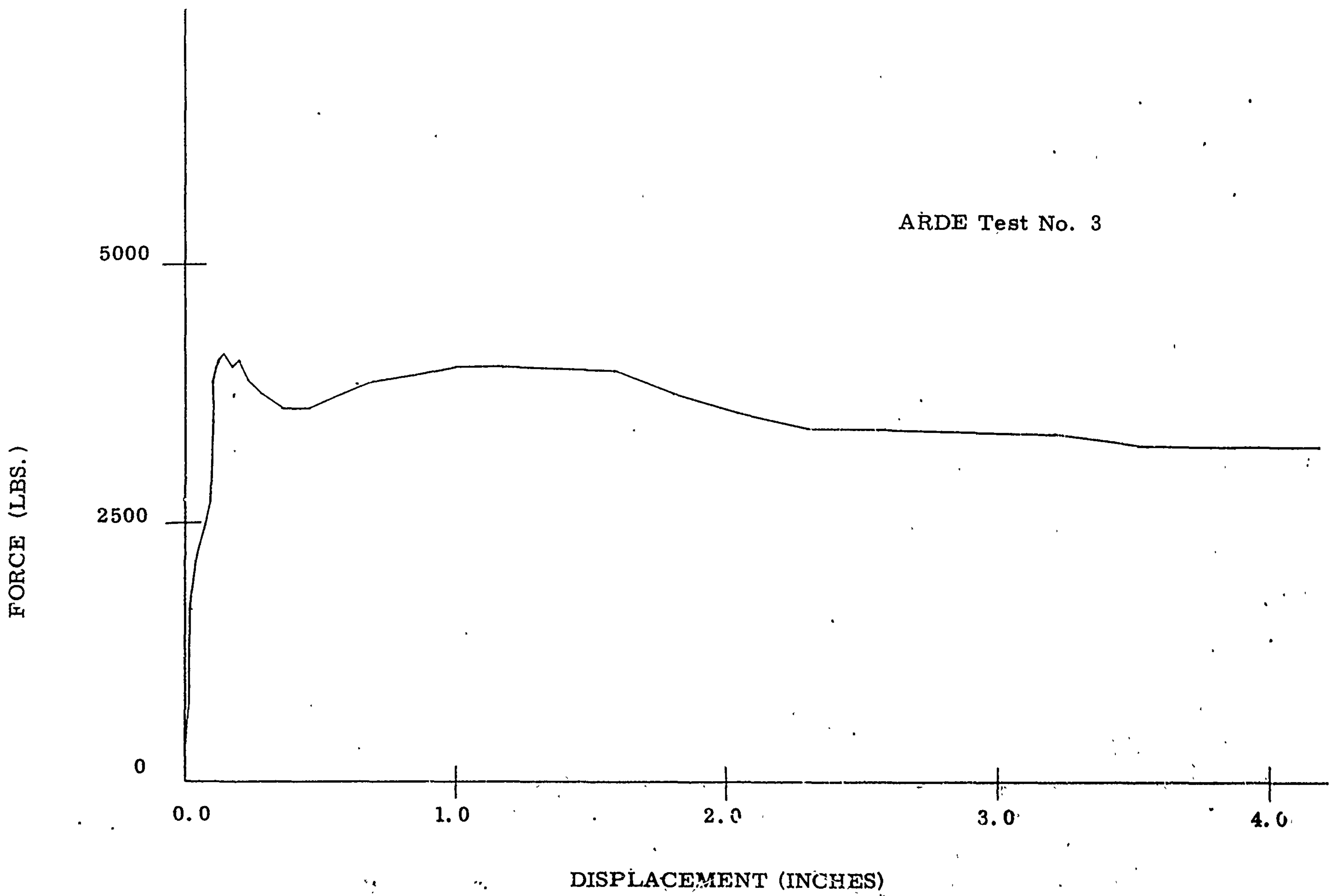

ARDE Test No. 3
5000
2500
0
FORCE (LBS.)
0.0
1.0
2.0
3.0
4.0
DISPLACEMENT (INCHES)

FIGURE IV - 7

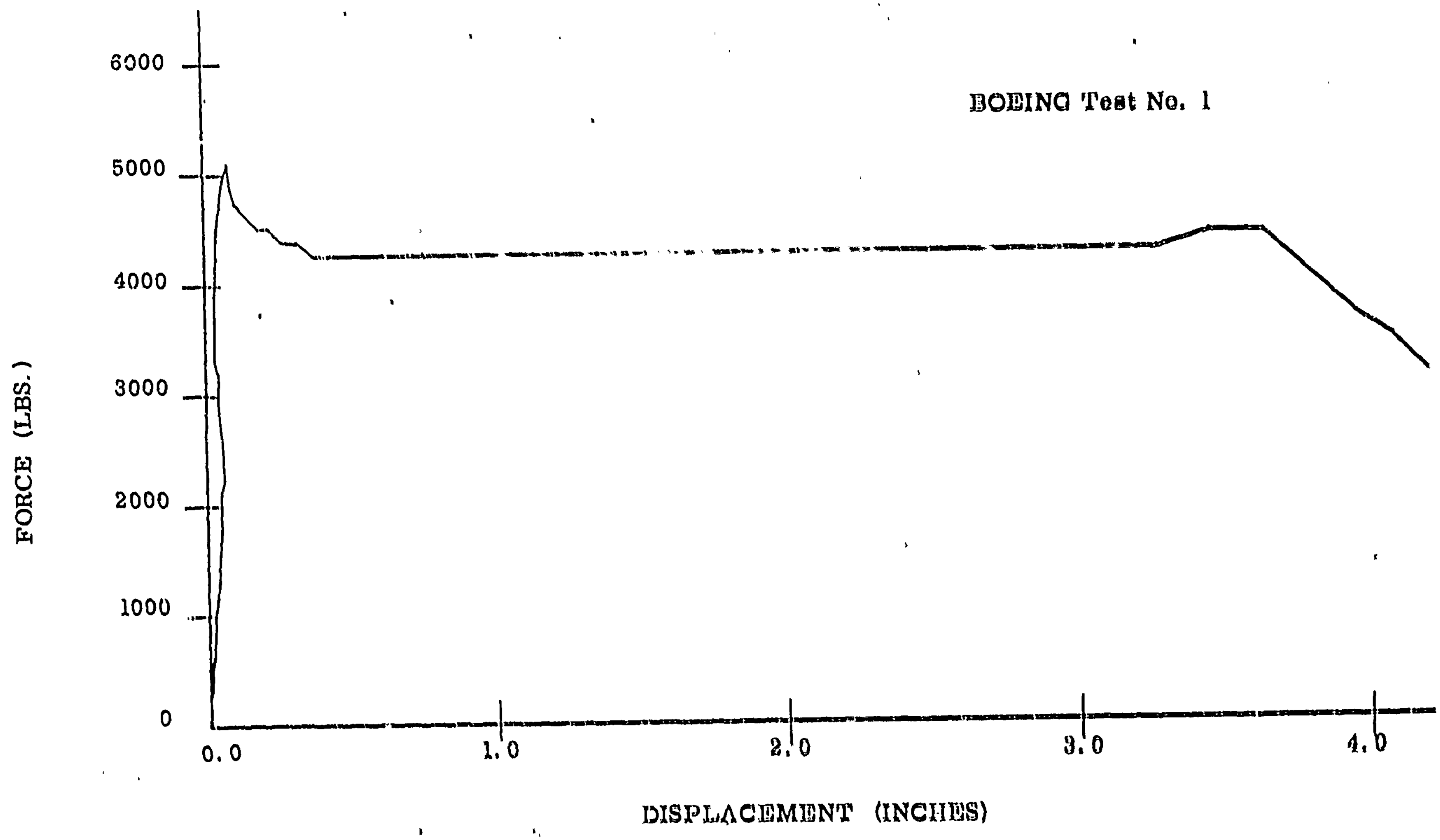
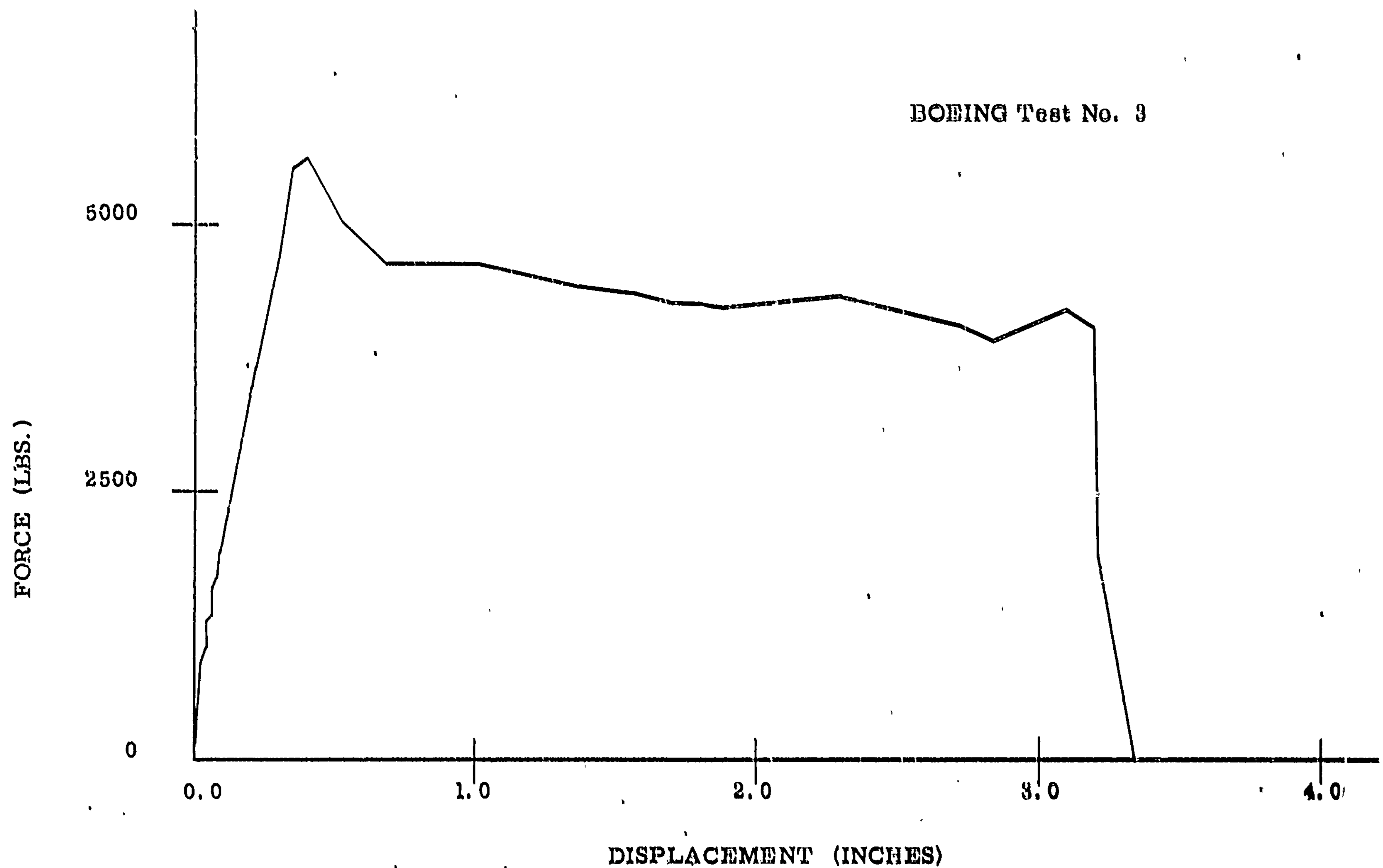

BOEING Test No. 1
FORCE (LBS.)
6000
5000
4000
3000
2000
1000
0
0.0
1.0
2.0
3.0
4.0
DISPLACEMENT (INCHES)

FIGURE IV - 8



BOEING Test No. 3
5000
2500
0
FORCE (LBS.)
0.0
1.0
2.0
3.0
4.0
DISPLACEMENT (INCHES)

FIGURE IV - 9

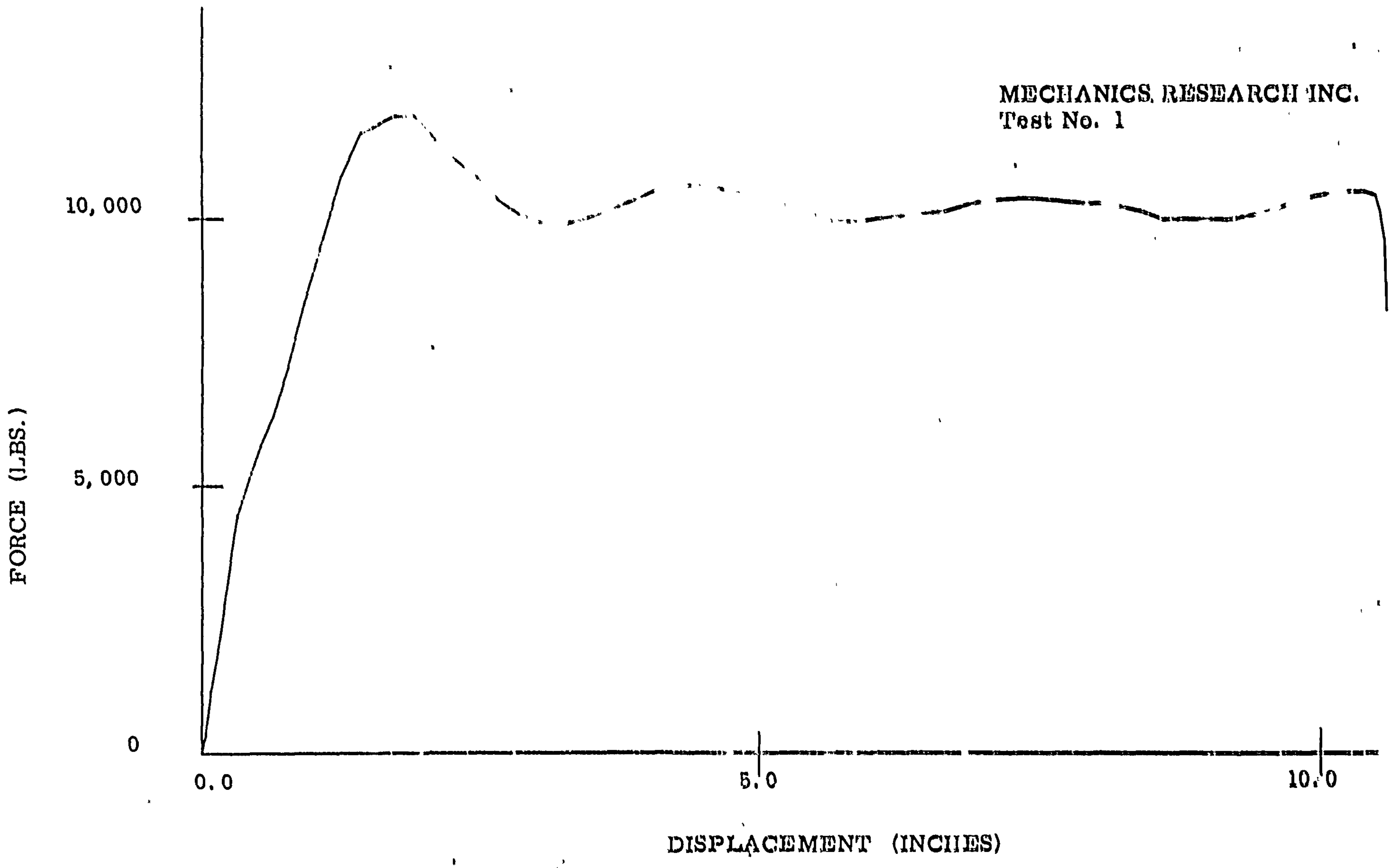

MECHANICS RESEARCH INC.
Test No. 1
FORCE (LBS.)
10,000
5,000
0
0.0
5.0
10.0
DISPLACEMENT (INCHES)

FIGURE IV - 10

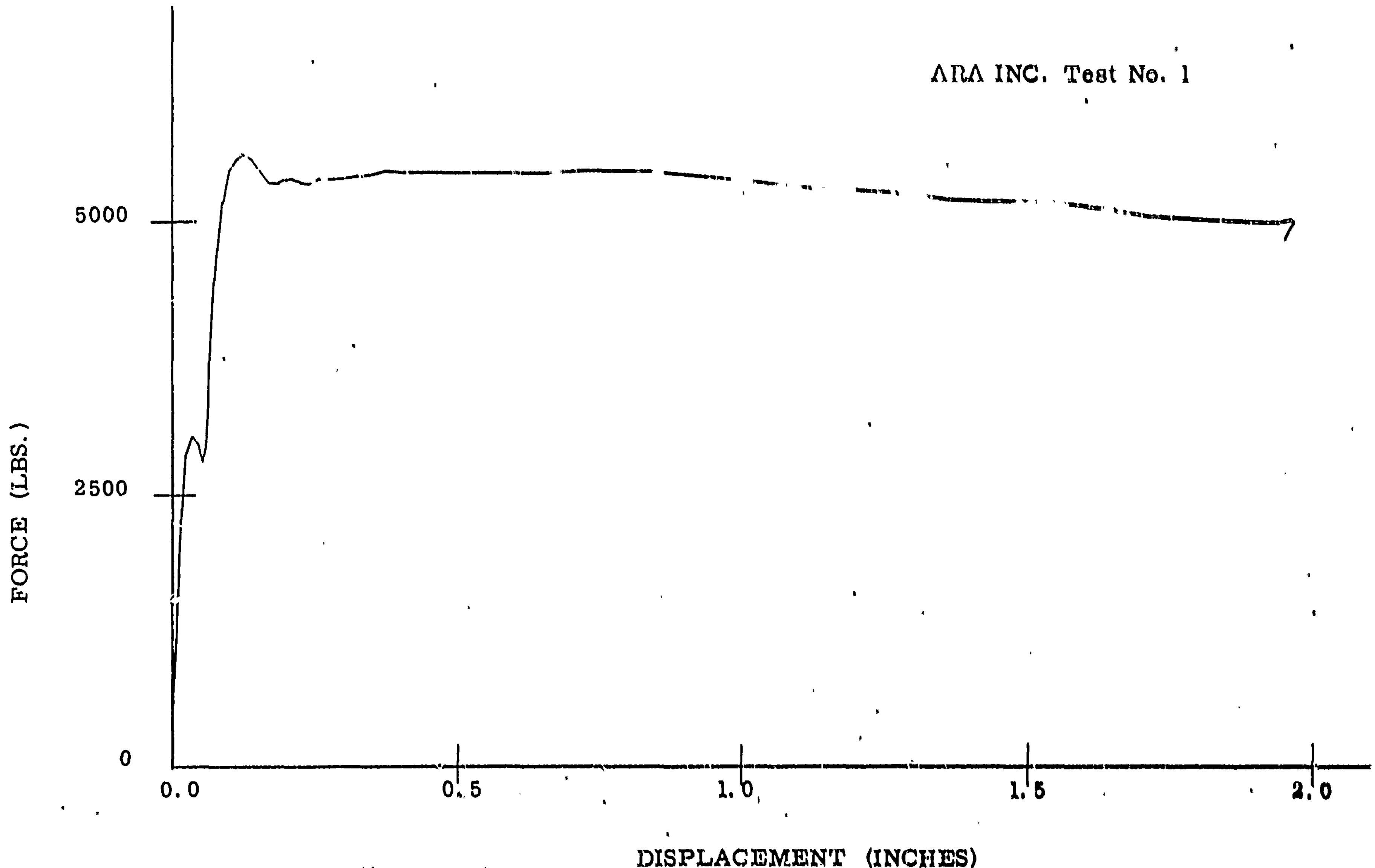

ARA INC. Test No. 1
5000
2500
0
FORCE (LBS.)
0.0
0.5
1.0
1.5
2.0
DISPLACEMENT (INCHES)

FIGURE IV - 11

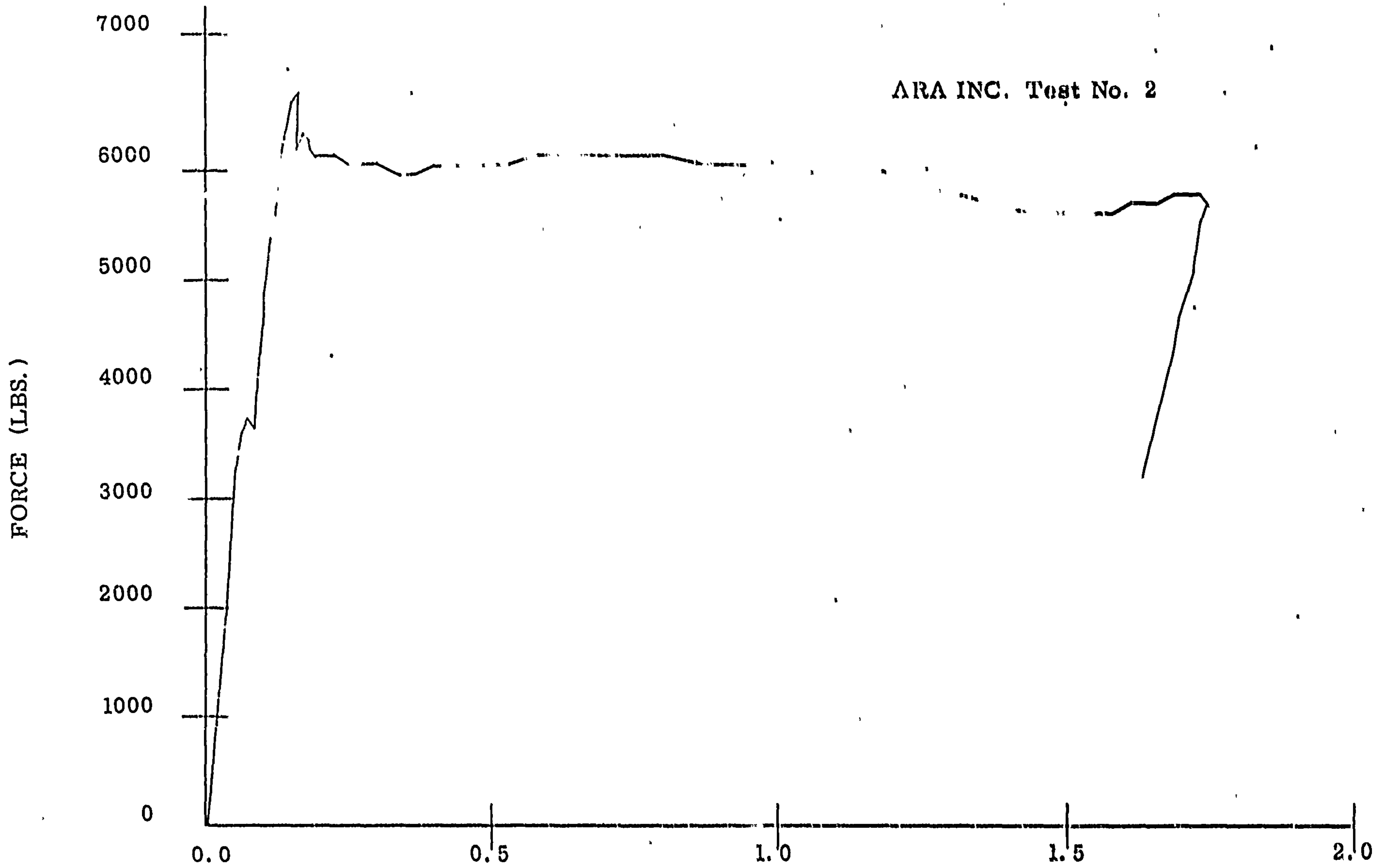

ARA INC. Test No. 2
7000
6000
5000
4000
3000
2000
1000
0
FORCE (LBS.)
0.0
0.5
1.0
1.5
2.0
DISPLACEMENT (INCHES)

FIGURE IV - 12

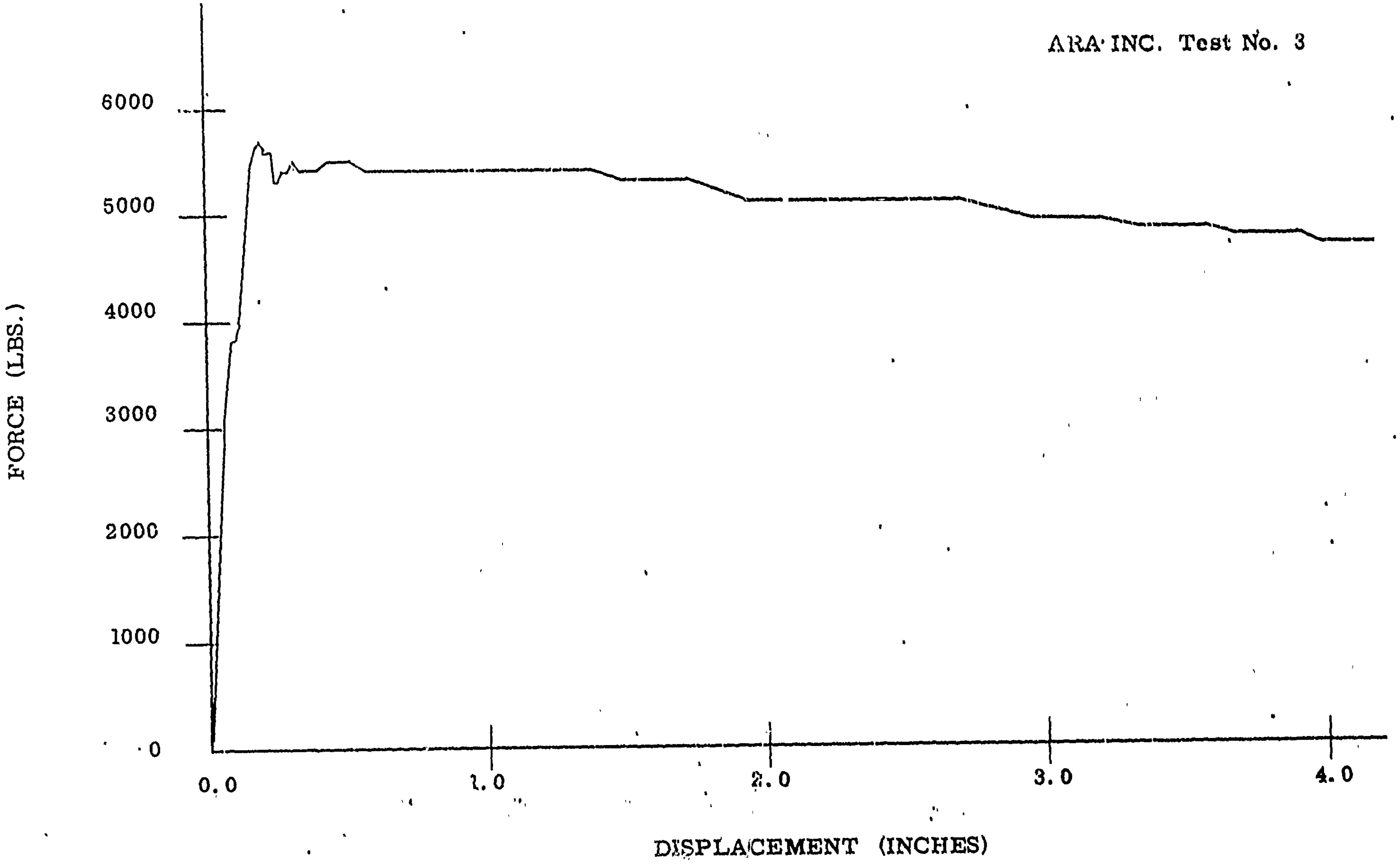
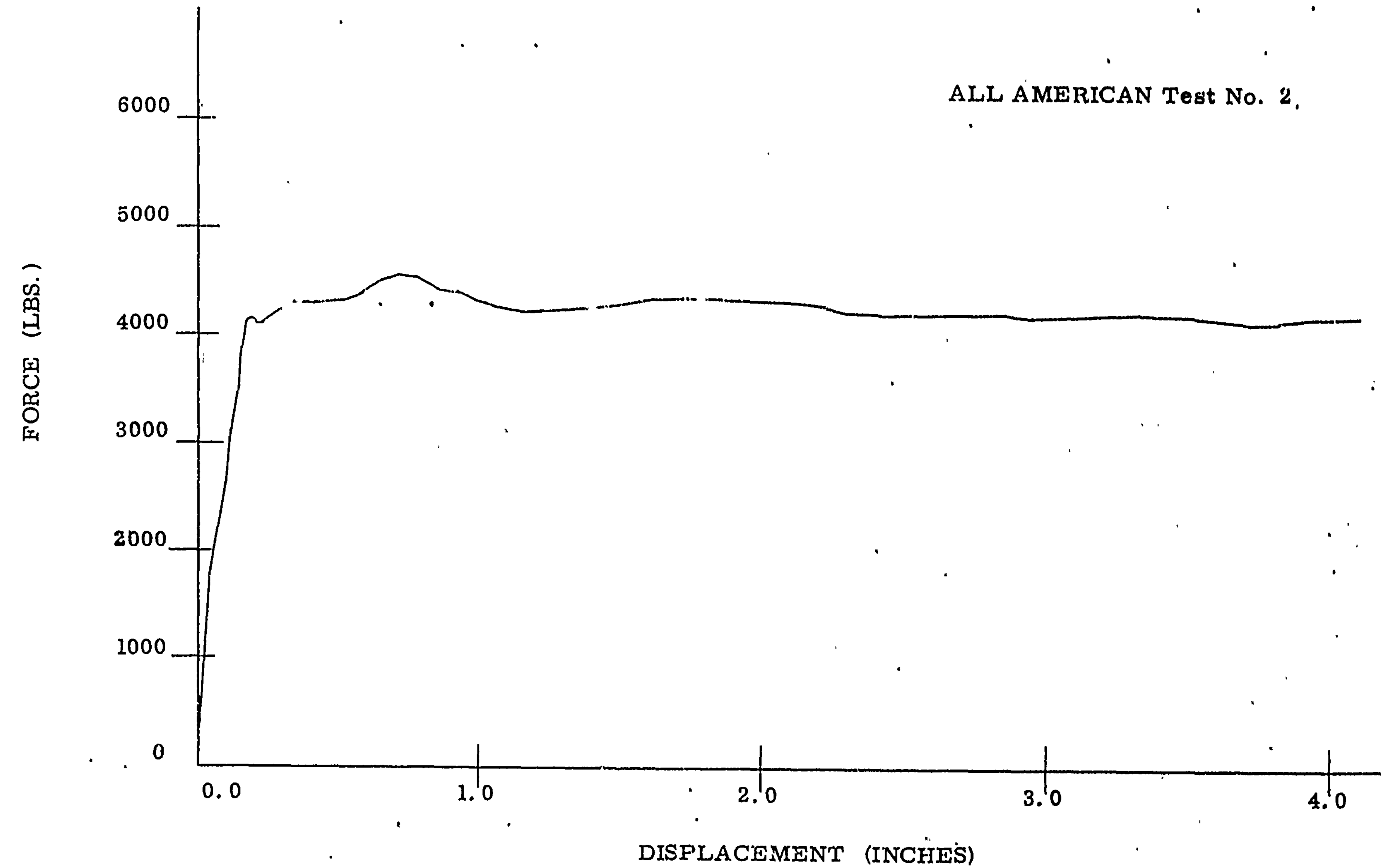
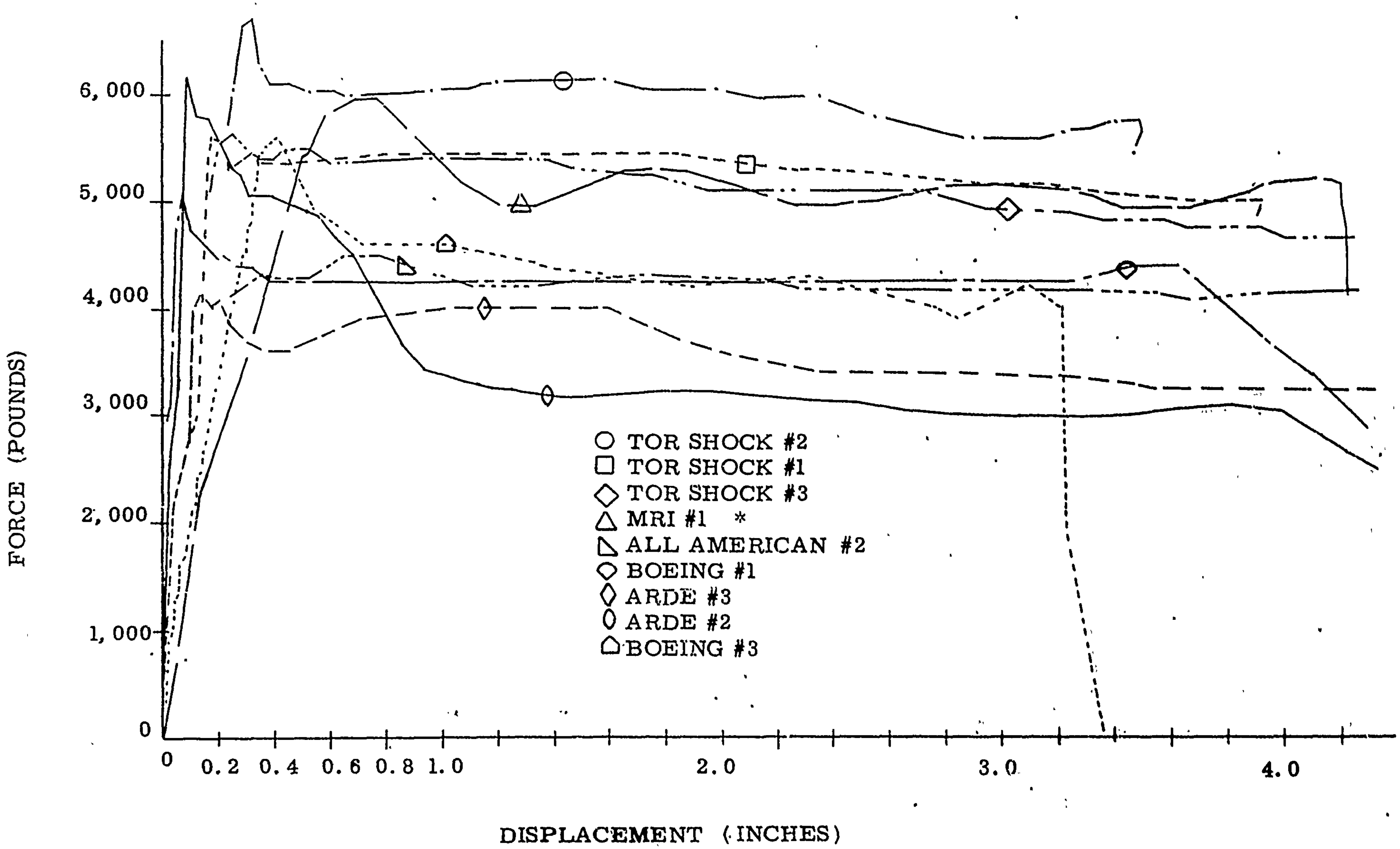

ARA INC. Test No. 3
6000
5000
4000
3000
2000
1000
0
FORCE (LBS.)
0.0
1.0
2.0
3.0
4.0
DISPLACEMENT (INCHES)

FIGURE IV - 13



ALL AMERICAN Test No. 2
FORCE (LBS.)
6000
5000
4000
3000
2000
1000
0
0.0
1.0
2.0
3.0
4.0
DISPLACEMENT (INCHES)

FIGURE IV - 14

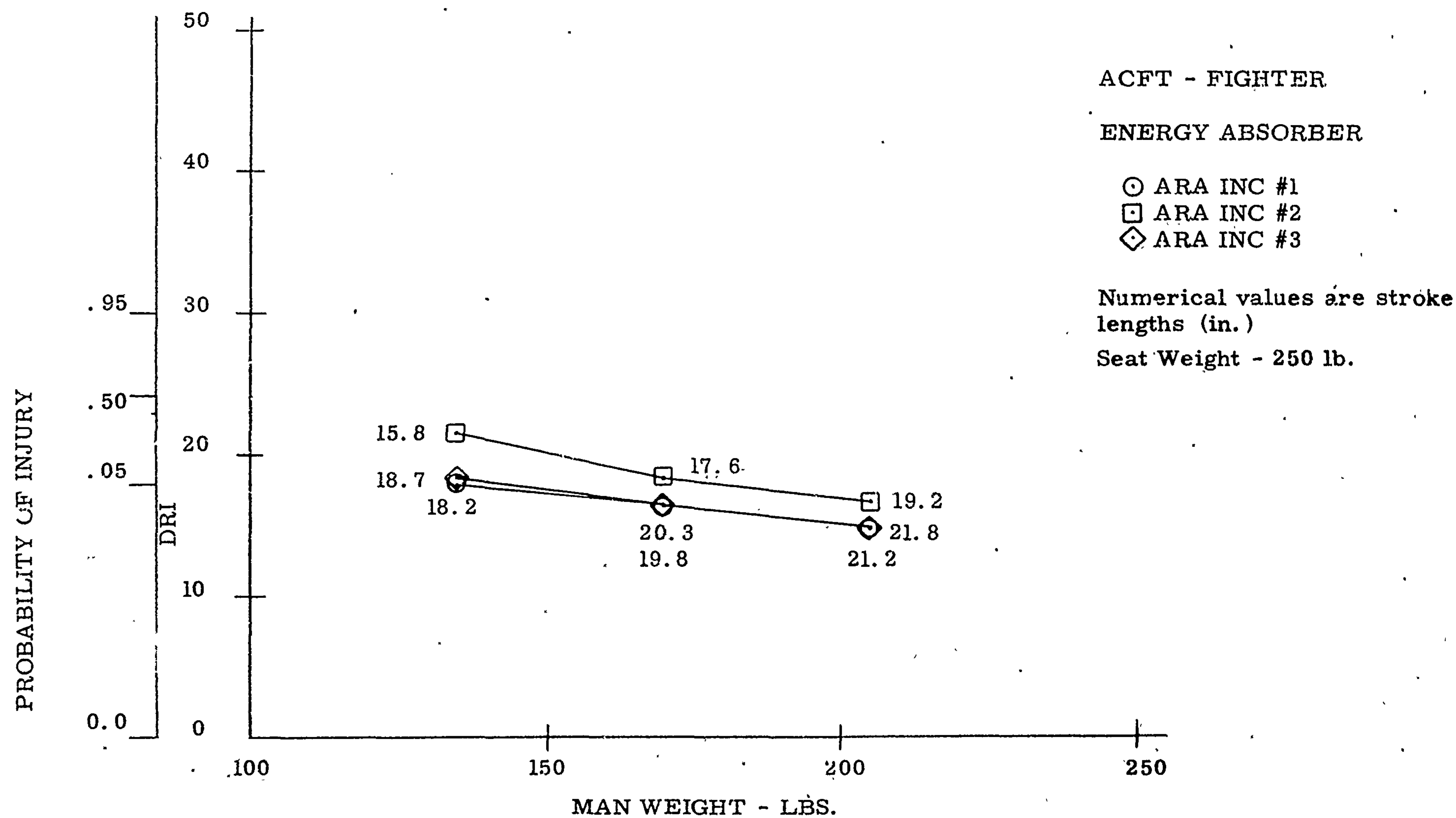


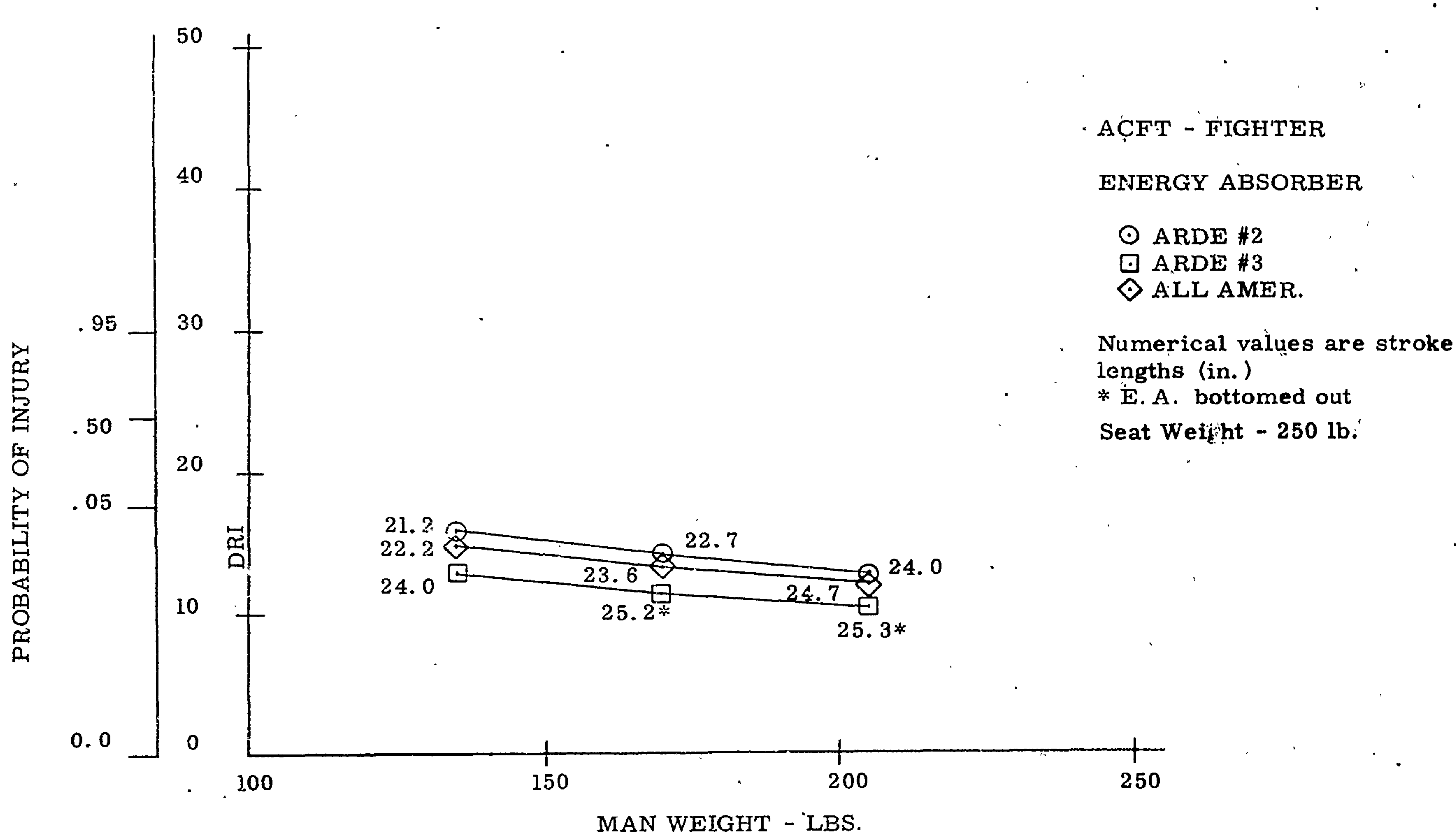
ENERGY ABSORBER CHARACTERISTIC CURVES

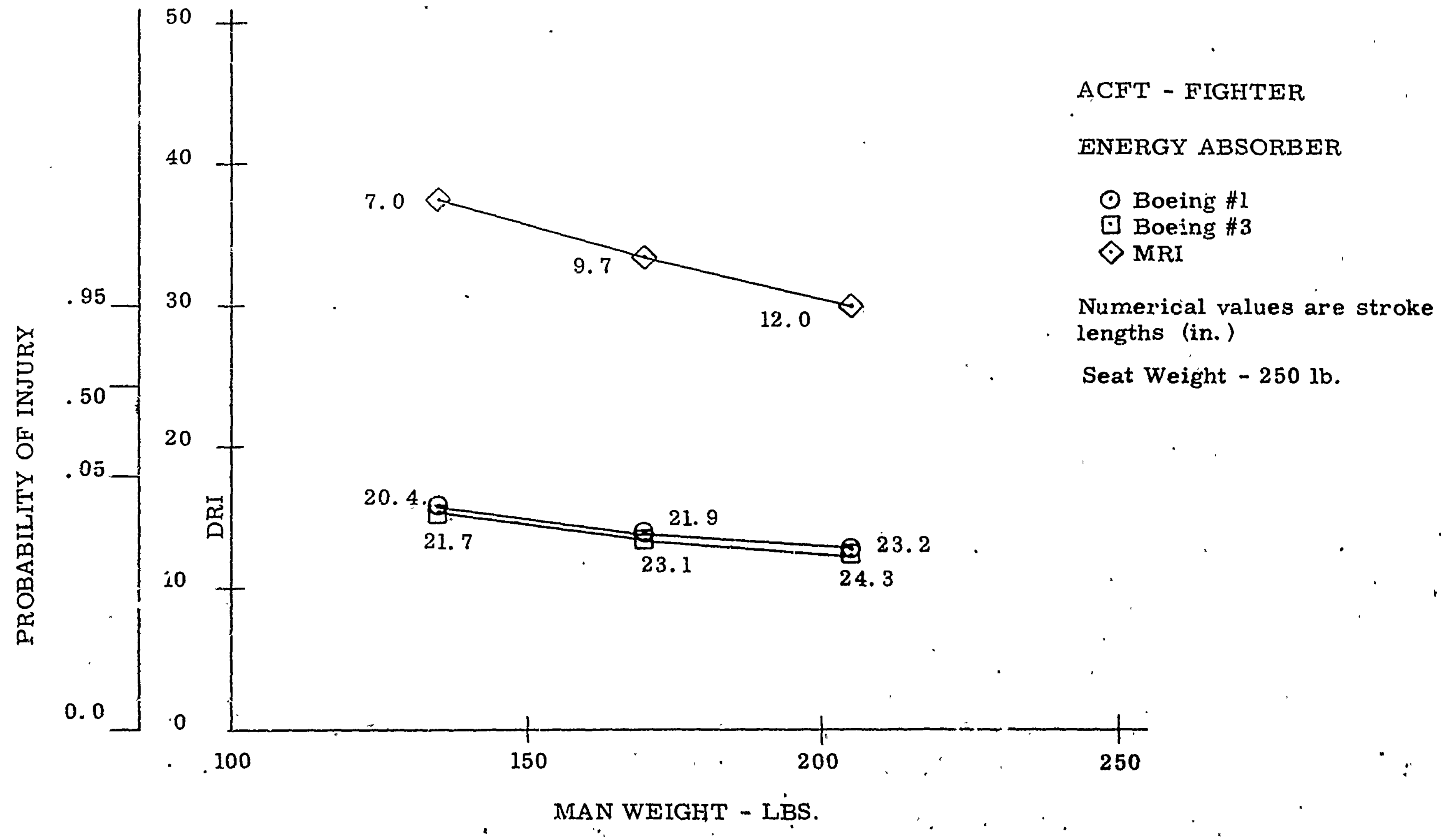
* Force Scale X2

APPENDIX V

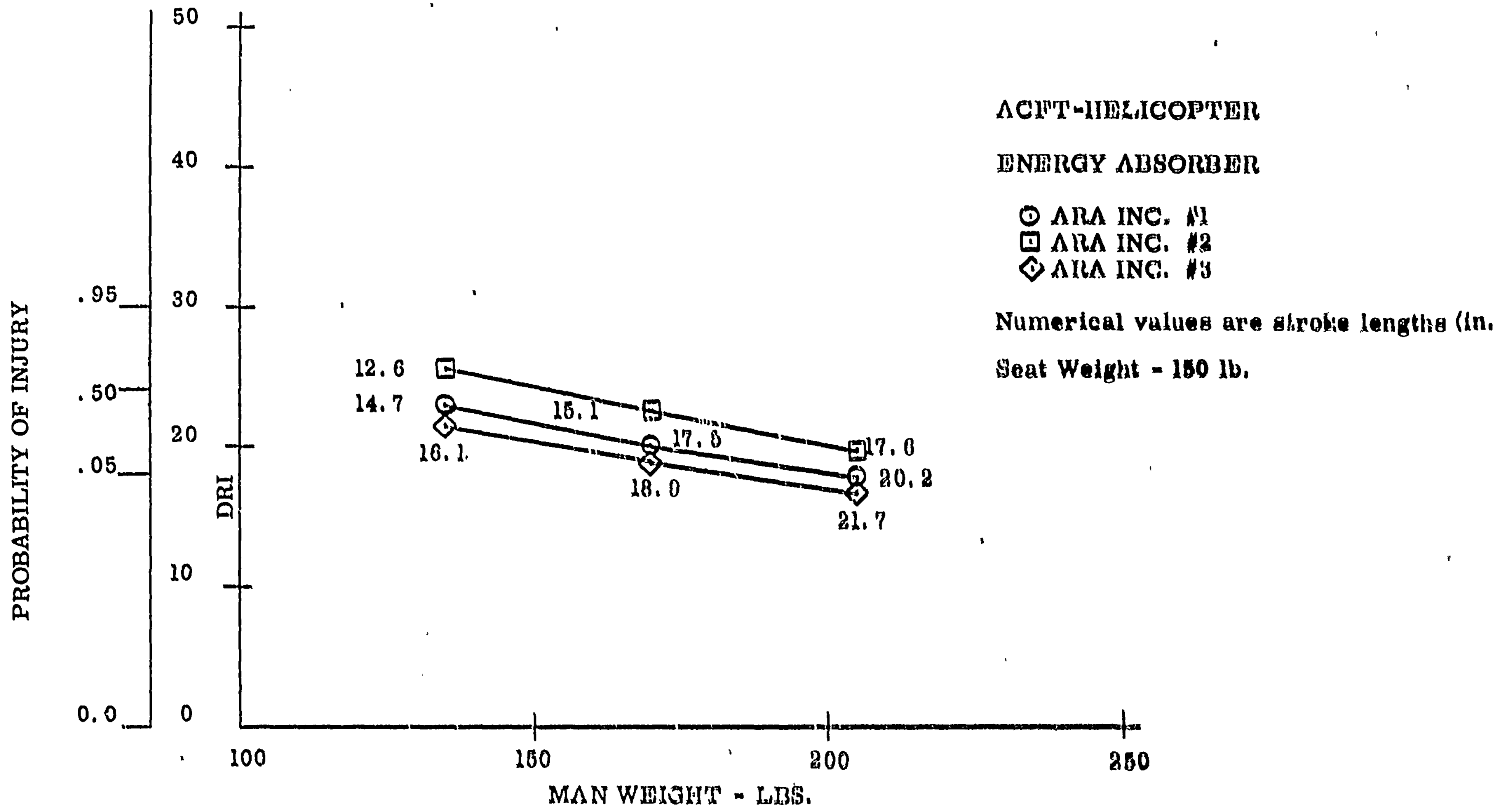
ENERGY ABSORBER EVALUATION

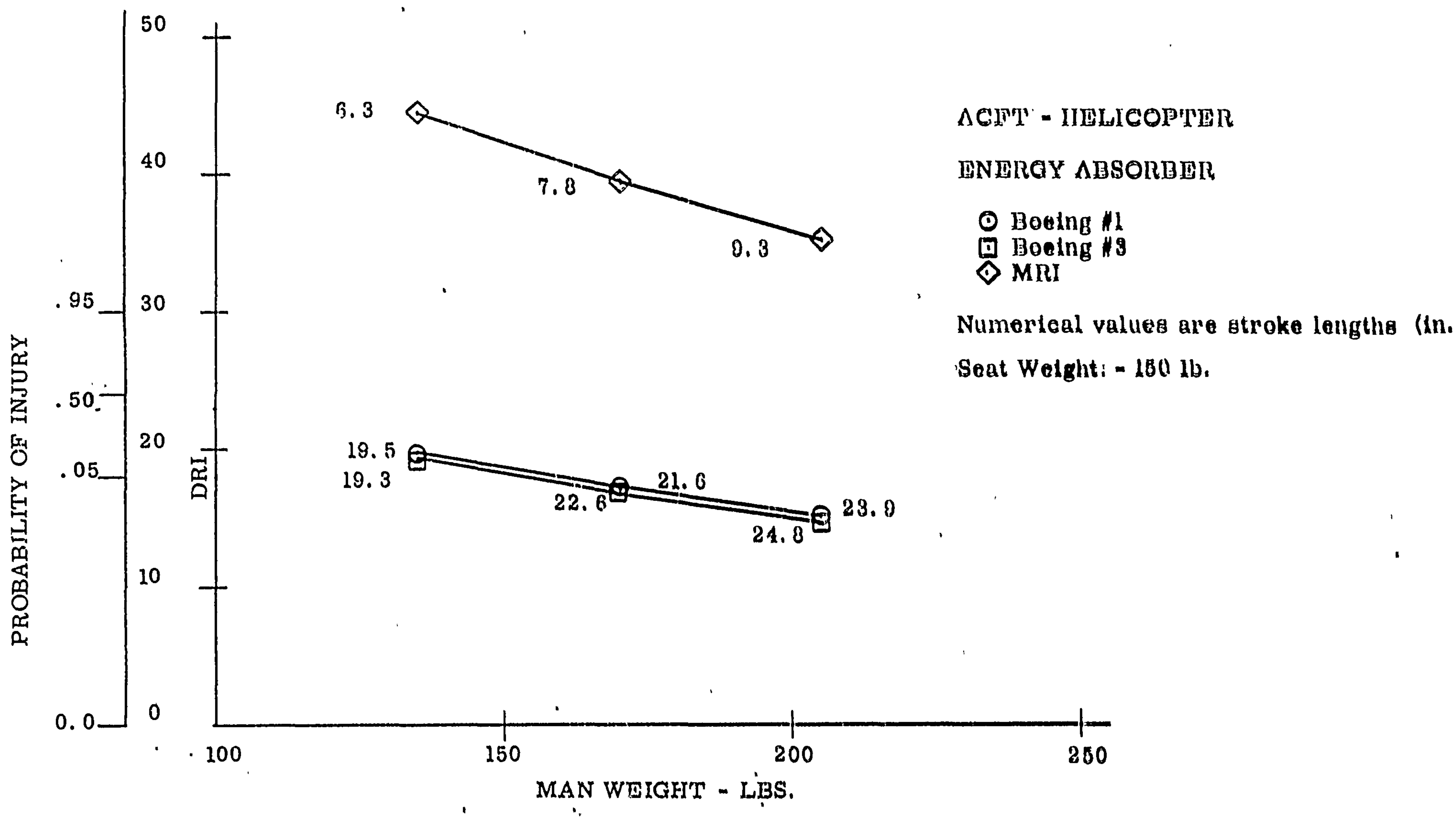

ACFT - FIGHTER
ENERGY ABSORBER
ARA INC #1
ARA INC #2
ARA INC #3
Numerical values are stroke lengths (in.)
Seat Weight - 250 lb.
PROBABILITY OF INJURY
.95
.50
.05
0.0
DRI
50
40
30
20
10
0
15.8
17.6
19.2
18.7
18.2
20.3
19.8
21.8
21.2
100
150
200
250
MAN WEIGHT - LBS.

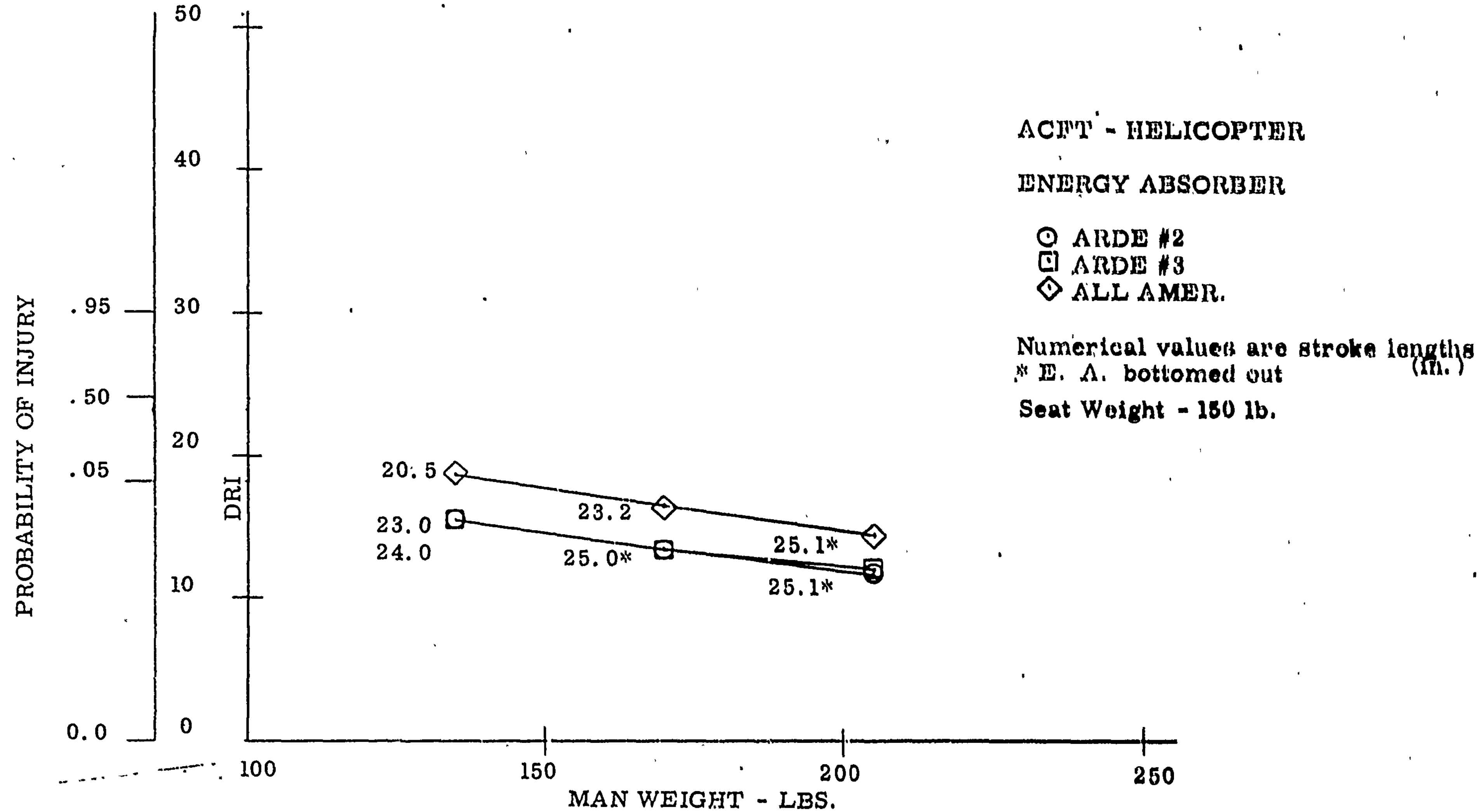

ACFT - FIGHTER
ENERGY ABSORBER
ARDE #2
ARDE #3
ALL AMER.
Numerical values are stroke lengths (in.)
* E. A. bottomed out
Seat Weight - 250 lb.
PROBABILITY OF INJURY
.95
.50
.05
0.0
DRI
50
40
30
20
10
0
21.2
22.2
24.0
22.7
23.6
25.2*
24.0
24.7
25.3*
100
150
200
250
MAN WEIGHT - LBS.



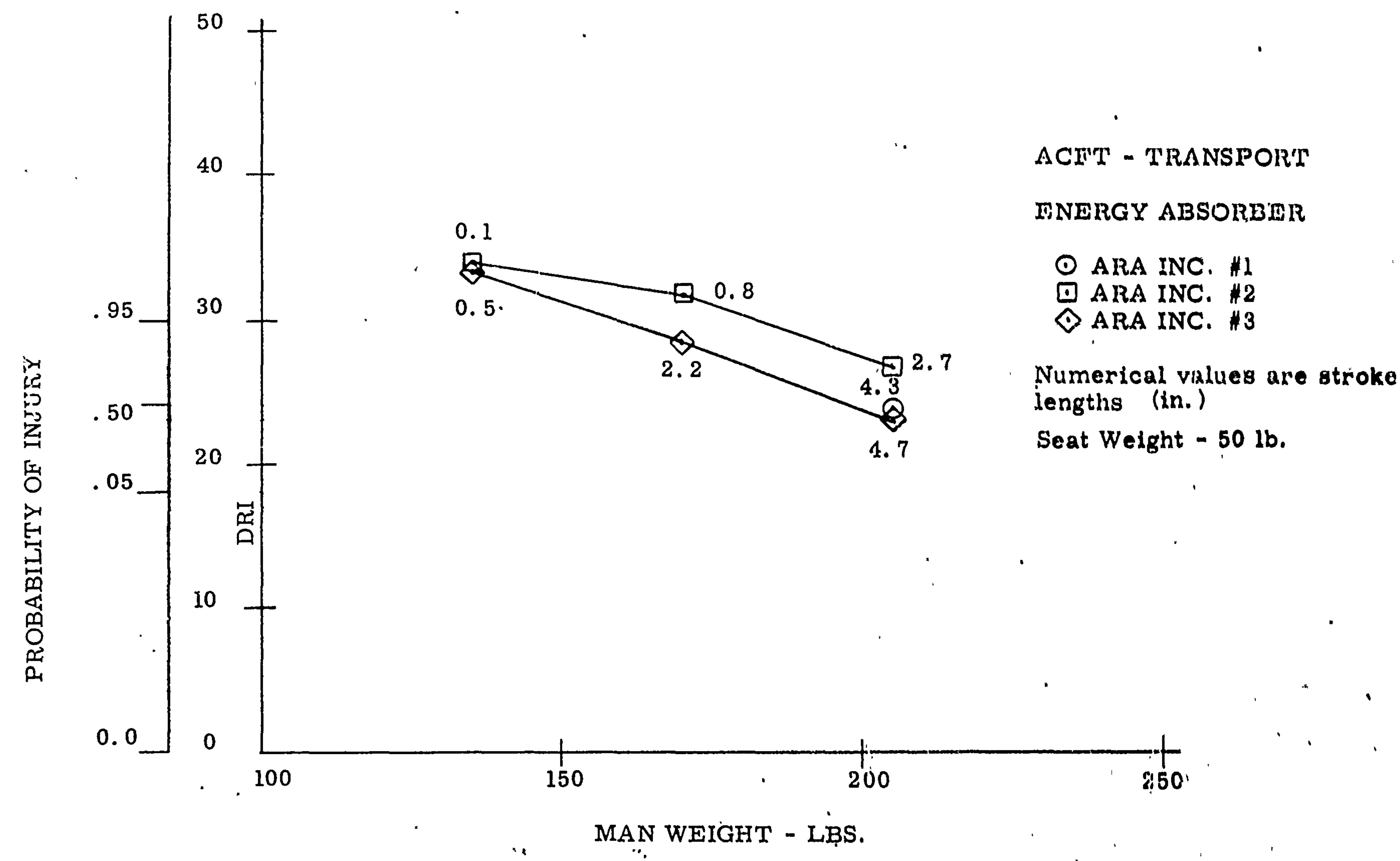
ACFT - FIGHTER
ENERGY ABSORBER
Boeing #1
Boeing #3
MRI
Numerical values are stroke lengths (in.)
Seat Weight - 250 lb.
PROBABILITY OF INJURY
.95
.50
.05
0.0
DRI
50
40
30
20
10
0
100
150
200
250
MAN WEIGHT - LBS.
7.0
9.7
12.0
20.4
21.7
21.9
23.1
23.2
24.3


PROBABILITY OF INJURY
.95
.50
.05
0.0
DRI
50
40
30
20
10
0
100
150
200
250
MAN WEIGHT - LBS.
12.6
14.7
16.1
15.1
17.8
18.0
17.6
20.2
21.7
ACFT-HELICOPTER
ENERGY ABSORBER
ARA INC. #1
ARA INC. #2
ARA INC. #3
Numerical values are stroke lengths (in.
Seat Weight - 150 lb.

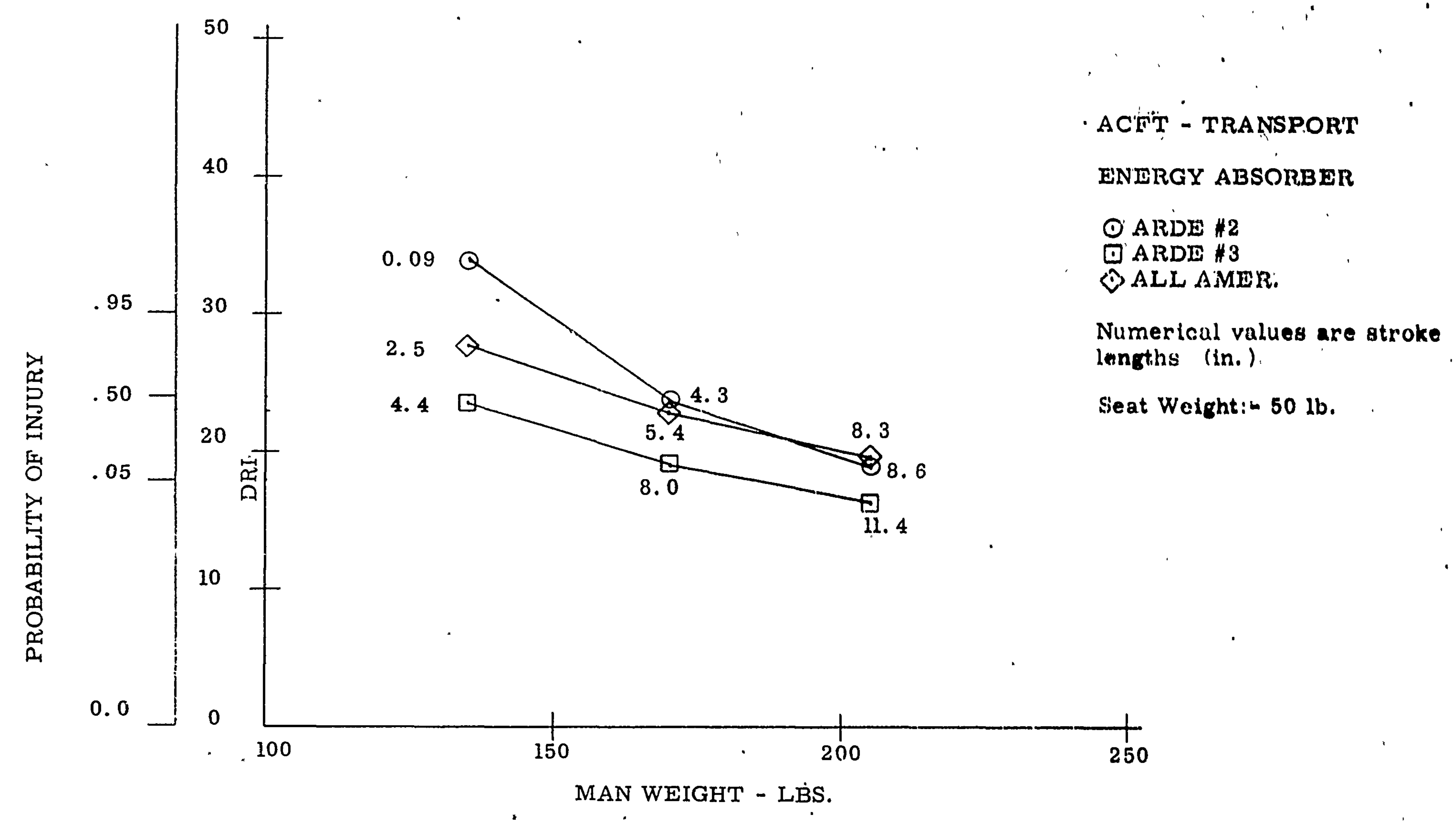

ACFT - HELICOPTER
ENERGY ABSORBER
Boeing #1
Boeing #3
MRI
Numerical values are stroke lengths (in.
Seat Weight: - 150 lb.
6.3
7.8
9.3
19.5
19.3
21.6
22.6
23.9
24.8
PROBABILITY OF INJURY
.95
.50
.05
0.0
DRI
50
40
30
20
10
0
100
150
200
250
MAN WEIGHT - LBS.

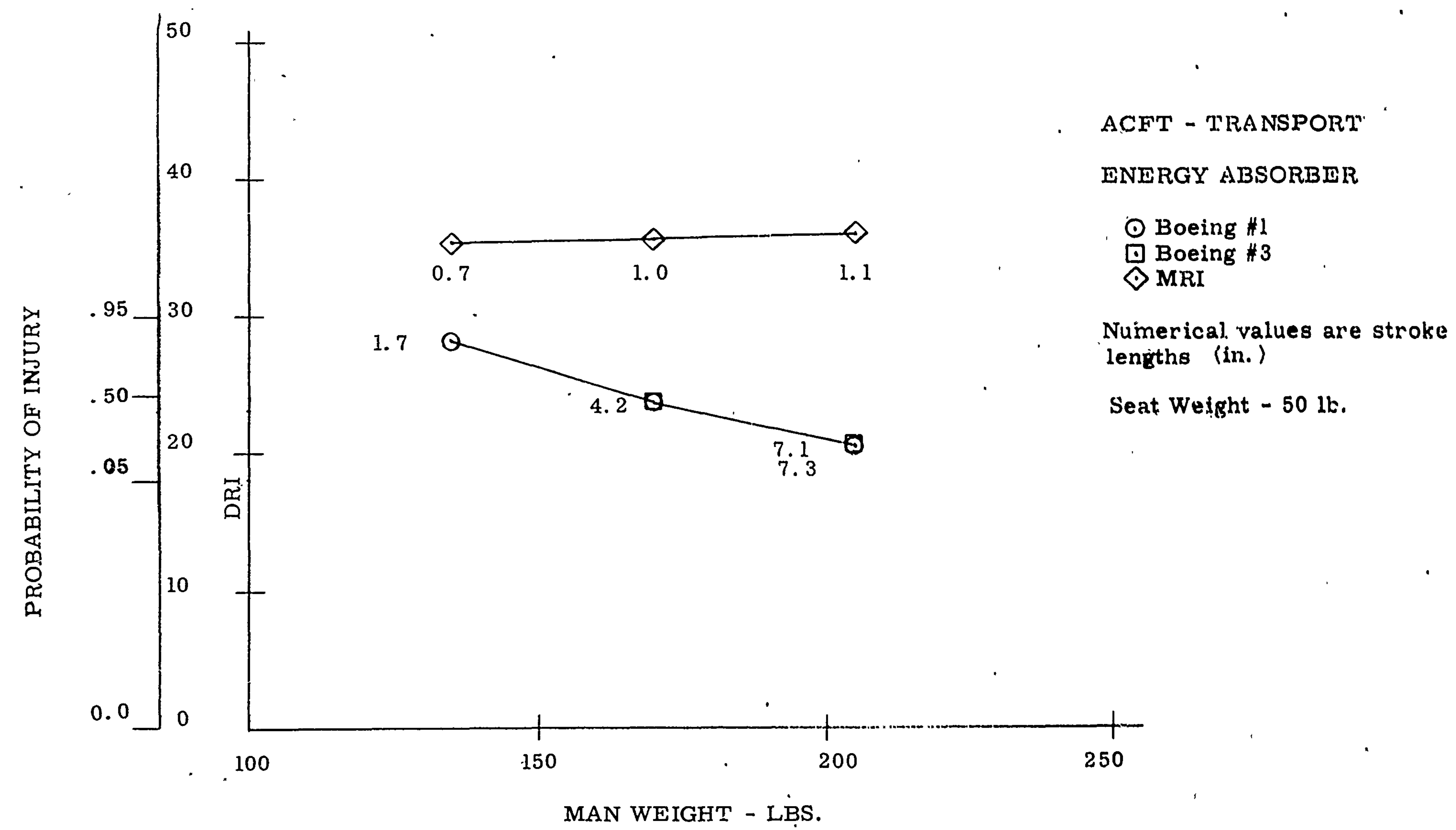


PROBABILITY OF INJURY
.95
.50
.05
0.0
DRI
50
40
30
20
10
0
100
150
200
250
MAN WEIGHT - LBS.
20.5
23.2
25.1*
23.0
24.0
25.0*
25.1*
ACFT - HELICOPTER
ENERGY ABSORBER
ARDE #2
ARDE #3
ALL AMER.
Numerical values are stroke lengths (in.)
* E. A. bottomed out
Seat Weight - 150 lb.



ACFT - TRANSPORT
ENERGY ABSORBER
ARA INC. #1
ARA INC. #2
ARA INC. #3
Numerical values are stroke lengths (in.)
Seat Weight - 50 lb.
PROBABILITY OF INJURY
.95
.50
.05
0.0
DRI
50
40
30
20
10
0
0.1
0.5
0.8
2.2
2.7
4.3
4.7
100
150
200
250
MAN WEIGHT - LBS.


ACFT - TRANSPORT
ENERGY ABSORBER
ARDE #2
ARDE #3
ALL AMER.
Numerical values are stroke lengths (in.)
Seat Weight: = 50 lb.
PROBABILITY OF INJURY
.95
.50
.05
0.0
DRI
50
40
30
20
10
0
0.09
2.5
4.4
4.3
5.4
8.0
8.3
8.6
11.4
100
150
200
250
MAN WEIGHT - LBS.


ACFT - TRANSPORT
ENERGY ABSORBER
Boeing #1
Boeing #3
MRI
Numerical values are stroke lengths (in.)
Seat Weight - 50 lb.
PROBABILITY OF INJURY
.95
.50
.05
0.0
DRI
50
40
30
20
10
0
0.7
1.0
1.1
1.7
4.2
7.1
7.3
100
150
200
250
MAN WEIGHT - LBS.

UNCLASSIFIED

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2763 CULVER AVENUE
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2a. REPORT SECURITY CLASSIFICATION

UNCLASSIFIED

2b. GROUP

3. REPORT TITLE

DEFINITION OF DESIGN CRITERIA FOR ENERGY ABSORPTION SYSTEMS

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

FINAL REPORT - 20 OCTOBER 1969 - 1 MAY 1970

5. AUTHOR(S) *(Last name, first name, initial)*

CARR, RICHARD W. AND PHILLIPS, NORMAN S.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
11 JUNE 1970	159	11

8a. CONTRACT OR GRANT NO. N00156-70-C-1374	9a. ORIGINATOR'S REPORT NUMBER(S) NADC-AC-7010
b. PROJECT NO.	
c. TASK AREA NO. R011-01-01	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
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WASHINGTON, D. C. 20360

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This report concerns Phase III, Part II of a research program to determine systems and materials that can be used to attenuate, to a tolerable limit, the forces imposed by high impact in both ejection and non-ejection seats. The goal of this research effort was to determine the optimum design criteria for energy absorbers that would best protect the pilots and passengers of fighter, helicopter and troop transport aircraft.

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DYNAMIC RESPONSE INDEX (DRI)						
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