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MODEL STUDIES OF INFLATION
UNIFORMITY OF CLUSTERED PARACHUTES

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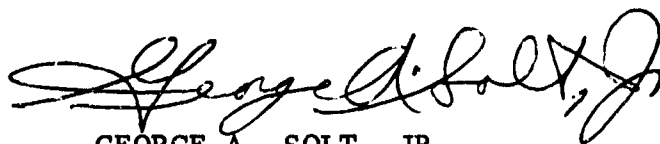*R. H. MONAHAN*

UNIVERSITY OF MINNESOTA

FOREWORD

This report was prepared by the Department of Aerospace Engineering and Mechanics of the University of Minnesota in compliance with U. S. Air Force Contract No. F33615-68-C-1227, "Theoretical Deployable Aerodynamic Decelerator Investigations," Task 606503, "Parachute Aerodynamics and Structures," Project 6065, "Performance and Design of Deployable Aerodynamic Decelerators." The work on this report was performed between 16 December 1967 and 15 October 1969.

The work accomplished under this contract was sponsored jointly by U. S. Army Natick Laboratories, Department of the Army; Bureau of Aeronautics and Bureau of Ordnance, Department of the Navy; and Air Force Systems Command, Department of the Air Force, and was directed by a Tri-Service Steering Committee concerned with Aerodynamic Retardation. The work was administered under the direction of the Recovery and Crew Station Branch, Air Force Flight Dynamics Laboratory, Research and Technology Division. Mr. James H. DeWeese was the project engineer.

The study was conducted in cooperation with Thomas R. Hektner and several students of Aerospace Engineering of the University of Minnesota. The authors wish to express their gratitude to all who rendered their services to the accomplishment of this work in particular to Messrs. Edward Giebutowski, U. S. Army Natick Laboratories; and James H. DeWeese, U. S. Air Force; for their periodic reviews and numerous suggestions.

This report was submitted by the authors in November, 1970.

This technical report has been reviewed and is approved.

GEORGE A. SOLT, JR.
Chief, Recovery and Crew Station Branch
Air Force Flight Dynamics Laboratory

ABSTRACT

The uniformity of the opening characteristics of free flying model parachute clusters with and without inflation aids was investigated. Models of 5 ft nominal diameter with low stiffness index were fired from a compressed air catapult and the parachute forces versus time were recorded. The ratio of included and suspended masses, the scaling parameter, was, with a few exceptions, identical to that for three 100 ft solid flat parachutes with a suspended weight of 8,850 lb. The measurements were combined with qualitative observations of the load-parachute systems for the establishment of comparative qualifications. The model tests showed that in clusters of three parachutes the configurations of the standard parachute with riser extension of $0.2\ D_0$ and the standard parachute with an internal canopy without riser extension had the best performance characteristics in view of the low averaged descent velocity and standard deviations. The times from the instant of snatch to the development of peak force of all configurations were about equal with the standard parachute having the largest deviations. Two configurations with combinations of riser extensions and centerlines as inflation aids failed to the extent that their testing was discontinued. The few values obtained for these configurations are not included in the numerical evaluation of the experiments described.

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SYMBOLS

D_o canopy nominal diameter

F_{max} maximum force

F_p peak force

F_p/F_{max} average force ratio, $\sum (F_p/F_{max})/n$

L_c length of centerline

L_r length of riser extension

L_s length of suspension line

m_a apparent mass

m_i included mass - mass of air inside canopy

m_s mass of suspended load

m^* mass ratio, $m^* = m_i/m_s$

t_i time from snatch to impact*

t_p time to peak force

v velocity

α angle of attack

σ standard deviation $\sigma = \sqrt{\frac{1}{N}\sum(x_i - \bar{x})^2}$

η stiffness index (Ref 1)

Superscript:

—   indicates averaged value

      Additional symbols, when used, are defined in
the text.

*The time increment from release to the instant of snatch is
the same for all configurations.

Intermediate Opening Stage of a Cluster
of Three Model Parachutes, D_O = 5 ft

x

I. INTRODUCTION

Individual parachutes combined into parachute clusters and attached to a load, show considerable non-uniformity of their inflation tendencies, opening forces, their position relative to the system axis of symmetry, and the magnitude of force transmitted to the suspended weight. For actual applications, reliability and promptness of inflation as well as uniform opening and steady force characteristics of all parachutes involved are the most important performance characteristics of parachute clusters. It has been reasoned that single parachutes which display relatively fast and uniform inflation with good repeatability may provide parachute clusters with desirable performance characteristics. From field and model tests it is known that the performance characteristics of single parachutes can be improved by so-called inflation aids such as centerlines, internal canopies, and combinations thereof.

The objective of this study was to investigate whether cluster non-uniformities could be reduced and the full inflation of all parachutes expedited by means of inflation aids, which, in effect, resulted in the problem of measuring the effect of various inflation aids upon the performance characteristics of model parachute clusters. In view of this objective, the inflation characteristics and vertical descent of freely floating single and clustered parachute models were observed and recorded.

The parachute models primarily used in this study had a nominal diameter, D_O, of 5 ft and had the same number of gores and suspension lines as the 64 ft, G-12D parachute. They were constructed as flexible as possible (Ref 1) and for the purpose of this study assumed to be representative of the G-12D as well as the G-11A parachutes. The inflation aids used to modify the opening characteristics were:
1) cluster riser extensions of 0.2 D_O, 0.4 D_O, and 0.6 D_O;
2) centerlines of 0.88 D_O and 0.97 D_O; 3) internal parachutes with a nominal diameter of 0.2 D_O of the main parachutes; and 4) combinations of riser extensions, centerlines, and internal parachutes.

The free flight tests were conducted using a pneumatic catapult to provide a uniform initial velocity of 90 ft/sec to the model parachutes and the suspended load. Force sensors located between the suspended load and parachutes measured the opening force of the individual parachutes.

The performance nonuniformities were then analyzed by determining the average velocity from parachute release to impact, peak opening forces of each parachute, and the time at which peak force occurs. These results are presented in graphs and tables.

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II. CATAPULT FACILITY AND INSTRUMENTATION

The model tests were conducted using a pneumatic catapult (Ref 2) to provide the initial system velocity. The individual parachute forces at opening, descent, and ground impact were measured and recorded during each test by means of strain gages and related electronic equipment.

A. Catapult Facility

Conventionally one would tend to examine the non-uniformities of cluster openings in a suitable subsonic wind tunnel. However, a closer evaluation of the type of wind tunnel tests that could be conducted at the University of Minnesota, showed that several factors would severely pre-judice the usefulness of the results. The main restraints would be small model size, probably restricted horizontal flight path and questionable chances to record the equili-brium speed of the various configurations or infinite mass opening conditions. Therefore, it was decided to use the catapult facility of the University of Minnesota (Ref 2) to. provide the required initial velocity of the parachutes with their suspended weight. In this manner relatively large models could be used for the observation and recording of the finite mass openings as well as the free descent.

The catapult (Fig 1) consists of a six-inch diameter piston contained in a three-foot long cylinder. A shaft, 44 inches long and 1-3/8 inches in diameter, is connected to the piston and extends through the base of the cylinder. Air pressure in the reservoir drives the piston and shaft down-ward when the electrically operated trigger assembly releases the shaft. At the end of the stroke, the piston and shaft are stopped by polyurethane foam cushions located at the cylinder base. Prior to firing, the parachute models are stored in "line-first-deployment containers". The suspended weight, which is mounted on the protruding end of the shaft, slides off when the piston begins to decelerate and deploys the parachutes. The initial velocity can be controlled by varying the air pressure, and it was found that a reservoir pressure of 80 psig generates a system "snatch" velocity of 90 fps which was used throughout this study.

The catapult is mounted on a platform near the ceiling of the laboratory hall which gives a vertical drop distance of approximately 28 ft (Fig 2). This distance proved to be sufficient for almost all well functioning configurations to reach equilibrium speed.

2
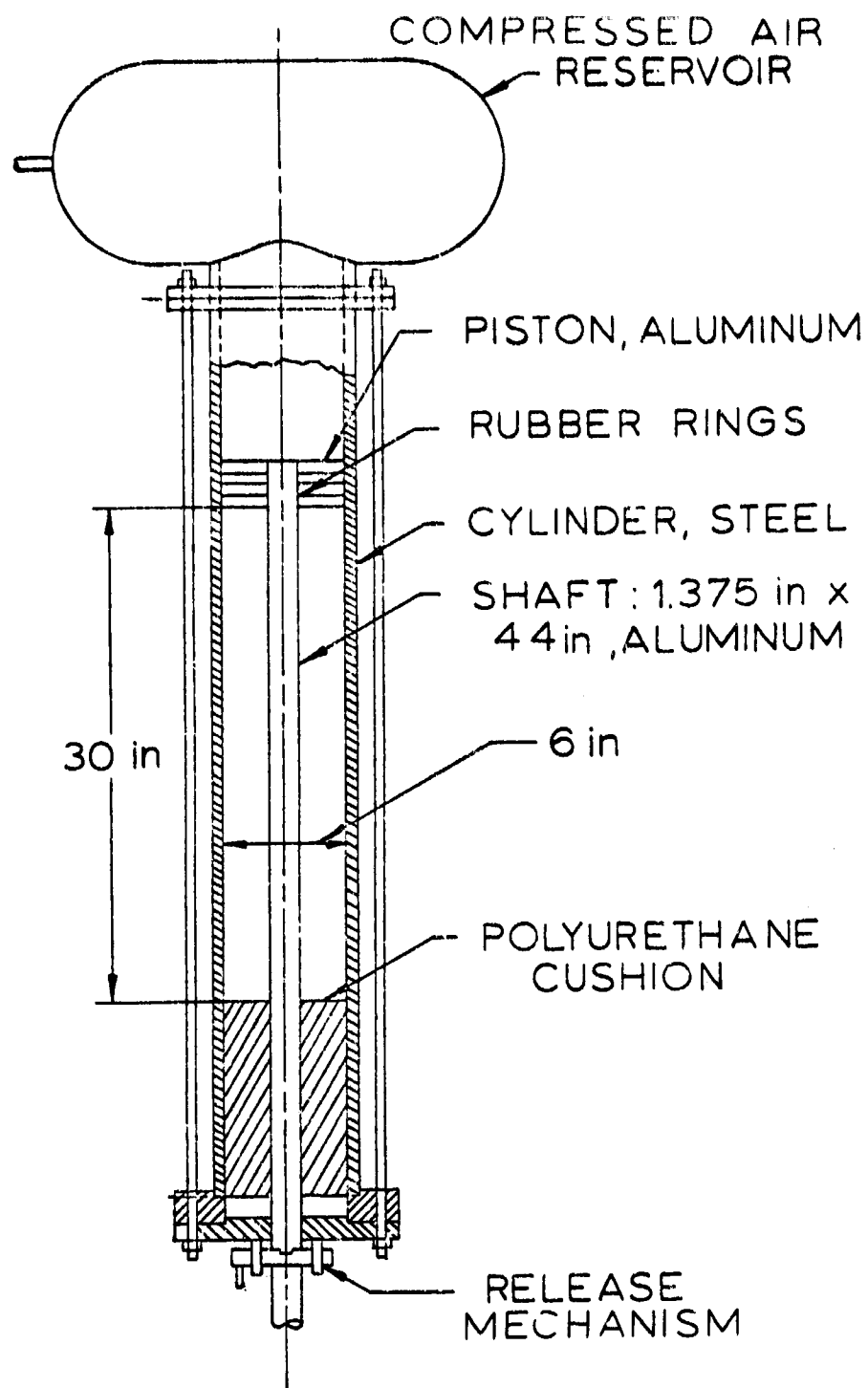
Fig 1   Compressed Air Catapult used for Model Testing (Ref 2)

Labels in figure:
- COMPRESSED AIR RESERVOIR
- PISTON, ALUMINUM
- RUBBER RINGS
- CYLINDER, STEEL
- SHAFT: 1.375 in × 44 in ,ALUMINUM
- 6 in
- 30 in
- POLYURETHANE CUSHION
- RELEASE MECHANISM

HIGH PRESSURE
RESERVOIR

INITIAL
POSITION

PARACHUTE
DEPLOYMENT
CONTAINERS

BALCONY

SHAFT

SUSPENSION LINES
AND RISER

SUSPENDED
WEIGHT

28 ft*

* 28 ft MAXIMUM,
DECREASES WHEN
SHAFT EXTENSIONS
ARE USED

Fig 2   Position of Catapult and
Suspended Weight at Time
of Release

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B.   Instrumentation

Strain gage force sensors installed between the
suspended load and each parachute's confluence point enabled
measuring the opening force of each model parachute. As
shown in Fig 3 the sensors consisted of a cylindrical housing
of steel and a hollow tension cylinder of aluminum which
carries the active and temperature compensating strain gages.
One end of the housing is connected to the suspended weight
while the free end of the tension cylinder is fastened with
a swivel to the parachute confluence point. Figure 4 shows
the load and sensor assembly.

The electric output of each force sensor was
fed into a D. C. amplifier and recorded by means of an oscillo-
graph. The connection between the force sensors and recording
instruments was a small shielded cable also shown in Fig 4.
The cable was long enough to allow it to follow the load
downward during the free descent. Dead weight calibrations
of the force sensors showed accuracy and repeatability of
better than ± 0.05 lb for each sensor.

High speed movies of the motion of the cable during
a test indicated that the cable could possibily exert forces
on the weight which would cause the parachutes to feel a
lighter or heavier load depending on the time observed.
However, motion pictures of tests with and without cables
did not indicate differences in parachute opening character-
istics. Therefore, one may conclude that the effect of the
cable is negligible.

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Fig 3 Force Sensor Assembly

ALL DIMENSIONS IN INCHES

STEEL

ALUMINUM

6-32 SCREW

½ × 20 nf THREADS

0.37 PIANO WIRE

ACTIVE GAGE

COMPENSATION GAGE

FORCE

6

Fig 4   Suspended Weight with Force Sensors

III. SELECTION OF MODELS AND SCALING CONSIDERATIONS

A. Parachutes

Initially, three 48 inch, 28 gore models of the C-9 parachute were available and used for exploratory catapult tests. The construction of the models was similar to that used in full s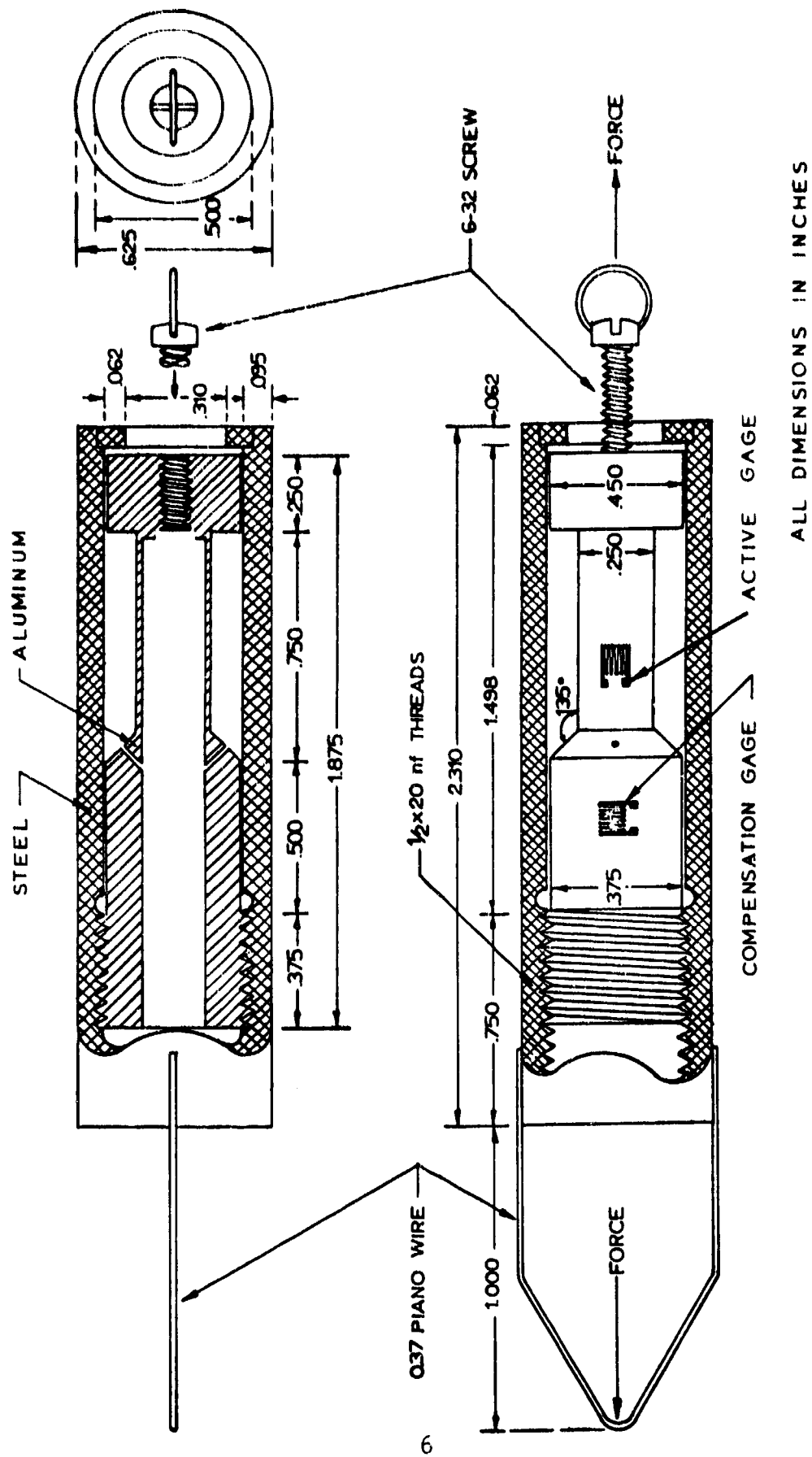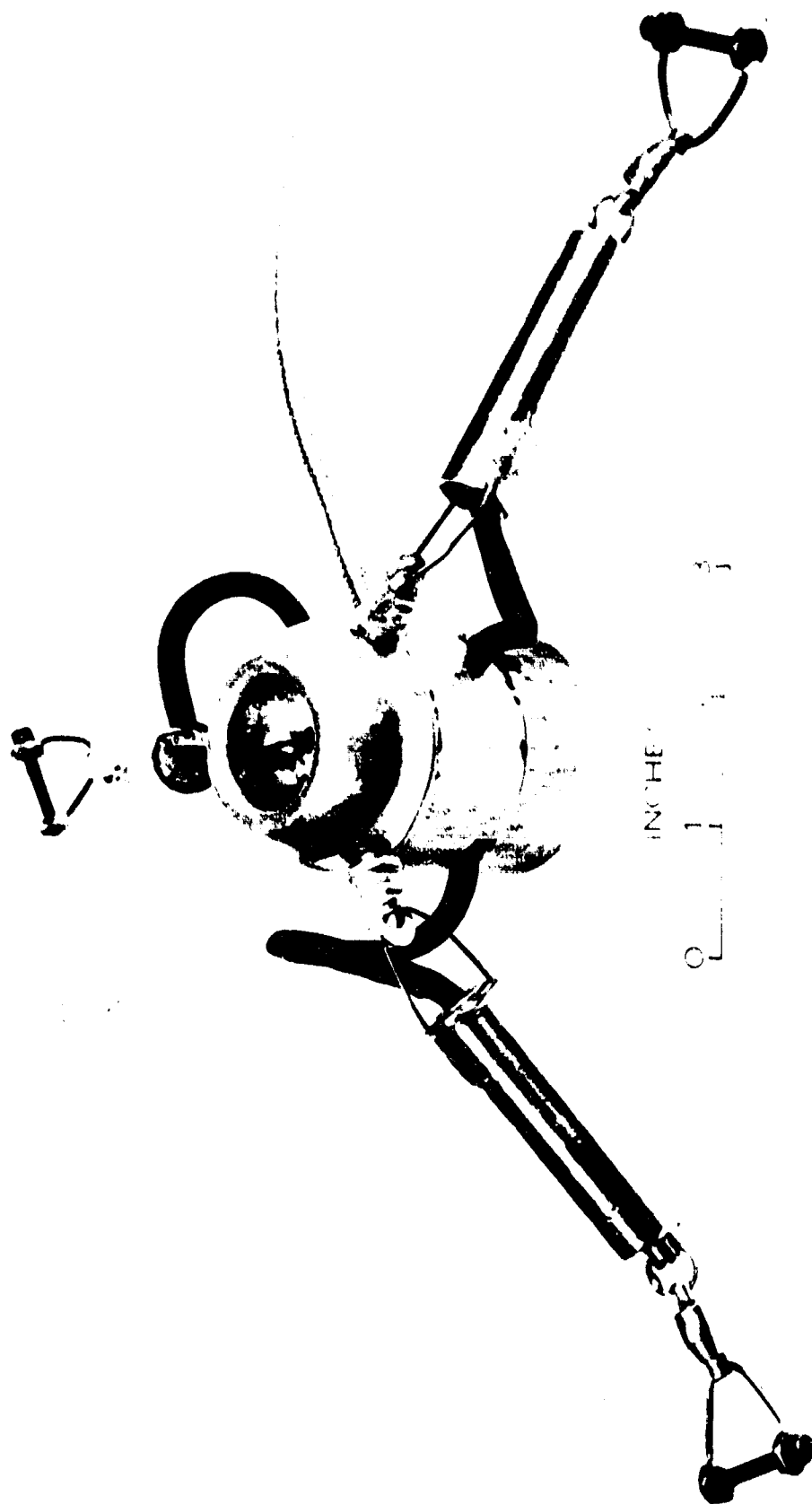ize parachutes having individual gores of 1.1 oz nylon cloth joined by means of seams. The skirt construction consisted of a rolled hem with reinforcements at the points of suspension line attachment. The suspension lines were made from 100 lb nylon parachute cord and sewn to each gore seam at the skirt. These models were also chosen because they appeared to fit the estimated size limitations imposed by the vertical drop distance.

After some testing of these parachutes at different loads and snatch velocities (more details of this phase are described later) it became apparent that the inherent stiffness of these models caused unrealistic rapid inflation and the tests with these conventionally built models were limited to sizing the suspended weight. For the actual opening study somewhat larger D_0 = 5 ft highly flexible models in accordance with the experience of Ref 1, were used.

The higher flexibility of these models arises from the fact that in the 5-ft size there is only one seam in the entire canopy and that the suspension lines run from the confluence point over the top of the canopy and back to the confluence point. They are fastened to the cloth by means of a zig-zag stitch thus eliminating practically all gore connecting seams and the need for a relatively strong connection point at the skirt (Fig 5).

The flexible models were made of 1.1 oz nylon cloth while the suspension lines were twist braided 20 lb ultimate strength nylon fishing line with the center core removed. Each suspension line was stitched to the canopy at the points where it met the skirt and vent using fine thread and a drop of glue. In connection with the zig-zag stitches, the suspension lines then divide the canopy into gores without the need of the usual heavy seams. The models were scaled from a D_0 = 64 ft G-12D and had 64 suspension lines 47.5 inches long, and four risers 5.5 inches long, each of which holds 16 of the suspension lines (Fig 6). The stiffness index, Ref 1, of these models was $\eta = 0.35$.

These highly flexible models were tested with a snatch velocity of 100 fps both singly and in clusters of three to see if the light construction was still strong

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TYPICAL 64 GORE SECTION OF PARACHUTE

FRENCH SEAM

D_O = 5 ft

VENT DIAMETER
3.125 in

SUSPENSION LINE

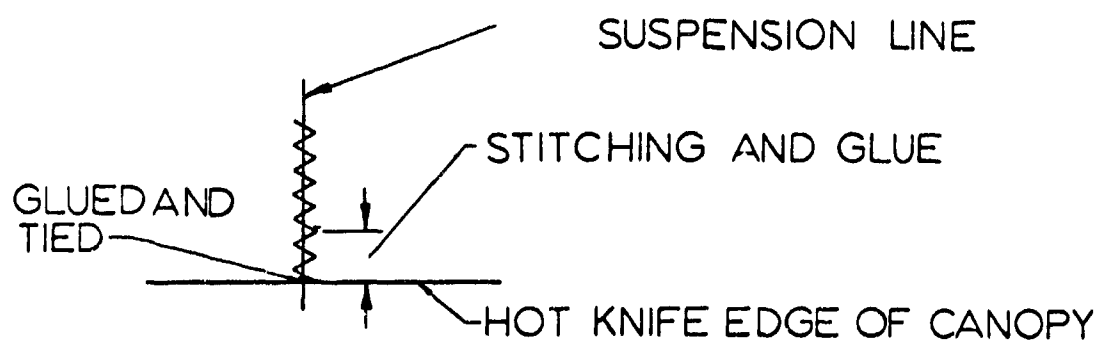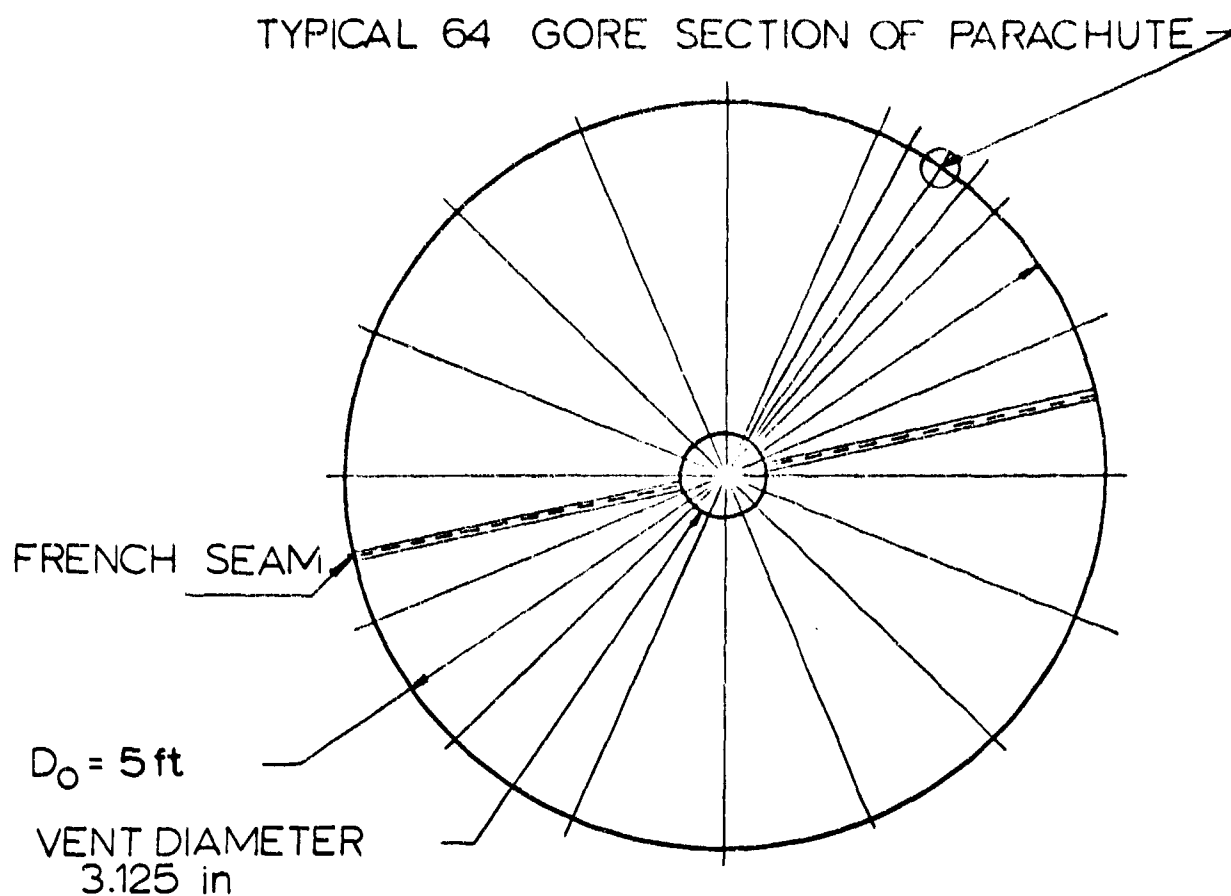STITCHING AND GLUE

GLUED AND
TIED

HOT KNIFE EDGE OF CANOPY

Fig 5 Construction Details of Parachute
Model, η = 0.35, Nominal Diameter
D_o = 5 ft

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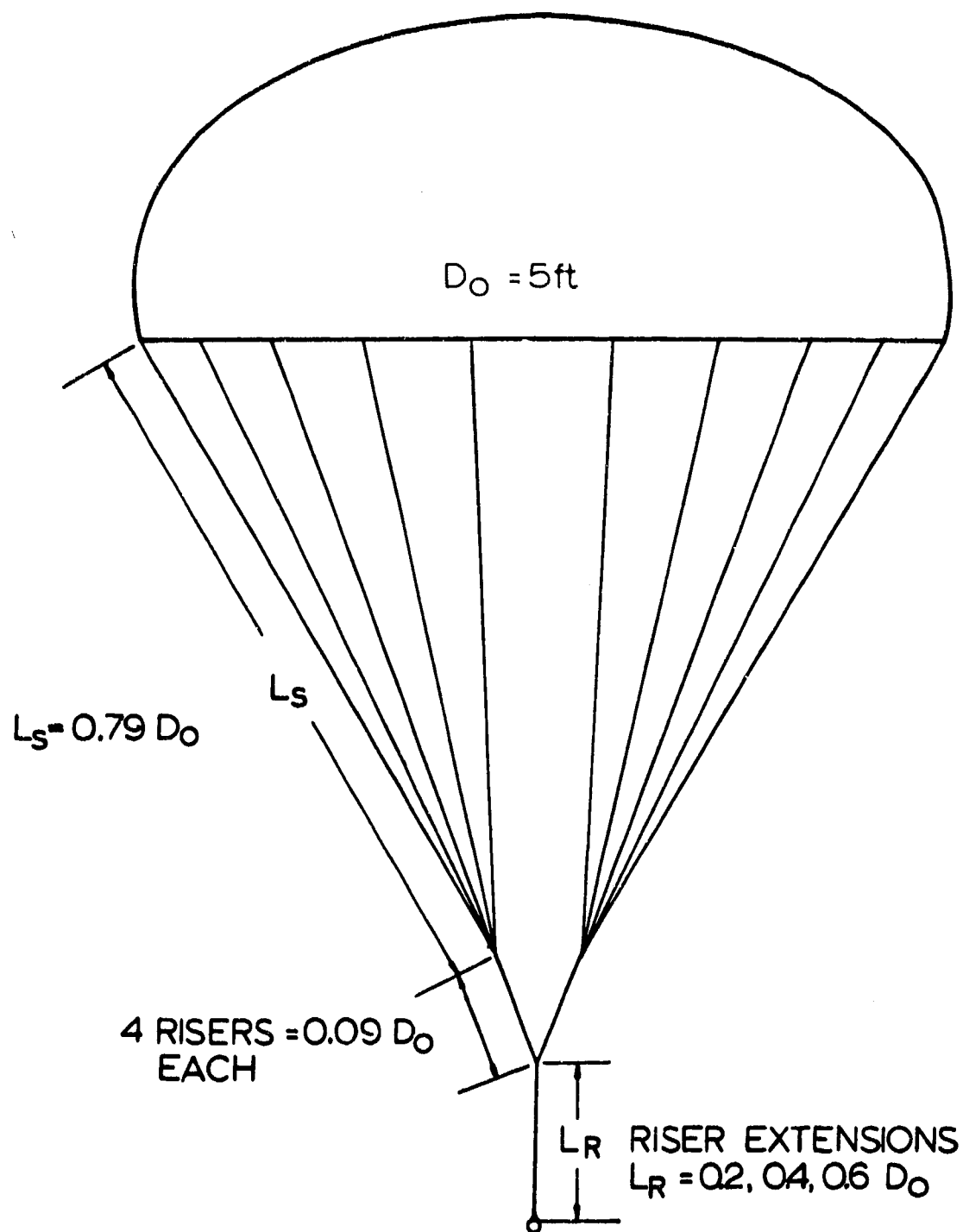Fig 6   Parachute Model with Suspension
Lines, Risers, and Riser
Extensions ; $D_O = 5$ ft

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enough to withstand the loading during the opening process.
No structural damage was observed. High speed motion pic-
tures showed that the new models did not exhibit the rapid
openings of conventional models, but they inflated much
smoother with a certain fluttering motion of the canopy as is
frequently observed in openings of full size parachutes.
The opening sequences of the conventional and flexible models
are shown in Figs 7A and 7B. After more than 600 firings the
flexible models were still fully intact. The flexible design
appears to have satisfactory strength.

The internal parachutes (Ref 3), $D_O = 1$ ft, used
in this study were constructed in the same manner as the
flexible main canopies, except that the smaller size made it
possible to cut the canopy from one piece of 1.1 oz nylon
cloth. These internal canopy models were of solid flat
circular design with 12 suspension lines.

B.   Scaling of the Suspended Weight

The equation of motion of an inflating parachute
shows, among other details, the parameters of surface loading,
W/S, and the mass ratio $(m_i + m_a)/m_s$ (Ref 4). For the purpose
of model scaling the apparent mass, m_a, can be neglected
because the apparent mass can be presented as a multiple of
the included mass, which factor is equal for prototype and
model parachutes of the same parachute type (Refs 5,6).
Presently it has not definitely been shown which of the two
parameters is the most influential. It is the opinion of the
authors, that with all due consideration of unknown possibili-
ties, the mass ratio is the more significant one of the two
parameters. However, in view of the uncertainties the first
attempt of model test scaling was made in view of the surface
loading parameter. In accordance with this concept, the sus-
pended weight of a model cluster follows from the relationship

$$W_m = W_p \cdot \frac{S_m}{S_p}$$

where

W   suspended weight

S   canopy area

m,p   model, prototype, respectively.

The suspended weight of the prototype or full size
configuration chosen was 8,850 lb for a cluster of three $D_O = 100$ ft parachutes. With the scaling on the basis of equal
surface loading, one obtains for three 4 ft models a suspended
weight of 14 lb.

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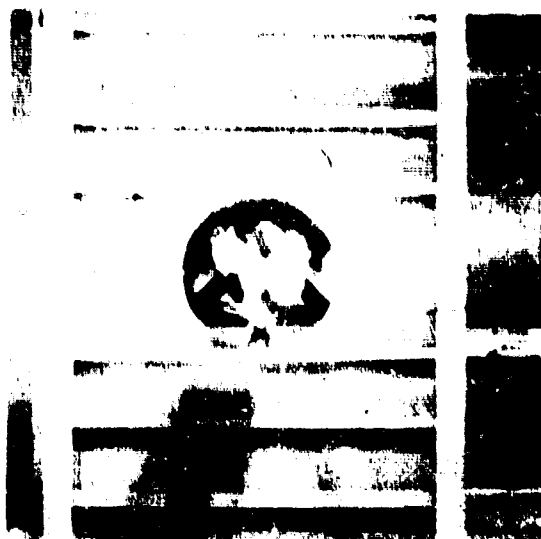
Fig 7A   Cluster of Three Conventional
          Parachutes : $D_O = 4$ ft , Inflation
          Sequence ; Approximately 1/60
          sec   Intervals

(e)　(f)

(g)　(h)

Fig 7A Concluded

Fig 7B Cluster of Three Flexible
Parachutes : D_O = 5 ft , Inflation
Sequence , Approximately 1 / 60
sec   Intervals

14

(e)

(f)

(g)

(h)

Fig 7B Continued

15

(i) (j)

(k) (l)

Fig 7B Concluded

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A combination weight and instrument package was designed which could be adjusted to weigh from 5 lb to 16 lb. In order to avoid destruction of the parachute models in the 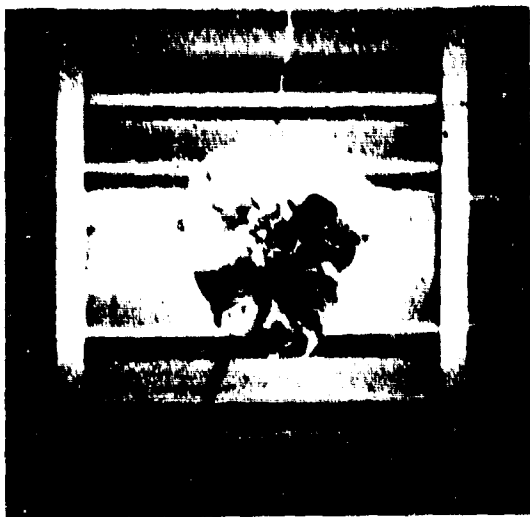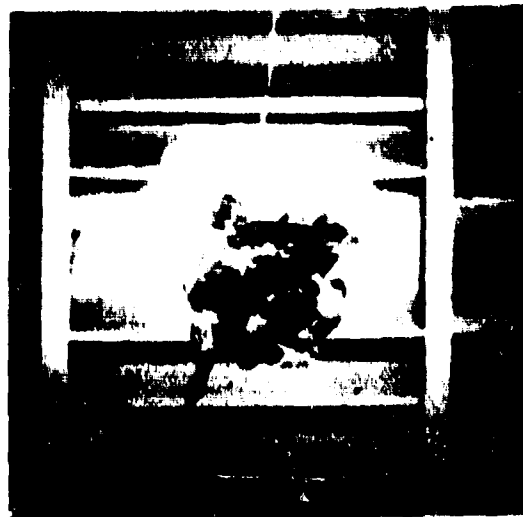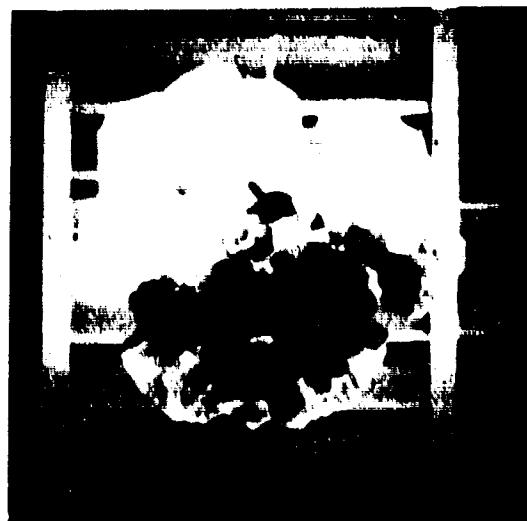initial tests, it was decided to start the testing with the smaller load followed by a slow increase of suspended weight. Analyzing the respective high speed motion pictures and force traces, it was found that when the load had been increased from 5 lb to 7 lb the parachutes were overloaded to the extent that they did not develop to the well known profile of fully inflated parachutes. Also, the peak forces of the individual parachutes were very high, opening times very short, and the nonuniformities in the openings were on a much smaller scale than experienced in full-size drop tests. The suspended weight was then decreased to 2 lb which was not small enough for equal mass ratios, but was considerably closer than the previous 5 lb or 7 lb. The results of these tests showed opening performance closer to that of typical full scale clusters. The opening times were longer, peak forces lower, and there was generally less uniform performance than the heavier loadings. However in view of the findings of Ref 1, one must expect that the stiffness of these 4 ft models would still severely detract from the correlation of model and full-scale tests.

The next experiments were based on the mass ratio as parameter and the D_O = 5 ft flexible models were used. The mass of air contained inside each parachute canopy, called included mass, is approximately equal to the mass included in a hemisphere having a diameter amounting to 70 percent of the nominal canopy diameter. Assuming again a prototype configuration of three 100 ft parachutes and 8,850 lb suspended weight provides for the model tests with three parachutes of 5 ft diameter, a suspended weight of 1.1 lb. The related figures are 642 slugs and 0.08 slugs total included mass for three 100 ft and three 5 ft parachute models respectively, assuming sea level air density. The following study was then primarily based on this mass ratio, called $m* = m_i/m_s$, amounting to 2.33.

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IV. TEST PROCEDURE

A. Model Parachute Packing

The model parachutes were packed such that the packing procedure would be as uniform and repeatable as possible. The canopies were first accordion pleated gore by gore, then S-folded longitudinally several times from the skirt to the vent and placed into a sheet metal container which represented a deployment bag. The deployment container had a rigid flap with elastic loops for stowing the suspension lines. Figure 8 illustrates packing and deployment procedures of the canopies. The deployment containers were mounted uniformly around the catapult cylinder, and releasing the catapult trigger initiated a lines first deployment procedure of the packed parachutes. The stroke of the catapult piston was short enough so that the suspended weight had separated from the piston shaft before parachute deployment began.

B. Catapult Testing

The procedure for each separate test was to pack the parachutes, fasten the containers, mount the suspended weight on the shaft, connect the force sensors to the risers, balance the electric instruments, pressurize the catapult, and fire the catapult. Generally this procedure was repeated until at least ten tests were obtained with complete force recordings. In cases where the parachute inflation was so uncertain that a damage to the force sensors appeared to be likely, the testing was discontinued regardless of the number of records obtained.

Several high speed motion pictures were taken of each configuration in order to have a means of determining whether or not something might have interferred with the deployment and opening of the parachutes. The pictures were taken from the floor below the catapult with a wide angle lens, but in general the parachutes moved out of field of camera view before they were fully inflated. However, the motion pictures satisfied the intended purpose.

In general, a sufficient number of tests were made in order to obtain 10 diagrams containing recordings of all characteristic features. In the case of the configuration with internal canopies, the first inflation aid tested, 15 recordings were made because the recorded features differed so much from previous tests that a more thorough testing appeared to be necessary.

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a

b

c

d

e

f

Fig 8 Simulated Deployment also
Illustrating the Model
Parachute Packing Procedure

V. TEST PROGRAM

The test program consisted of three major categories, namely, tests of openings of a single and two and three clustered model parachutes. Within these major categories tests were conducted on different configurations which utilized various inflation aids and combinations. In the following sections the characteristics of each inflation aid are described and the test program actually conducted is tabulated.

A total of approximately 600 catapult firings were made. Of this total, 159 were valid, and 150 tests could be evaluated numerically. Except for the group of preliminary and exploratory tests to select a suitable scaling ratio, the remaining tests involved malfunctions of either the mechanical, electrical or optical systems pertaining to one or more parachutes in the cluster. Faultless functioning of all three systems was required for a valid test.

A. Inflation Aids

1. Riser Extensions

Three different lengths of cluster riser extension were tested. The cluster riser extension, as shown in Fig 6, was a single line from each individual parachute confluence point to the suspended weight. The procuring agency specified lengths of $0.2\ D_o$, $0.4\ D_o$, and $0.6\ D_o$ as being of interest, and these were used in the respective configurations.

2. Centerlines

Using a centerline to pull the parachute vent towards the confluence point has recently gained considerable attention as a method to both increase steady state drag and reduce opening time (Ref 7). Also wind tunnel tests (Ref 8) were conducted using different centerline lengths (Fig 9). Figure 9, taken from Ref 8, shows the tangent force coefficients measured at an angle of attack* of 20°. Although a suspension line length of $L_s = 0.88\ D_o$ was not tested in Ref 8, the trend of the data indicates that the maximum steady state drag will be obtained in the region of $1.0 \leq L_c/L_s \leq 1.1$, which fact leads to the selection of the centerline length of $L_c = 0.88\ D_o$ or $L_c = 1.0\ L_s$ and $L_c = 0.97\ D_o$ or $L_c = 1.10\ L_s$ for this study.

3. Internal Parachutes

An internal solid flat circular parachute of $D_o = 1$ ft was also used as an inflation aid. The size and
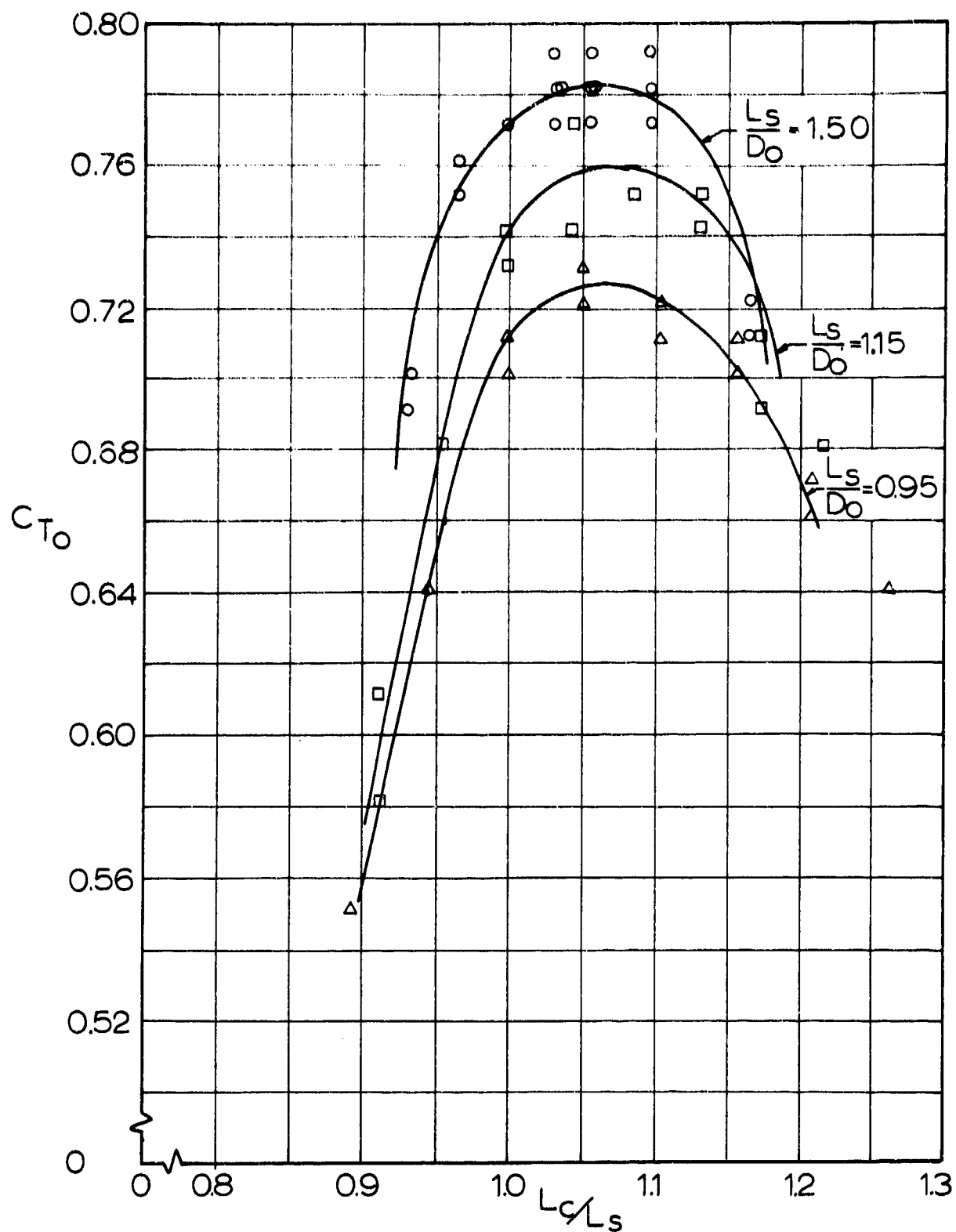
*Trim angle $\alpha_T \approx 20^o$.

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Fig 9   Tangent Force Coefficients of a G-11A
Parachute at an Angle of Attack of $\alpha = 20°$
with Different Suspension and Center
Lines.   (Ref 8, $D_O = 40$ in)

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location of the internal parachute were selected on the basis
of previous experience particularly in view of Ref 3. The
results of Ref 3 showed that the filling time and its deviations
of a parachute is reduced considerably as the diameter of
the internal parachute is increased up to about 18% of the
main parachute; beyond this point, the effect of the internal
parachute begins to level off. Thus, both for convenience
and to insure nearly optimum performance, an internal para-
chute of $D_O = 1$ ft, equivalent to 20% of the nominal diameter
of the main parachute, was located 1 inch or 1.67% D_O behind
the skirt of the main parachute.

B.   Test Program

The test program included 19 configurations which
are tabulated below:

    I.   Three Parachute Cluster (m* = 2.33)

    a.   No Riser Extension with:

        1.   Standard Parachutes

        2. $L_c = 0.88\ D_O$ Centerline

        3. $L_c = 0.97\ D_O$ Centerline

        4.   Internal Parachute, 0.2 D_O

    b.   0.2 D_O Riser Extension with:

        1.   Standard Parachutes

        2. $L_c = 0.97\ D_O$ Centerline

    c.   0.4 D_O Riser Extension with:

        1.   Standard Parachutes

        2. $L_c = 0.88\ D_O$ Centerline

        3. $L_c = 0.97\ D_O$ Centerline

        4.   Internal Parachute, 0.2 D_O

    d.   0.6 D_O Riser Extension with:

        1.   Standard Parachutes

II. <u>Two Parachute Cluster</u> ($m* = 1.57$)

a. $0.2 \ D_O$ Riser Extension with:

   1.   Standard Parachutes

III. <u>Single Parachute</u> ($m* = 2.33$, unless stated)

a.   No Riser Extension with:

   1.   Standard Parachutes

   2.   Standard Parachutes ($m* = 1.57$)

   3. $L_C = 0.97 \ D_O$ Centerline

b. $0.4 \ D_O$ Riser Extension with:

   1.   Standard Parachutes

   2. $L_C = 0.88 \ D_O$ Centerline

   3. $L_C = 0.97 \ D_O$ Centerline

   4.   Internal Parachute, $0.2 \ D_O$

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VI. RESULTS

The results of these experiments will be presented in three summarizing tables and a number of graphs showing averaged numerical values.

As guidelines for the review of these results it may be stated that the total down time of the configurations reflects the degree of uniformity and quickness of inflation of the system. From the down time and the total drop altitude a fictitious velocity can be derived. The down time is a good characteristic, but the average velocities are more conclusive since they incorporate the variation of drop distance of the individual configurations. Using average values of this velocity and the standard deviations, one gets a fairly reliable picture of the opening and descent performance of the various configurations. This particular characteristic together with the total length from the load to the canopy skirt may be significant for low altitude parachute operations.

Conceivably, one could observe very uniform down times, while the actual inflation characteristics of the individual canopies in the cluster differ considerably. This behavior was never observed and uniformity of down time always indicated uniformity of inflation in view of the time intervals involved.

At this point, it should be mentioned that uniformity of parachute cluster performance can, of course, be based on other criteria, for example, on peak force uniformity. The authors have selected a particular averaging technique. For evaluations in view of a different prime characteristic, other averaging techniques could be used, and different interpretations may be obtained.

The first presentation of the test results is shown below in the form of tabulated statements (Tables I, II, and III). It will be noted that a few configurations had to be omitted from the averaged results because their performance was too erratic to be evaluated; their repeated malfunctions endangered the force sensors due to high speed ground impacts, and these test series were discontinued after a few trials. Also, one should remember that the figures of opening distances are estimates.

For the numerical evaluation of the experiments the following system has been used. Figure 10 shows schematically some of the cluster performance characteristics which were measured. First, the times to peak force, t_{p1}, t_{p2}, t_{p3}, are ordered such that $t_{p1} \leq t_{p2} \leq t_{p3}$. Then the magnitudes of the peak forces are paired with the peak times so that F_{p1} occurred at t_{p1}, etc. The largest peak force, F_{max}, is

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TABLE I

THREE PARACHUTE CLUSTER TESTS, GENERAL RESULTS*

	Configuration	Observations and Remarks
	No Riser Extension	
(1)	Standard Parachute	All parachutes opened close to ground, (available drop distance approximately 28 ft) down time 0.75 sec.
(2)	$L_c = 0.88 \, D_o$	Opening distance approximately 14 ft; down time 1.79 sec.
(3)	$L_c = 0.97 \, D_o$	Opening distance slightly longer than (2); down time 1.69 sec.
(4)	Internal Parachute, $0.2 \, D_o$	Opening distance about same as (2); down time 1.82 sec.
	Riser Extension	
(5)	$L_r = 0.2 \, D_o$	Opening distance approximately 14 ft; down time 1.79 sec.
(6)	$L_r = 0.2 \, D_o$ $L_c = 0.97 \, D_o$	In four tests unsatisfactory parachute inflation. Omitted from further tests.
(7)	$L_r = 0.4 \, D_o$	Opening distance slightly longer than (2); down time 1.49 sec.
(8)	$L_r = 0.4 \, D_o$ $L_c = 0.88 \, D_o$	In four tests two parachutes did not show signs of inflation, streamers, while one parachute inflated partially without progressing further, squidding. In one test two parachutes streamed, one parachute inflated fully. Configuration omitted from further testing.
(9)	$L_r = 0.4 \, D_o$ $L_c = 0.97 \, D_o$	In five out of ten tests at least one parachute failed to inflate; down time 1.62 sec.

Opening distances are estimated and averaged values, down times measured and averaged values. Mass ratio, $m = 2.33$, suspended weight, $W_s = 1.1$ lb, $W_s/3S_o = 0.019$ lb/ft^2.

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TABLE I (CONT.)

THREE PARACHUTE CLUSTER TESTS, GENERAL RESULTS

Configuration	Observations and Remarks
Riser Extension	
(10) $L_r = 0.4 \, D_o$ and Internal Parachute, $0.2 \, D_o$	Opening distance approximately the same as (2); down time 1.85 sec.
(11) $L_r = 0.6 \, D_o$	Opening distance longer than (2); down time 1.53 sec.

TABLE II

TWO PARACHUTE CLUSTER TESTS, GENERAL RESULTS*

Configuration   Observations and Remarks

Riser Extensions

(1) Standard Parachutes   Opening distance approximately 14 ft;
    $L_r = 0.2\ D_o$ down time 1.30 sec.

*Opening distances are estimated and averaged values, down times measured and averaged values. Mass ratio, $m^* = 1.57$, suspended weight 1.1 lb, $W_s/2S_o = 0.028\ lb/ft^2$.

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TABLE III

Configuration	Observations and Remarks

No Riser Extensions

(1) Standard Parachute — Very mild canopy pulsation; average peak time, $\bar{t}_p = 0.19 \pm 0.04$ sec.

(2) Standard Parachute ($m^* = 1.57$) — Slow, even opening, canopy pulsation somewhat stronger than configuration (1), but still mild; average peak time, $\bar{t}_p = 0.20 \pm 0.02$ sec.

(3) $L_c = 0.97 \, D_o$ — Canopy pulsation approximately as configuration (1), average peak time, $\bar{t}_p = 0.21 \pm 0.03$ sec.

Riser Extensions

(4) $L_r = 0.4 \, D_o$ — Canopy pulsation about as configuration (1); average peak time, $\bar{t}_p = 0.19 \pm 0.02$ sec.

(5) $L_r = 0.4 \, D_o$ and $L_c = 0.88 \, D_o$ — Canopy pulsation very noticeable, in one out of five tests nearly complete collapse was observed, but in all cases equilibrium speed seemed to be established before ground impact. Average peak time, $\bar{t}_p = 0.24 \pm 0.03$ sec.

*The remarks concerning canopy pulsation are based on interpretation of force-time recordings. Average times to peak force, $\bar{t}_p$, are extracted from force-time recordings. Down times were not obtainable because of minimal steady state and impact forces. Mass ratio, $m^* = 2.33$, unless stated otherwise. Suspended weights, $W_s = 0.37$ lb, and $W_s = 0.55$ lb and surface loading, $W_s/S_o = 0.019$ lb/ft^2 and $W_s/S_o = 0.028$ lb/ft^2, respectively.

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TABLE III (CONT.)

SINGLE PARACHUTE TESTS, GENERAL RESULTS

| Configuration	Observations and Remarks
(6) $L_r = 0.4 \ D_o$ and $L_c = 0.97 \ D_o$	Canopy pulsation about the same as in configuration (5) with possibly a little lower force amplitude. Also one near collapse was observed. Average peak time, $\bar{t}_p = 0.20 \pm 0.03$ sec.
(7) $L_r = 0.4 \ D_o$ and Internal Parachute, $0.2 \ D_o$	Canopy pulsation in general milder than configuration (5), except in one out of five tests; canopy was in the status of elevated force when ground impact occurred. In this case, equilibrium speed was probably not established. Average peak time, $\bar{t}_p = 0.17 \pm 0.01$ sec.
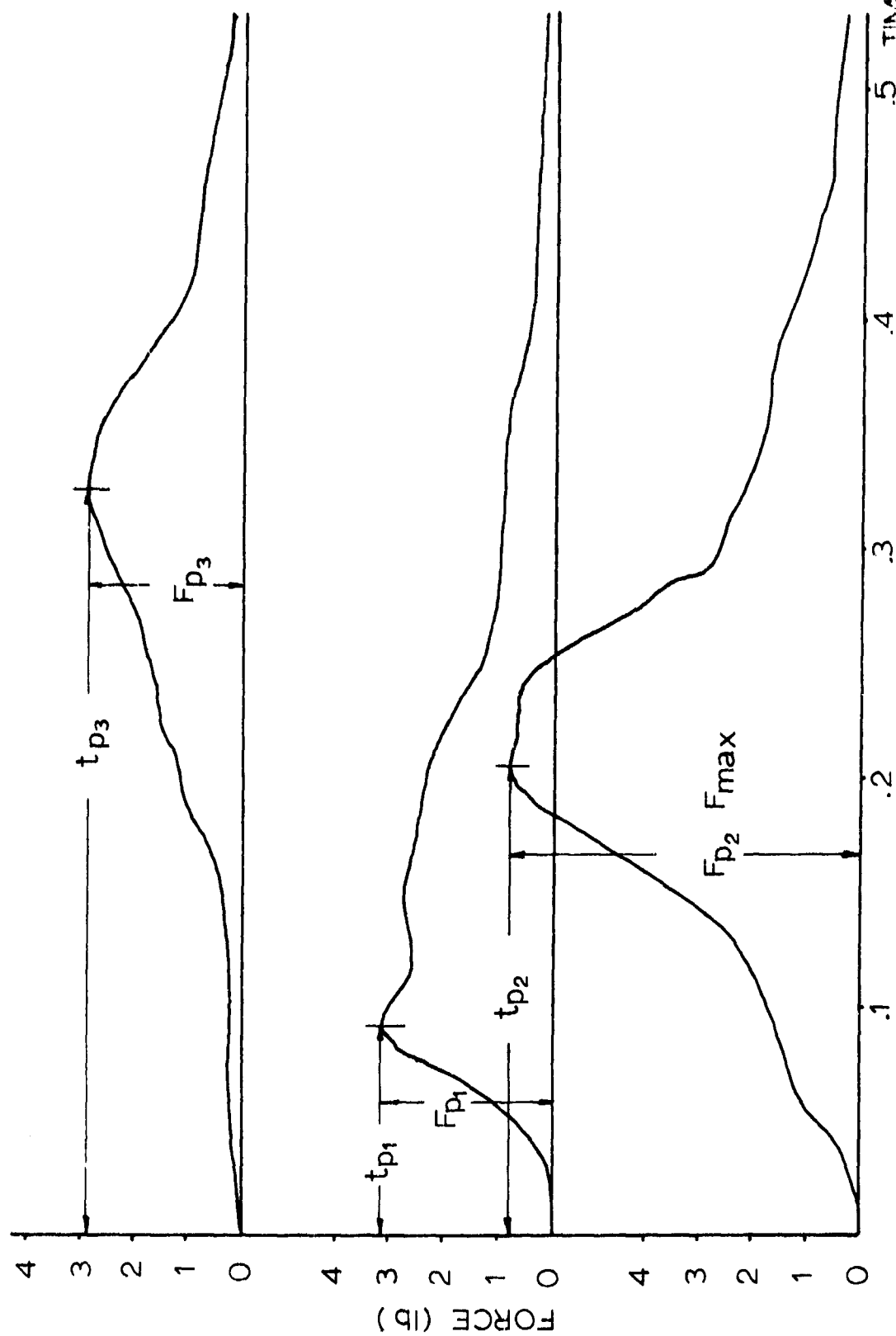
Fig 10 Schematic Explanation of Terms used in Presentation of Cluster Performance Chacteristics

defined as the highest of the three forces, regardless of the time when it occurred; for the characteristics shown schematically in Fig 10, $F_{max} = F_{p_2}$.

The down time for each test was measured from the force traces as the time from catapult release until the ground impact of the suspended weight. The measured down times are not presented in the figures because the available drop distance varied corresponding to the model configuration. Since the deployment processes of all configurations had to be identical, it was necessary to adjust the free length of the catapult shaft corresponding to longer or shorter riser extensions. Thus the drop distance differed slightly for the various configurations. The average velocity was obtained by dividing the actual drop distance by the measured down time.

Figures 11 to 23 present average values of the measured and derived opening characteristics. The derived characteristics are ratios of F_p/F_{max} and t_p/t_{p_1}. Most aspects of these figures are self explanatory, but some explanations may be helpful for the interpretation of the results.

All the values presented are averages of all tests made for a particular configuration which was suitable for numerical evaluation. Thus with averaged values of a number of tests, it is, for example, not necessary that one of the F_p/F_{max} ratios is unity. However, for any single test there is, of course, one force ratio, F_p/F_{max} unity, since by definition F_{max} is the largest F_p of that particular test.

Furthermore, in accordance with this mode of evaluation the force and time ratios, F_p/F_{max} and t_p/t_{p_1}, indicate the uniformity characteristics of the cluster opening in view of force and time. The configuration with the most uniform force-time performance is the one with F_p/F_{max} and t_p/t_{p_1} values that are about equal and near unity. Of course, one has to consider also the force level. To exclude misjudgments, the standard deviations shown in the presentation of other characteristics must also be considered, and a favorable configuration should also have small standard deviations.

The time duration of the opening process and completeness of inflation is reflected in the average systems velocity. For this characteristic it can be said that the configuration with the lowest velocity, smallest standard deviations and having the shortest total length would require the lowest operational release altitude.
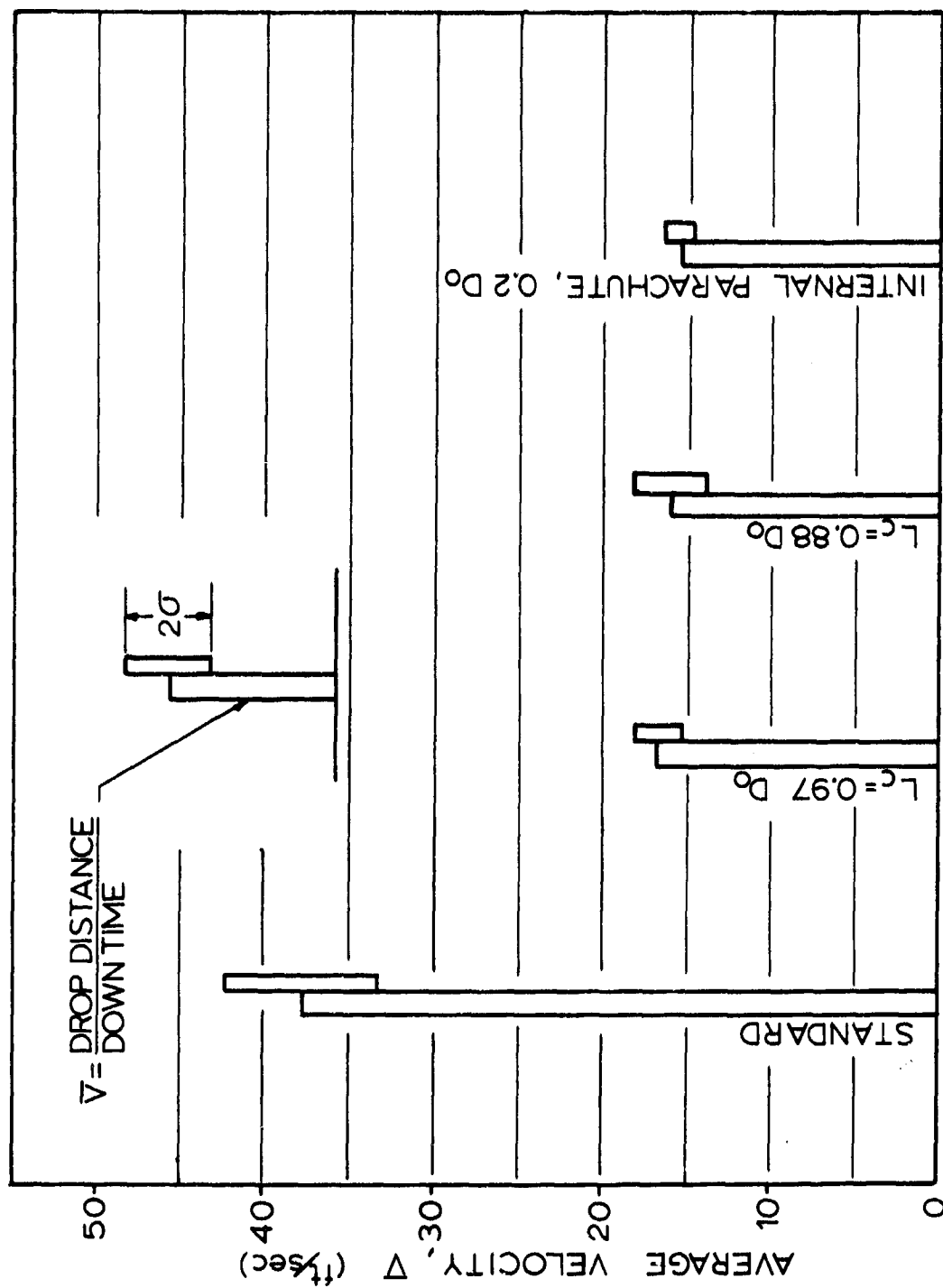
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Fig 11 Cluster of 3 Parachutes without Riser Extensions, Average Velocity and Standard Deviation
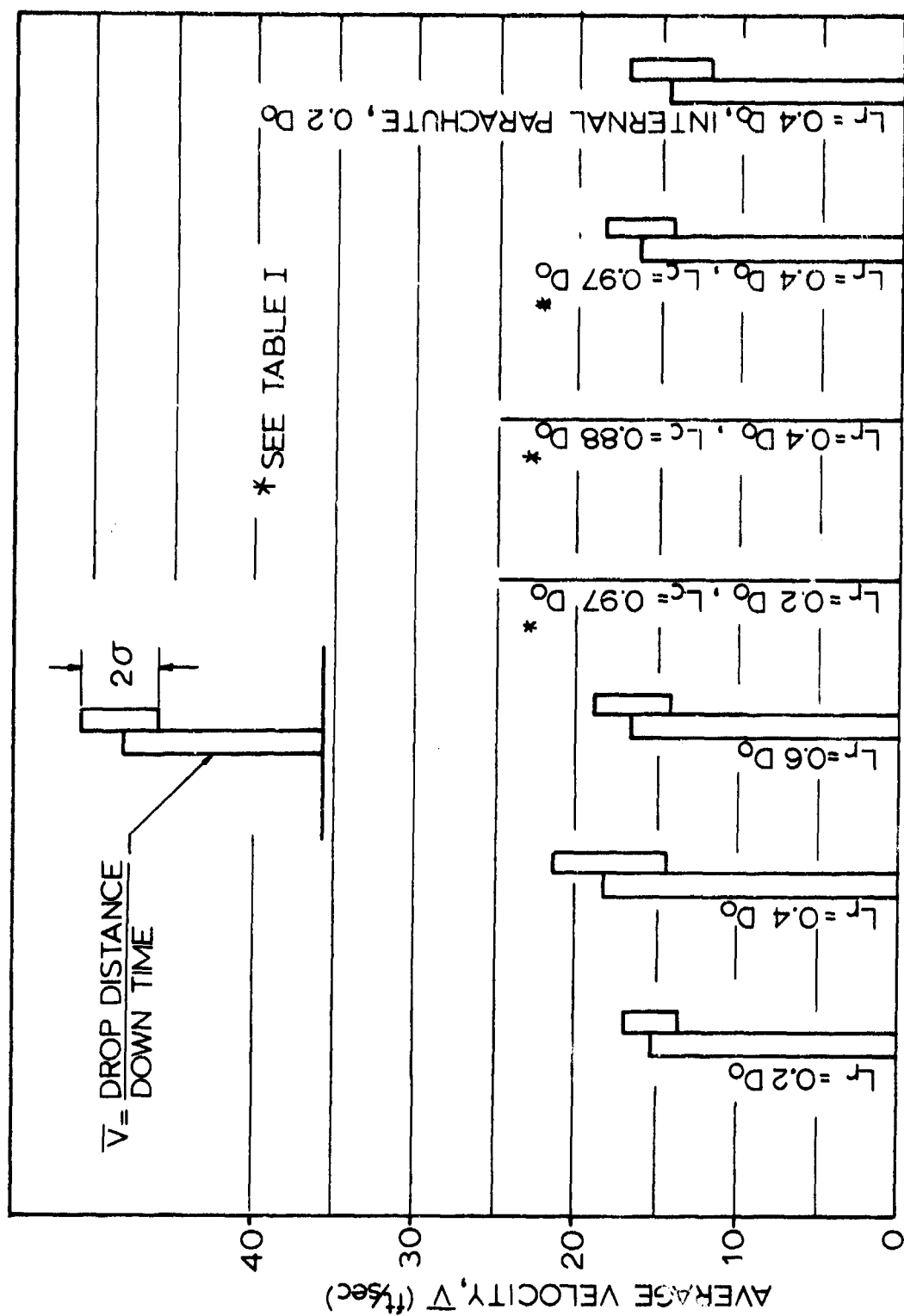
Fig 12 Cluster of 3 Parachutes with Riser Extensions, Average Velocity and Standard Deviation
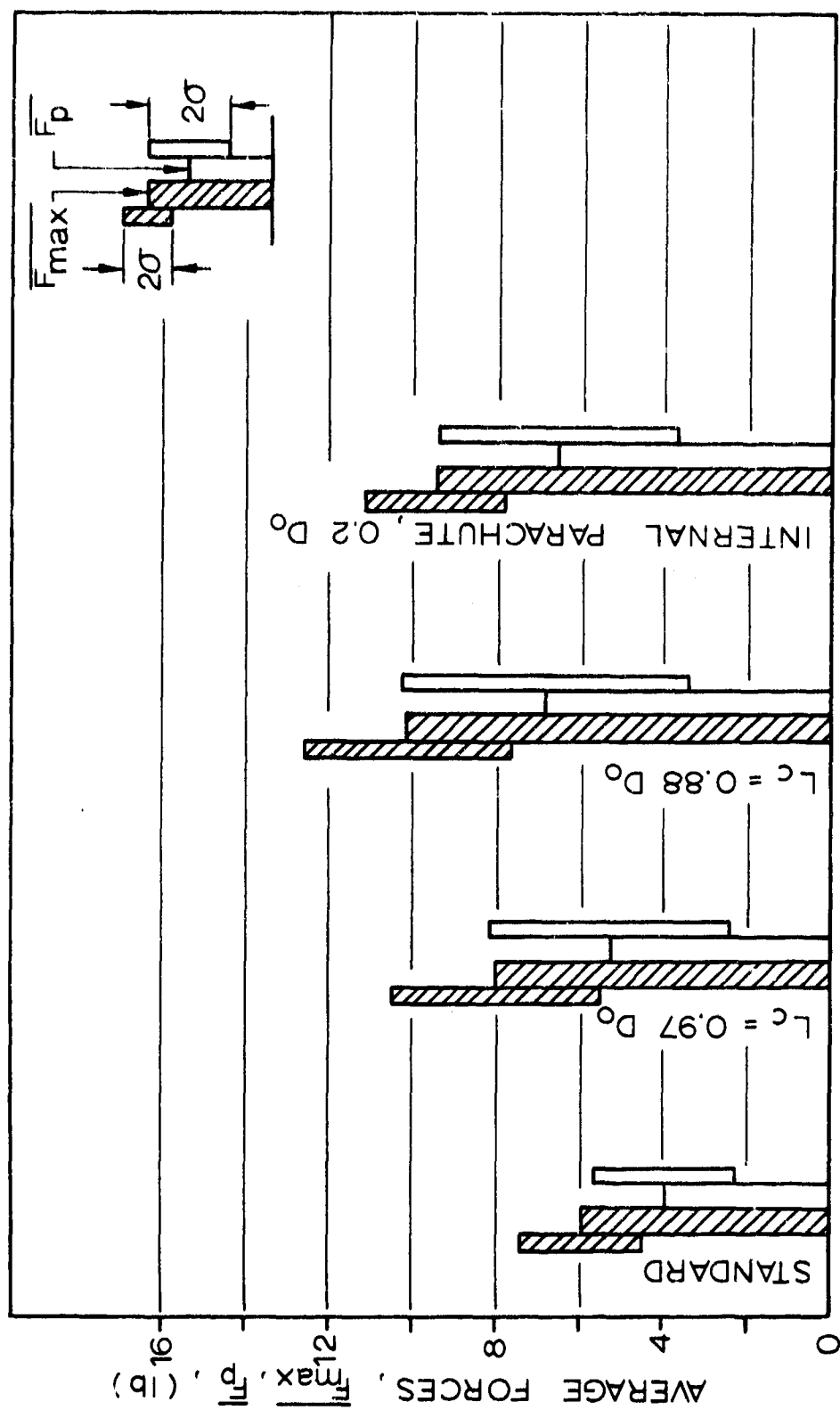
33

Fig 13 Cluster of 3 Parachutes without Riser Extensions, Average Forces and Standard Deviation
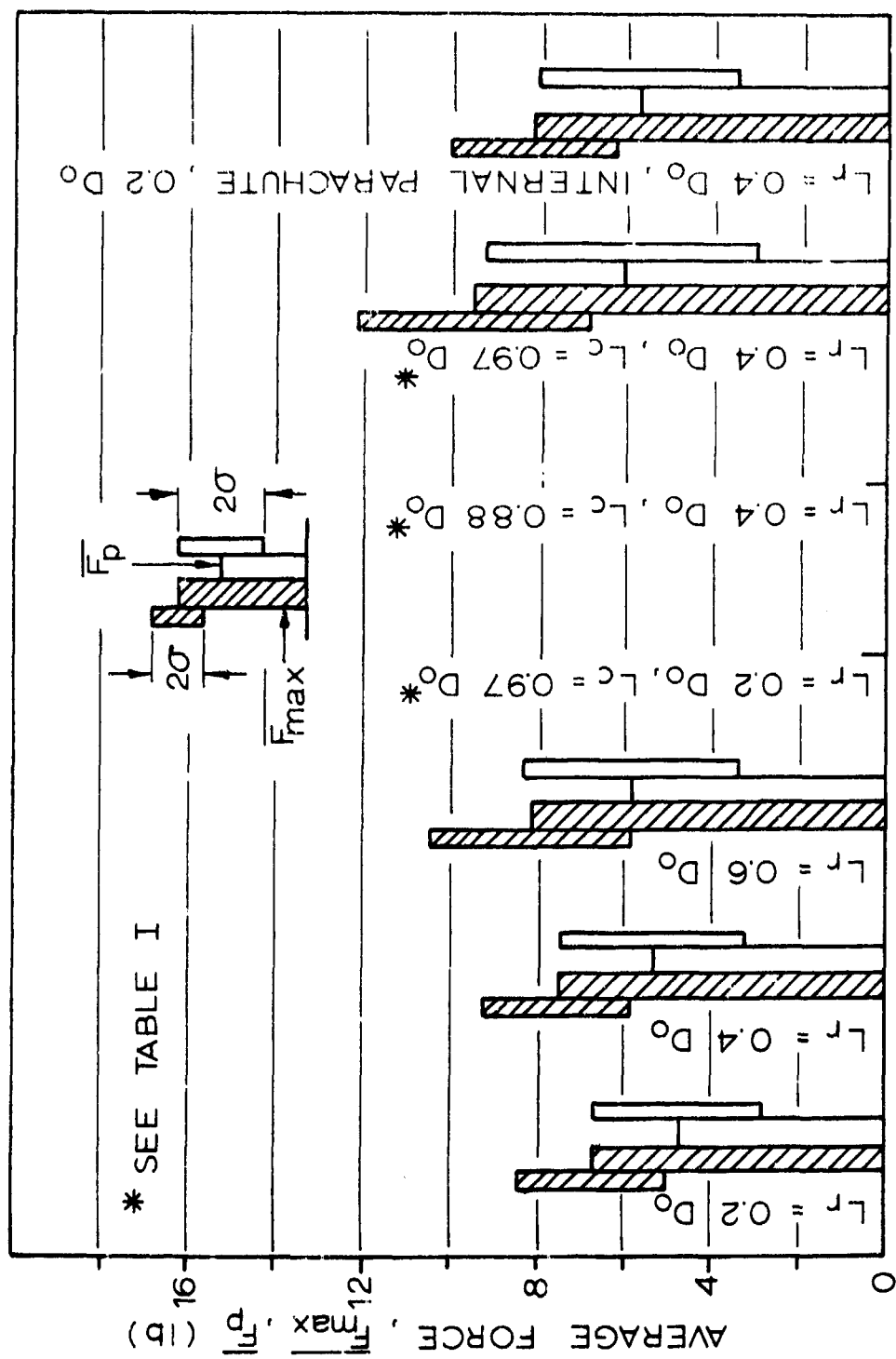
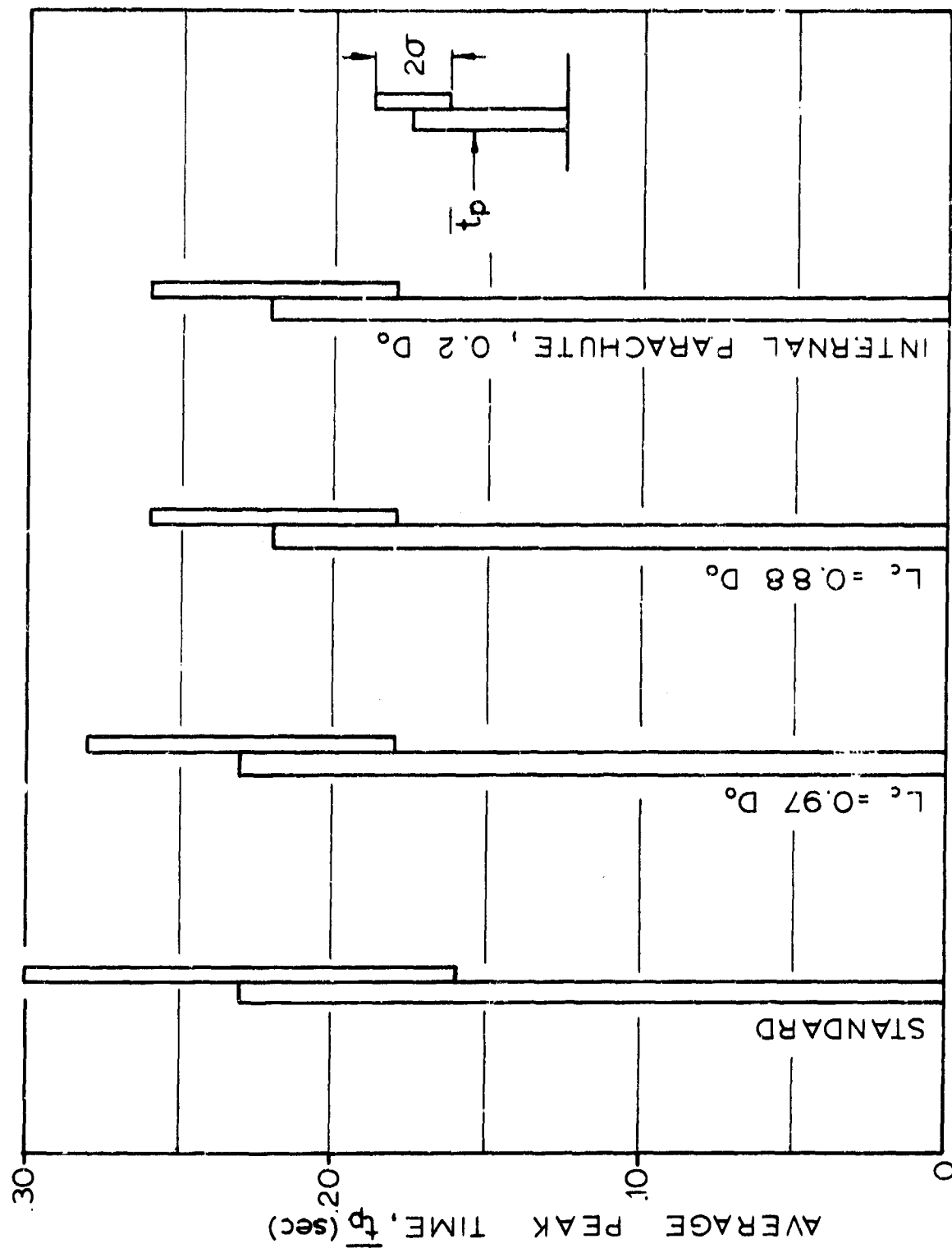Fig 14 Cluster of 3 Parachutes with Riser Extensions, Average Forces and Standard Deviation

Fig 15 Cluster of 3 Parachutes without Riser Extensions,
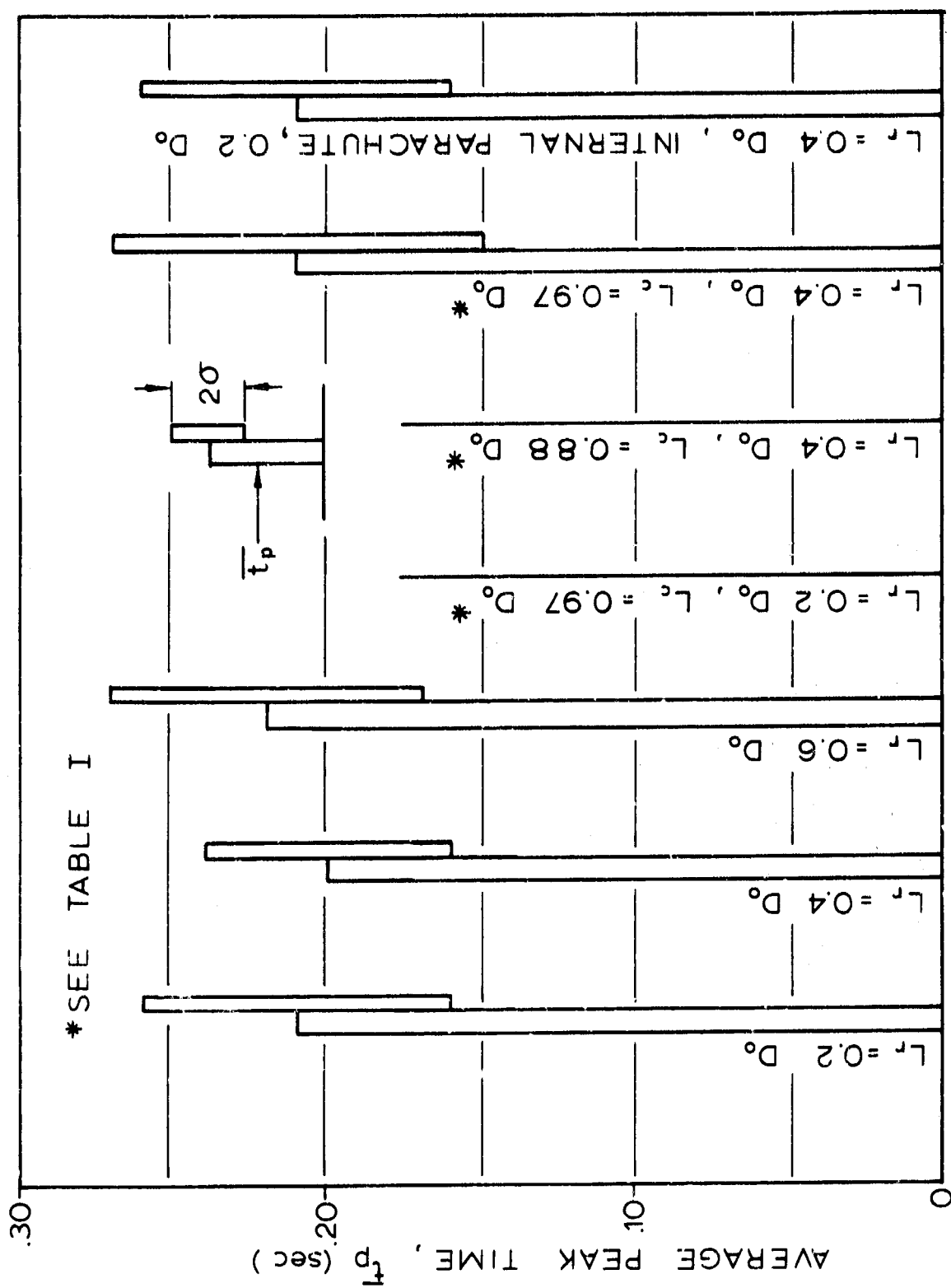Average Peak Time and Standard Deviation

Fig 16 Cluster of 3 Parachutes with Riser Extensions, Average Peak Time and Standard Deviation

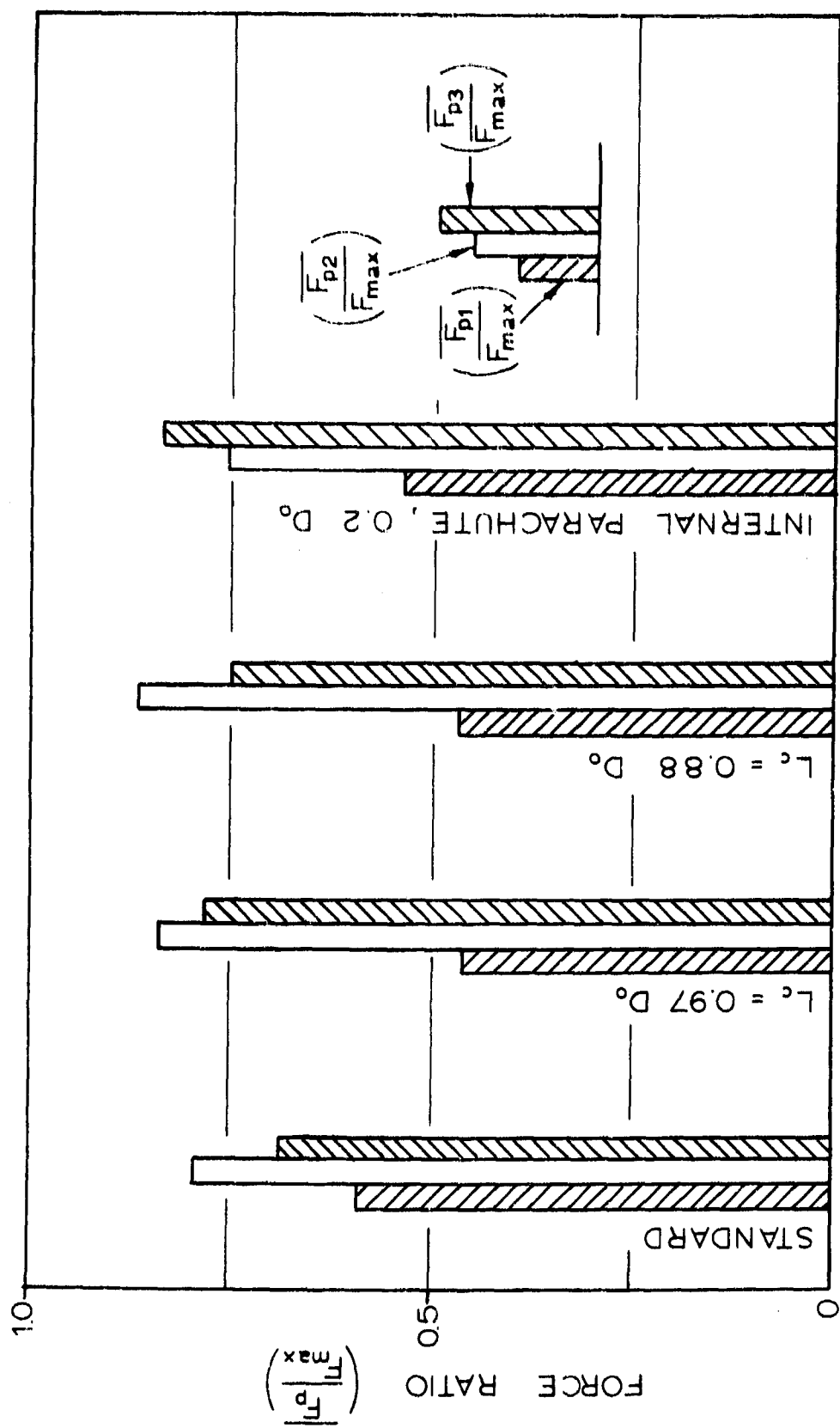Fig 17 Cluster of 3 Parachutes without Riser Extensions, Average Force Ratios
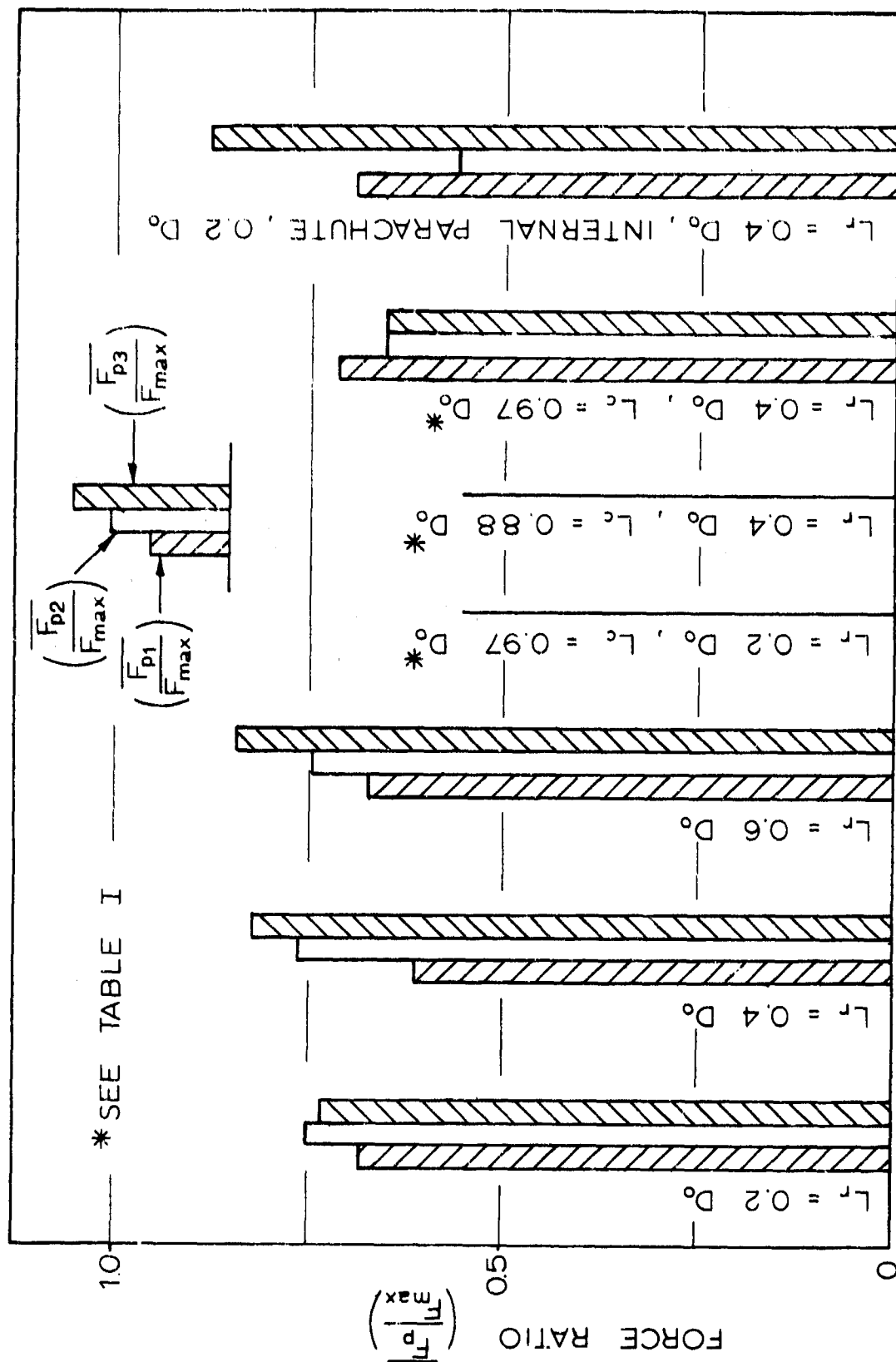
Fig 18 Cluster of 3 Parachutes with Riser Extensions, Average Force Ratios
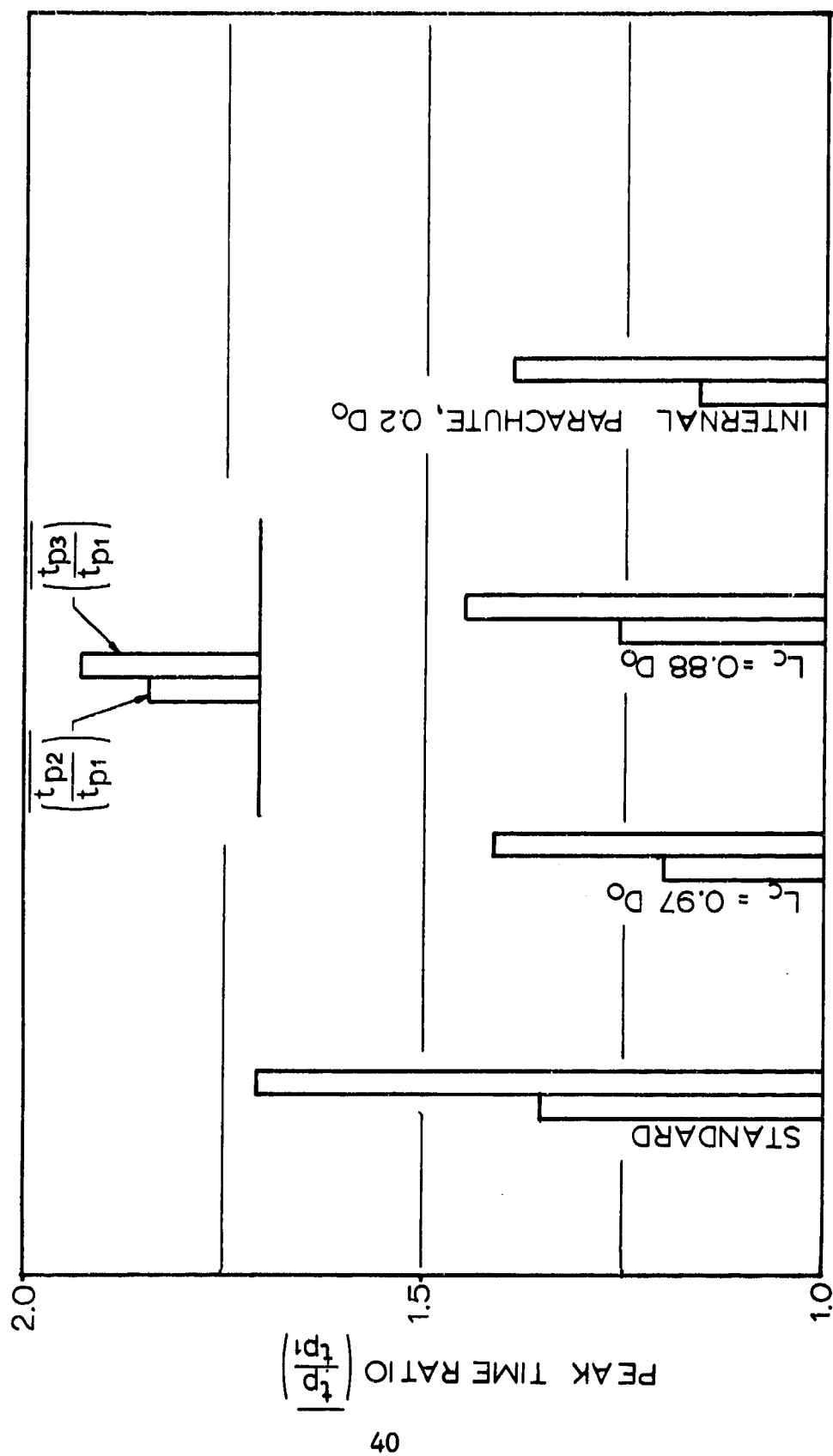
Fig 19 Cluster of 3 Parachutes without Riser Extensions. Average Time Ratios
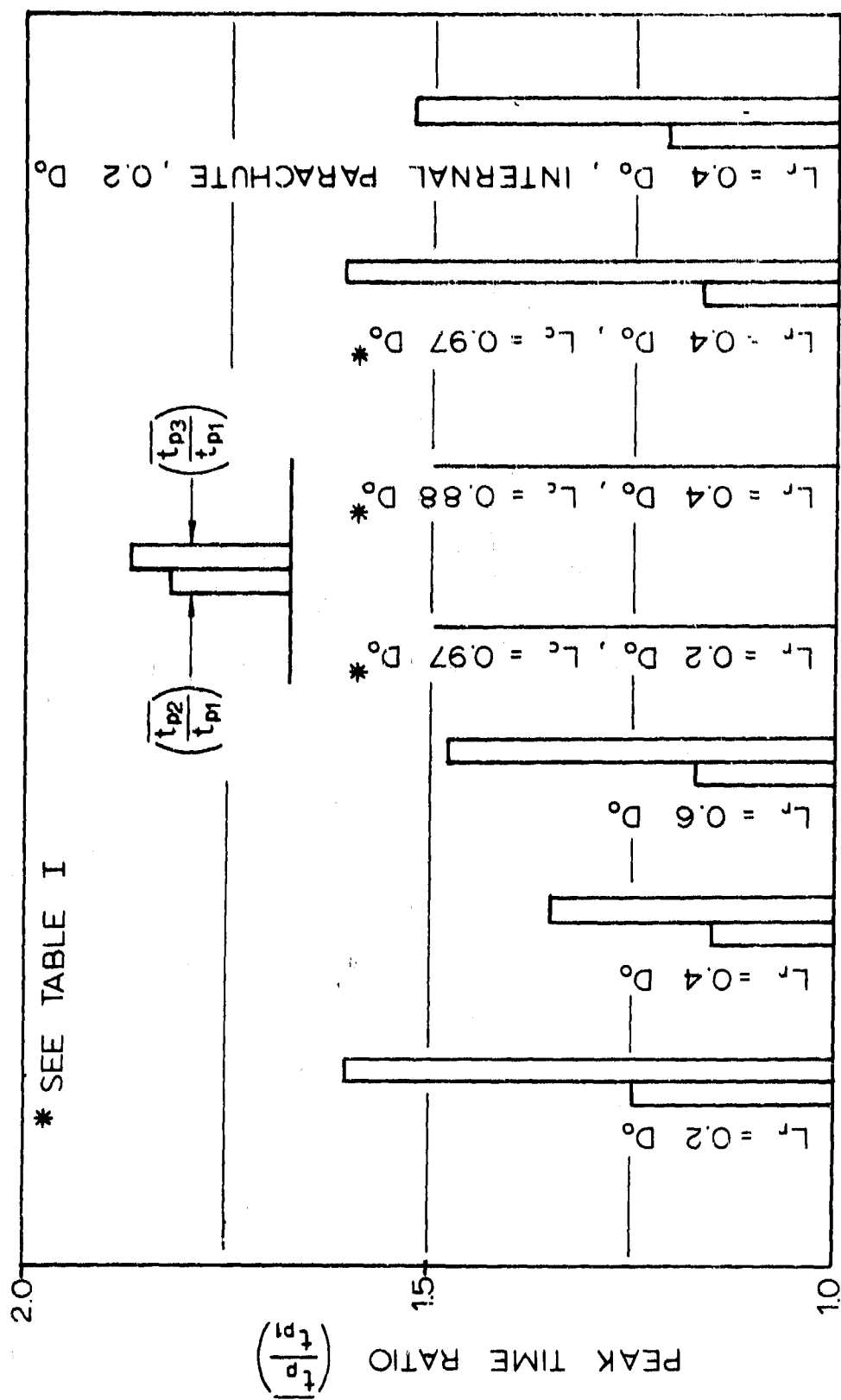
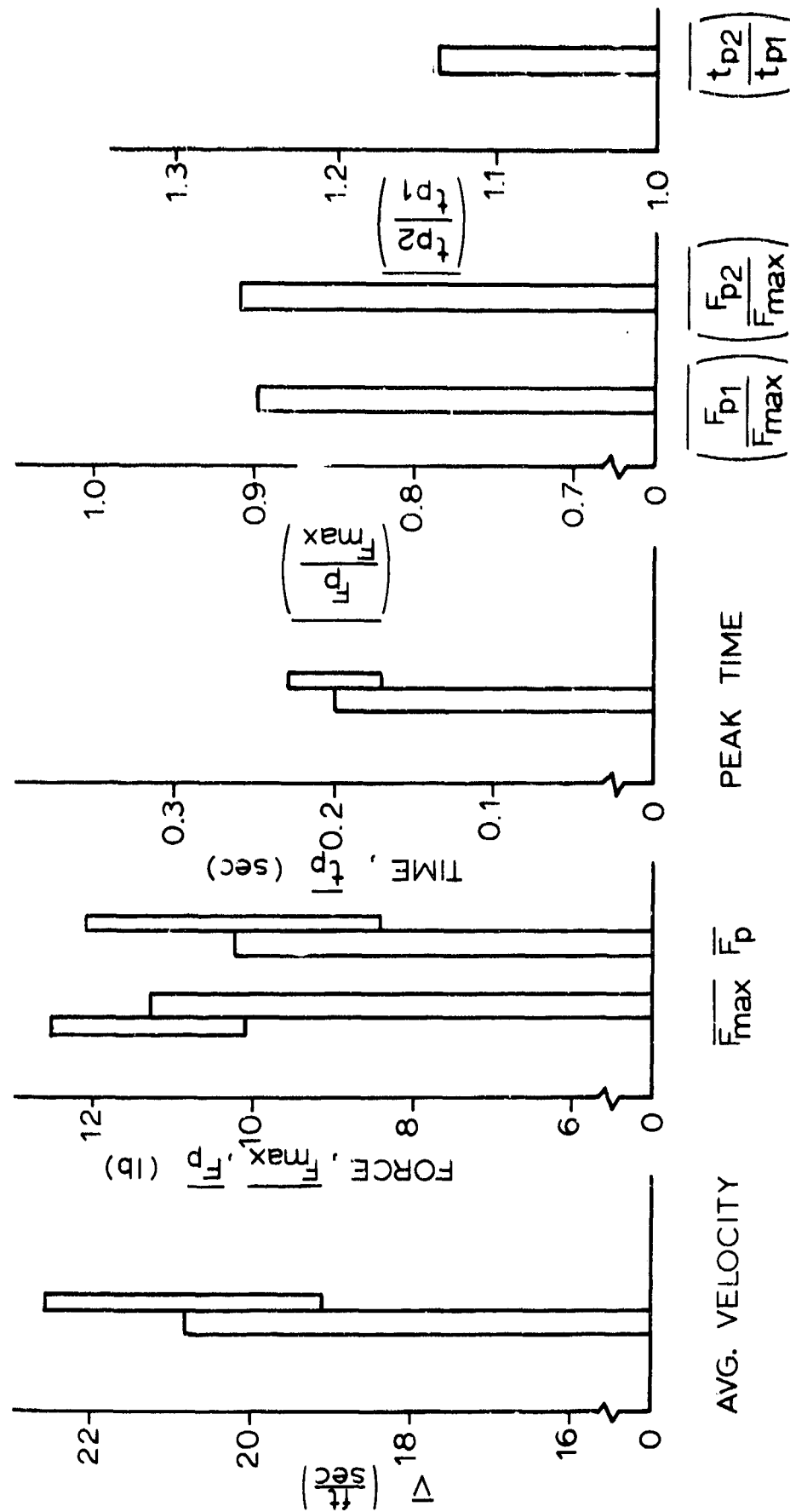Fig20 Cluster of 3 Parachutes with Riser Extensions, Average Time Ratios

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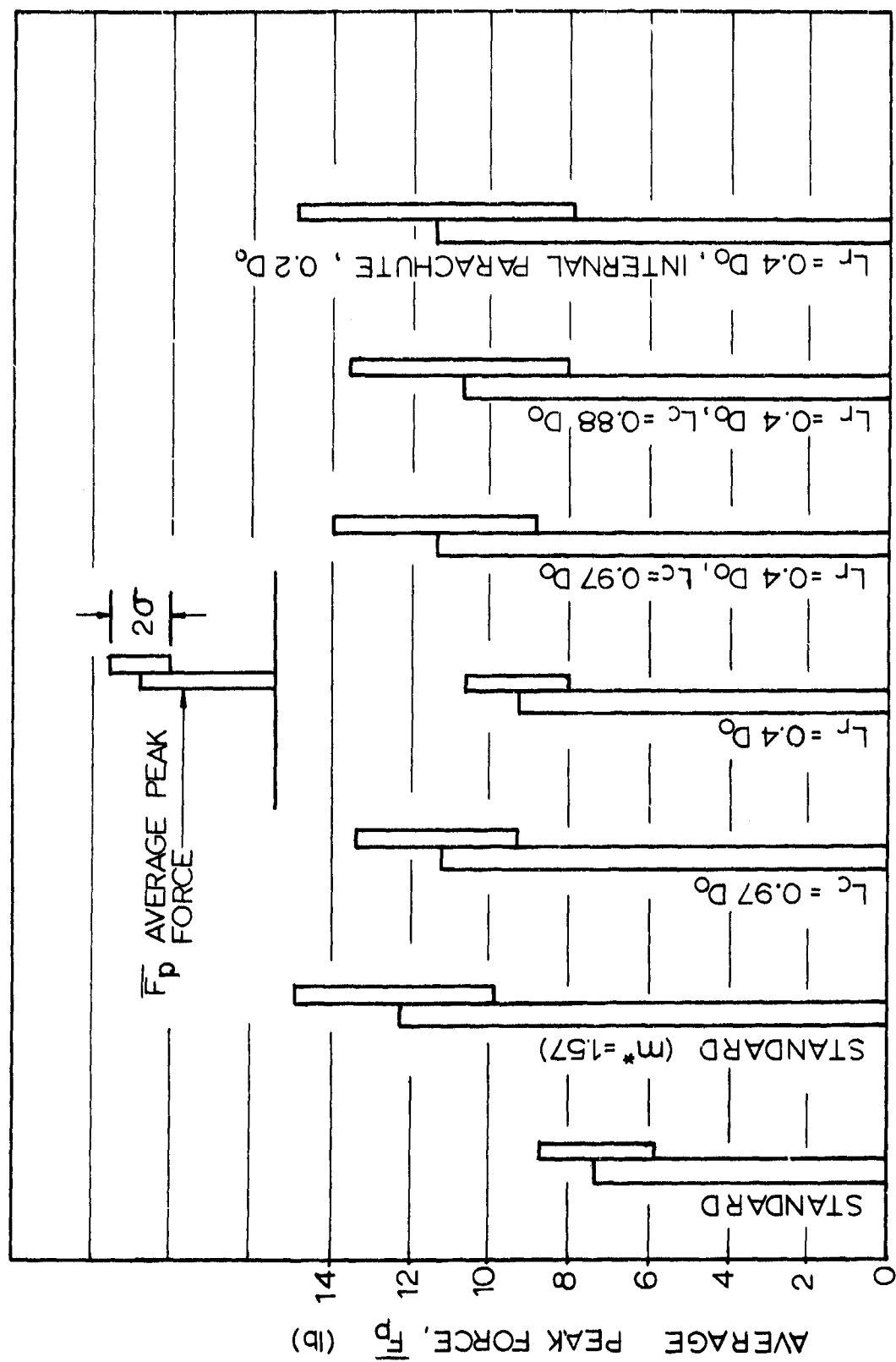Fig 21 Cluster of 2 Parachutes, Measured and Derived Results, $L_r = 0.2 \, D_0$, $m^* = 1.57$

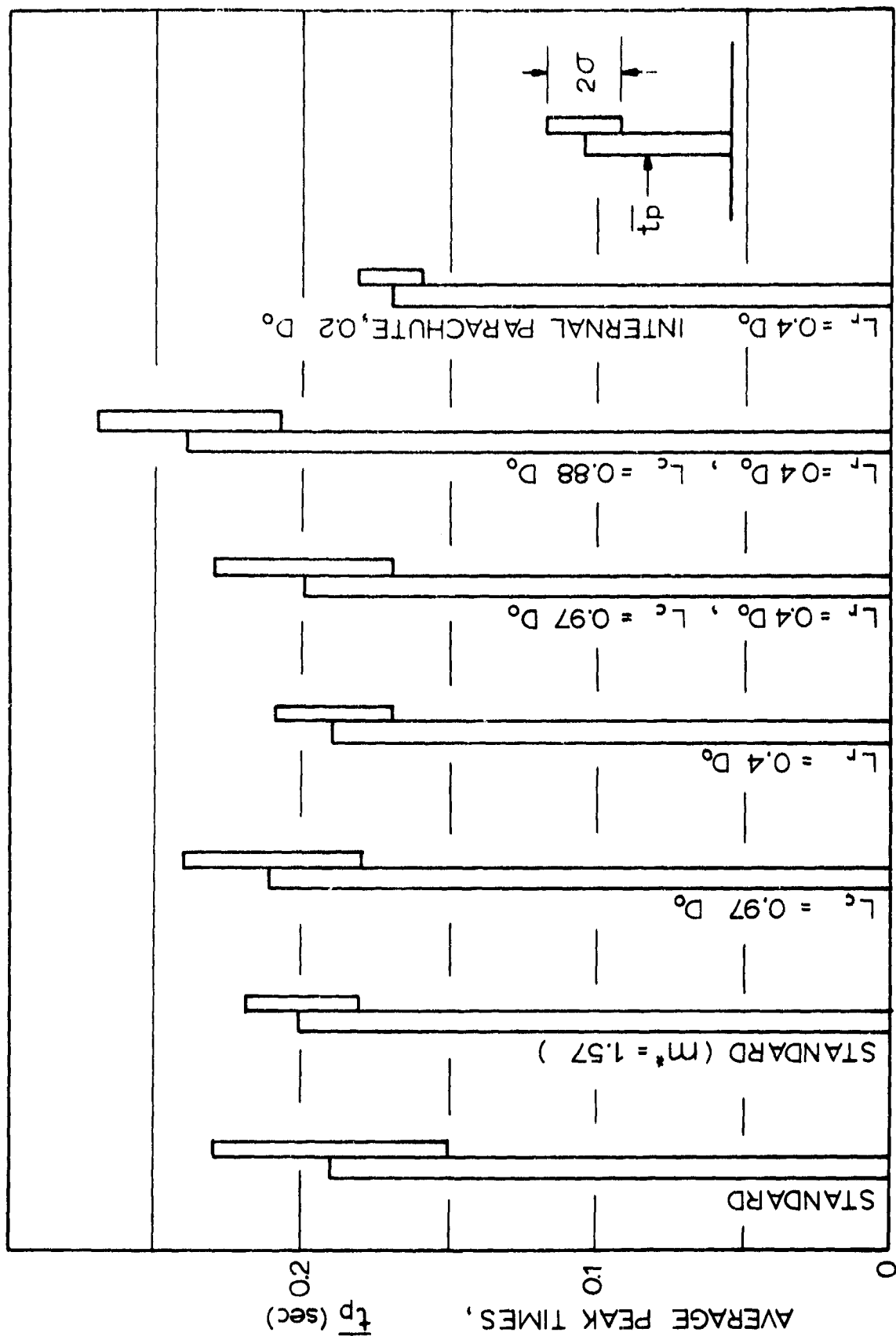Fig 22 Single Parachute with Various Inflation Aids, Average Peak Forces and Standard Deviation

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Fig 23 Single Parachute with Various Inflation Aids,
Average Peak Times and Standard Deviation

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VII. CONCLUDING REMARKS

Figures 11 through 23 represent the quantitative results of the performance uniformity study of clustered parachutes. Since both the investigation and the presentation of results is somewhat unusual, it appears to be justified to present the authors' interpretation of the results.

Figure 11 shows the characteristic velocity, $\bar{v}$, of the parachute cluster without riser extension both with and without inflation aids such as centerlines and internal canopies. One notices that the centerlines as well as the internal parachute significantly reduce the characteristic velocity as well as its standard deviation. In this group, the parachute with an internal canopy shows the lowest characteristic velocity and the lowest standard deviation.

Comparing Figs 11 and 12 it can be seen that riser extensions also impressively reduce the characteristic velocity of the cluster as well as the standard deviation as shown in Fig 12. In this group the configuration with riser extension, $L_r = 0.4 \, D_O$ and internal canopy, has the lowest average velocity, while the configuration with $L_r = 0.2 \, D_O$ has the lowest standard deviation. Again comparing Figs 11 and 12 one notices that the configuration with only an internal canopy has about the same average velocity but smaller standard deviation then the configuration with $0.2 \, D_O$ riser extension. Also, considering the total length of the load parachute system, one tends to assume that the cluster of three parachutes without riser extension but with internal canopy may be the most suitable configuration for low altitude release. It is also interesting to notice that the combinations with riser extensions and centerlines very often failed to inflate; and based on these model tests, these combinations must be considered the least suitable.

Figures 13 and 14 present the average values of the maximum and peak forces. As to be expected, the standard parachute without any inflation aids has the lowest force level. The second lowest force level was recorded with the configuration with $0.2 \, D_O$ riser extension, while the cluster with a centerline of $0.88 \, D_O$ had the highest force level.

Figures 15 and 16 indicate that the average peak times of all configurations are about equal, while the standard parachute without inflation aids has the largest deviation.

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Since, in these tests, the peak forces of the various configurations sometimes developed early or late in the inflation process, this information is considered to be more of academic interest.

In the following two figures, 17 and 18, an attempt is made to compare the level of the measured forces of the different parachutes of each configuration with each other.

As stated before, the most uniform performance, in view of forces developed, would occur when the average force ratios for first, second, and third parachute openings differ the least from each other and, in general, approach the value of unity. Applying this guideline to these two figures, it appears that centerlines in the configurations without riser extensions introduced a noticeable degree of non-uniformity. Two combinations of riser extensions and centerlines failed completely. The two configurations with $L_r = 0.2 \, D_O$ and $L_r = 0.4 \, D_O$ with $L_c = 0.97 \, D_O$ indicate the most uniform force development of all configurations tested. However in 50% of all experiments with the configuration having $0.4 \, D_O$ riser extension and $0.97 \, D_O$ centerline one parachute failed to inflate.

Related to the force ratios presented above are the time ratios shown in Figs 19 and 20. Here one observes that the time at which the last parachute inflates may be 1.7 times longer than the time of inflation of the first or lead parachute. In this respect the configuration without any inflation aids has the largest dispersion while the same parachutes with $L_r = 0.4 \, D_O$ have the smallest.

One configuration of a cluster of two parachutes was tested with 20% riser extensions only because this combination showed such favorable performance characteristics when tested in clusters of three canopies. All characteristics of this cluster are shown in Fig 21. One observes a reasonable uniformity and, in general, it appears that this cluster functions more uniformly than a similar cluster of three parachutes.

In concluding this study, it appeared to be of interest to investigate the reason for the considerable differences in performance characteristics and, in particular, it seemed to be important to find indications why combinations of riser extensions and centerlines completely or partially failed. Therefore, a number of experiments were made with single parachutes with various inflation aids. In view of this objective the time between the instant of snatch and peak force seems to be significant. However, the results shown in Figs 22 and 23 are not very conclusive. It can be seen that, as a single parachute, the configuration with 40%

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riser extension and an internal canopy showed the shortest time to peak force and the smallest standard deviations. It will be noticed that not all configurations which were tested in the series of clusters are incorporated in this single canopy testing. This restraint was necessary in view of the over-all complexities of this study and the availability of time and funds. From the results on hand it can merely be stated that the configuration which showed the shortest peak time and the minimum of deviation as a single parachute had very good performance characteristics in a cluster of three canopies.

As an over-all result of these model tests, it is the opinion of the authors that in clusters of three, the standard parachute with $0.2 \, D_O$ riser extensions and the standard parachute with an internal canopy showed the best over-all uniform performance characteristics. The fact that a configuration without riser extension has the minimum system length may have certain significance for low altitude parachute applications.

For the purpose of analysis of the established test data from a different point of view and other principally desirable or undesirable characteristics, tabulated data and traces of force-time recordings are shown in the appendix.

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APPENDIX

The numerical evaluations and the qualitative descriptions of the parachute cluster performance study shown above are based on individual recordings. Details of these recordings are given in the following diagrams and tables.

The diagrams contain numerous details not specifically analyzed and evaluated in this study. Therefore, it appears to be advisable to preserve these diagrams for any further studies with different objectives.

During actual testing the gain for each force sensor was adjusted and recorded to each run so that each sensor had nearly the same force sensitivity. In the figures that follow, the force scale presented is for use with all parachute forces on the figure. The scale is accurate to within about 3%; to achieve any greater accuracy the individual calibrations and actual oscillograph recordings should be consulted.

As stated earlier, the times shown are measured from catapult trigger release, which is not shown in the following figures, rather the time scales start at 0.10 sec after release. The time from release to 0.10 sec includes the period of initial acceleration of the weight and the deployment of the parachutes. During this period the acceleration of the suspended weight decreases from an initial value of more than 200 g's to 1 g after separation from the shaft. At the very high accelerations the force sensors not only sense the forces applied but also act as accelerometers because of the masses at each end of the sensing beam. Thus the recorded trace in the initial period has no correlation to deployment forces and is not shown in order to prevent any misinterpretation.

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TABLE IV

3 PARACHUTE CLUSTER, STANDARD PARACHUTES

DROP DISTANCE = 28.0FT   4° = 2.33

TEST	DOWN TIME (SEC)	VELOCITY (FT/SEC)	T(P) (SEC) 1	2	3	F(P) (LB) 1	2	3	F(MAX) (LB)	F(P1)/F(MAX)	F(P2)/F(MAX)	F(P3)/F(MAX)	T(P2)/T(P1)	T(P3)/T(P1)
1	.72	38.89	.17	.19	.27	3.00	9.50	4.00	9.50	.32	1.00	.42	1.15	1.4?
2	.59	47.86	.14	.20	.20	2.00	3.00	5.50	5.50	.36	.55	1.00	1.39	1.43
3	.75	37.33	.16	.21	.31	3.00	5.50	3.50	5.50	.55	1.00	.64	1.34	1.37
4	.89	31.64	.15	.25	.26	2.30	3.00	5.50	5.50	.42	.55	1.00	1.67	1.72
5	.64	43.41	.19	.21	.29	6.00	2.50	3.00	6.00	1.00	.42	.50	1.04	1.55
6	.75	37.33	.18	.20	.29	4.50	2.50	4.50	4.50	1.00	.56	1.00	1.11	1.04
7	.86	32.56	.21	.29	.45	3.30	6.00	2.30	6.00	.55	1.00	.38	1.39	2.09
8	.79	35.67	.21	.23	.24	3.50	3.50	4.00	4.00	.84	.88	1.00	1.12	1.17
9	.76	36.84	.14	.27	.32	2.00	7.00	3.50	7.00	.29	1.00	.50	1.93	2.29
10	.80	35.00	.15	.21	.24	3.00	6.00	2.50	6.00	.56	1.00	.42	1.3-	1.57
AVERAGE	.75	37.65	.17	.22 / .23	.29	3.26	4.85 / 3.98	3.83	5.95	.59	.79	.69	1.35	1.7?
STANDARD DEVIATION		4.61	.03	.03 / .07**	.07	1.16	2.21 / 1.70**	1.05	1.42					

** STANDARD DEVIATION FOR ENTIRE T(P) AND F(P) GROUPS

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TABLE Ⅴ

3 PARACHUTE CLUSTER, L(C) = 0.97 D(0)

DROP DISTANCE = 28.0FT   N* = 7.33

TEST	DOWN TIME (SEC)	VELOCITY (FT/SEC)	T(P) (SEC) 1	2	3	F(P) (LB) 1	2	3	F(MAX) (LB)	F(P1)/F(MAX)	F(P2)/F(MAX)	F(P3)/F(MAX)	T(P2)/T(P1)	T(P3)/T(P1)
1	1.59	17.61	.19	.21	.26	1.50	6.90	7.30	7.30	.21	.95	1.00	1.11	1.37
2	1.77	15.82	.18	.25	.40	1.00	7.50	8.00	8.00	.13	.94	1.00	1.39	2.22
3	1.73	16.18	.19	.26	.38	5.90	7.00	2.00	7.00	.84	1.00	.29	1.37	2.00
4	1.59	17.61	.21	.22	.25	2.00	13.00	4.50	13.00	.15	1.00	.35	1.05	1.19
5	1.63	17.18	.21	.22	.23	1.90	4.10	6.50	6.50	.29	.63	1.00	1.05	1.10
6	1.55	18.06	.21	.24	.24	3.50	3.30	10.00	10.00	.35	.33	1.00	1.14	1.14
7	1.48	18.92	.15	.21	.22	2.70	6.00	4.50	6.00	.45	1.00	.75	1.40	1.47
8	1.85	15.14	.17	.24	.24	4.00	4.00	7.00	7.00	.57	.57	1.00	1.41	1.41
9	1.88	14.89	.20	.21	.24	4.00	4.00	4.00	4.00	1.00	1.00	1.00	1.05	1.22
10	1.84	15.22	.21	.21	.21	6.50	11.50	5.00	11.50	.57	1.00	.43	1.05	1.00
AVERAGE	1.69	16.66	.19	.23	.27	3.30	6.73	5.88	8.03	.46	.84	.78	1.20	1.41
				.23			5.30							
STANDARD DEVIATION	1.33		.02	.02	.06	1.75	3.11	2.20	2.57					
				.05 **			2.83 **							

** STANDARD DEVIATION FOR ENTIRE T(P) AND F(P) GROUPS

TABLE VI

3 PARACHUTE CLUSTER, L(C) = 0.88 D(0)

DROP DISTANCE = 28.0FT   H* = 2.33

TEST	DOWN TIME (SEC)	VELOCITY (FT/SEC)	T(P) (SEC) 1	2	3	F(P) (LB) 1	2	3	F(MAX) (LB)	F(P1)/F(MAX)	F(P2)/F(MAX)	F(P3)/F(MAX)	T(P2)/T(P1)	T(P3)/T(P1)
1	1.98	14.14	.23	.24	.24	8.50	8.00	3.50	8.50	1.00	.94	.41	1.04	1.04
2	1.34	20.90	.18	.20	.25	3.90	12.50	8.50	12.50	.31	1.00	.68	1.11	1.39
3	1.65	16.97	.20	.25	.25	4.70	8.00	6.50	8.00	.59	1.00	.81	1.25	1.25
4	1.67	16.77	.13	.25	.30	2.00	14.00	5.50	14.00	.14	1.00	.39	1.92	2.31
5	2.08	13.46	.21	.24	.27	5.00	8.30	3.80	8.30	.60	1.00	.46	1.16	1.29
6	2.06	13.59	.18	.21	.21	3.00	5.70	9.00	9.00	.33	.63	1.00	1.17	1.17
7	1.83	15.30	.14	.21	.25	3.20	5.80	6.00	6.00	.53	.97	1.00	1.56	1.79
8	1.90	14.74	.17	.19	.20	8.00	10.80	10.30	10.80	.76	1.00	.95	1.12	1.18
9	1.80	15.56	.21	.22	.25	1.30	11.60	9.50	11.60	.11	1.00	.82	1.05	1.19
10	1.63	17.18	.14	.18	.26	4.00	1.50	13.00	13.00	.31	.12	1.00	1.29	1.06
AVERAGE	1.79	15.86	.18	.22	.25	4.36	8.62	7.56	10.17	.47	.87	.75	1.26	1.45
				.22			6.85							
STANDARD DEVIATION		2.11	.03	.02	.03	2.22	3.55	2.87	2.46					
				.04 **			3.44 **							

** STANDARD DEVIATION FOR ENTIRE T(P) AND F(P) GROUPS

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TABLE VII

3 PARACHUTE CLUSTER, INTERNAL PARACHUTE, 0.2 D(0)

DROP DISTANCE = 28.0FT   4S = 2.33

TEST	DOWN TIME (SEC)	VELOCITY (FT/SEC)	T(P) (SEC) 1	T(P) (SEC) 2	T(P) (SEC) 3	F(P) (LB) 1	F(P) (LB) 2	F(P) (LB) 3	F(MAX) (LB)	F(P1)/F(MAX)	F(P2)/F(MAX)	F(P3)/F(MAX)	T(P2)/T(P1)	T(P3)/T(P1)
1	1.84	15.18	.18	.22	.24	3.50	5.50	8.50	8.50	.41	.65	1.00	1.22	1.33
2	1.88	14.89	.16	.18	.28	1.50	11.00	6.50	11.00	.14	1.00	.59	1.16	1.75
3	1.83	15.30	.17	.19	.25	8.50	4.00	4.50	8.50	1.00	.47	.53	1.12	1.47
4	1.68	14.89	.19	.23	.24	6.50	3.50	8.50	8.50	.76	.41	1.00	1.21	1.26
5	1.67	16.77	.20	.21	.22	9.50	2.50	13.00	13.00	.73	.19	1.00	1.05	1.10
6	1.95	14.36	.14	.20	.22	3.50	9.00	9.50	9.50	.37	.95	1.00	1.43	1.57
7	2.00	14.00	.16	.18	.24	6.20	6.00	9.30	9.30	.67	.65	1.00	1.12	1.50
8	1.70	16.47	.22	.26	.36	3.30	10.80	3.50	10.80	.31	1.00	.32	1.18	1.64
9	1.80	15.56	.21	.25	.27	4.50	11.00	9.00	11.00	.41	1.00	.82	1.19	1.29
10	1.73	16.18	.24	.25	.29	5.50	7.80	8.40	8.40	.65	.93	1.00	1.04	1.21
11	1.76	15.91	.20	.22	.24	3.30	9.20	10.50	10.50	.31	.88	1.00	1.16	1.20
12	1.88	14.89	.20	.25	.26	3.50	7.50	5.20	7.50	.47	1.00	.69	1.25	1.30
13	1.90	14.74	.18	.20	.22	4.20	7.00	10.30	10.30	.41	.68	1.00	1.11	1.22
14	1.82	15.38	.24	.24	.27	5.90	6.00	3.30	6.00	.98	1.00	.55	1.06	1.12
15	1.63	17.18	.18	.21	.33	2.80	4.00	8.50	8.50	.33	.67	1.00	1.17	1.83
AVERAGE	1.82	15.45	.19	.22	.26	4.81	6.99	7.90	9.42	.53	.79	.83	1.16	1.39
				.22			6.57							
STANDARD DEVIATION	.87		.03	.03	.04	2.12	2.72	2.67	1.66					
				.04 **			2.83 **							

** STANDARD DEVIATION FOR ENTIRE T(P) AND F(P) GROUPS

TABLE XIII

3 PARACHUTE CLUSTER, L(R) = 0.2 D(O)

DROP DISTANCE = 27.0FT   W* = 2.33

TEST	DOWN TIME (SEC)	VELOCITY (FT/SEC)	T(P) (SEC) 1	2	3	F(P) (LB) 1	2	3	F(MAX) (LB)	$\frac{F(P1)}{F(MAX)}$	$\frac{F(P2)}{F(MAX)}$	$\frac{F(P3)}{F(MAX)}$	$\frac{T(P2)}{T(P1)}$	$\frac{T(P3)}{T(P1)}$
1	1.98	13.64	.20	.25	.27	4.50	4.50	2.80	4.50	1.00	1.00	.62	1.25	1.35
2	1.95	13.95	.19	.25	.27	3.50	9.30	4.80	9.30	.38	1.00	.52	1.32	1.42
3	1.41	19.15	.22	.25	.28	3.80	1.90	8.00	8.00	.47	.24	1.00	1.14	1.27
4	1.80	15.03	.17	.19	.25	6.30	4.50	9.30	9.30	.68	.48	1.00	1.13	1.49
5	1.69	15.98	.13	.14	.28	5.70	2.60	3.60	5.70	1.00	.46	.63	1.08	2.15
6	1.63	16.56	.18	.20	.22	6.00	3.30	2.80	6.00	1.00	.55	.47	1.11	1.22
7	1.99	13.57	.15	.18	.21	1.80	6.40	6.10	6.40	.28	1.00	.95	1.21	1.43
8	1.80	15.00	.15	.23	.26	3.50	8.30	3.00	8.30	.42	1.00	.36	1.53	1.73
9	1.64	16.48	.13	.21	.29	2.70	4.70	4.30	4.70	.57	1.00	.91	1.63	2.26
10	1.99	13.57	.18	.20	.30	5.20	3.80	4.50	5.20	1.00	.73	.87	1.11	1.67
AVERAGE	1.79	15.28	.17	.21	.26	4.30	4.93	4.92	6.74	.68	.75	.73	1.25	1.66
				.21			4.72							
STANDARD DEVIATION		1.71	.03	.03	.03	1.42	2.27	2.12	1.74					
				.05 **			1.99 **							

** STANDARD DEVIATION FOR ENTIRE T(P) AND F(P) GROUPS

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TABLE IX

3 PARACHUTE CLUSTER, L(R) = 0.4 D(0)

DROP DISTANCE = 26.0FT   M* = 2.33

TEST	DOWN TIME (SEC)	VELOCITY (FT/SEC)	T(P) (SEC) 1	2	3	F(P) (LB) 1	2	3	F(MAX) (LB)	$\frac{F(P1)}{F(MAX)}$	$\frac{F(P2)}{F(MAX)}$	$\frac{F(P3)}{F(MAX)}$	$\frac{T(P2)}{T(P1)}$	$\frac{T(P3)}{T(P1)}$
1	1.64	15.85	.13	.18	.18	1.80	6.00	9.20	9.20	.20	.65	1.00	1.38	1.38
2	1.23	21.14	.16	.19	.26	3.20	5.60	4.80	5.60	.57	1.00	.86	1.19	1.62
3	1.75	14.83	.16	.18	.25	3.60	6.30	9.20	9.20	.39	.68	1.00	1.11	1.54
4	1.62	16.09	.18	.18	.20	2.90	8.10	9.50	9.50	.31	.85	1.00	1.01	1.09
5	1.71	15.20	.18	.18	.27	7.00	3.30	4.70	7.00	1.00	.47	.47	1.00	1.50
6	1.20	21.67	.19	.19	.20	3.90	7.70	3.30	7.70	.51	1.00	.43	1.05	1.05
7	1.52	17.05	.18	.27	.27	4.30	4.80	5.70	5.70	.75	.84	1.00	1.50	1.50
8	1.02	25.44	.20	.22	.31	2.60	3.50	4.70	4.70	.55	.74	1.00	1.10	1.53
9	1.62	16.10	.18	.20	.21	5.80	5.60	6.90	6.90	.84	.81	1.00	1.00	1.17
10	1.61	16.15	.19	.20	.21	9.30	5.40	2.30	9.30	1.00	.58	.25	1.05	1.11
AVERAGE	1.49	17.95	.17	.20	.24	4.44	5.63	6.03	7.48	.61	.76	.82	1.14	1.35
				.20			5.37							
STANDARD DEVIATION		3.36	.02	.03	.04	2.17	1.47	2.44	1.68					
				.04 **			2.18 **							

** STANDARD DEVIATION FOR ENTIRE T(P) AND F(P) GROUPS

TABLE X

3 PARACHUTE CLUSTER, L(R) = 0.6 D(O)

DROP DISTANCE = 25.0FT   MO = 2.33

TEST	DOWN TIME (SEC)	VELOCITY (FT/SEC)	T(P) (SEC)			F(P) (LB)			F(MAX) (LB)	F(P1)/F(MAX)	F(P2)/F(MAX)	F(P3)/F(MAX)	T(P2)/T(P1)	T(P3)/T(P1)
			1	2	3	1	2	3						
1	1.36	18.38	.20	.21	.21	5.50	6.80	10.10	10.10	.54	.67	1.00	1.05	1.05
2	1.31	19.08	.19	.19	.24	4.90	5.50	2.10	5.50	.89	1.00	.38	1.00	1.26
3	1.38	18.12	.18	.21	.30	3.00	5.50	8.70	8.70	.34	.63	1.00	1.17	1.67
4	1.26	19.84	.17	.25	.25	1.50	11.00	4.80	11.00	.14	1.00	.44	1.47	1.47
5	1.85	13.51	.17	.18	.28	4.20	4.20	3.90	4.20	1.00	1.00	.93	1.06	1.65
6	1.87	13.37	.15	.18	.27	3.20	5.50	9.00	9.00	.36	.61	1.00	1.20	1.80
7	1.82	13.74	.18	.21	.21	5.00	5.00	5.00	5.00	1.00	1.00	1.00	1.17	1.17
8	1.28	19.53	.20	.31	.33	10.70	3.80	7.50	10.70	1.00	.36	.70	1.51	1.62
9	1.63	15.34	.16	.18	.24	7.50	5.30	8.70	8.70	.86	.61	1.00	1.11	1.50
10	1.52	16.45	.17	.17	.26	4.60	4.30	8.00	8.00	.57	.54	1.00	1.01	1.54
AVERAGE	1.53	16.74	.18	.21	.26	5.01	5.69	6.78	8.09	.67	.74	.84	1.17	1.67
				.22			5.83							
STANDARD DEVIATION		2.46	.02	.04	.04	2.43	1.95	2.50	2.29					
				.05 **			2.42 **							

** STANDARD DEVIATION FOR ENTIRE T(P) AND F(P) GROUPS

TABLE XI

3 PARACHUTE CLUSTER. L(R) = 0.4 D(O) + L(C) = 0.97 D(O)

DROP DISTANCE = 26.0FT   4* = 2.33

TEST	DOWN TIME (SEC)	VELOCITY (FT/SEC)	T(P) (SEC) 1	2	3	F(P) (LB) 1	2	3	F(MAX) (LB)	$\frac{F(P1)}{F(MAX)}$	$\frac{F(P2)}{F(MAX)}$	$\frac{F(P3)}{F(MAX)}$	$\frac{T(P2)}{T(P1)}$	$\frac{T(P3)}{T(P1)}$
1	1.56	16.67	.16	.17	.19	9.60	6.50	1.80	9.60	1.00	.68	.19	1.06	1.19
2	1.78	14.58	.17	.25	.28	3.00	12.20	1.90	12.20	.25	1.00	.16	1.42	1.56
3	1.87	13.93	.16	.26	.27	11.10	6.80	2.50	11.10	1.00	.61	.23	1.65	1.72
4	1.71	15.20	.19	.19	.26	3.50	6.10	12.30	12.30	.28	.50	1.00	1.03	1.38
5	1.45	17.93	.17	.18	.26	5.70	6.90	5.50	6.90	.83	1.00	.80	1.06	1.53
6	1.76	14.80	.17	.17	.23	5.40	5.40	12.50	12.50	.43	.43	1.00	1.01	1.39
7	1.92	13.54	.17	.18	.25	7.50	2.70	10.40	10.40	.72	.26	1.00	1.06	1.47
8	1.30	20.00	.17	.20	.21	2.90	4.80	3.70	4.80	.60	1.00	.77	1.18	1.24
9	1.44	18.06	.14	.17	.48	5.40	3.20	4.60	5.40	1.00	.59	.85	1.20	3.39
10	1.41	18.44	.18	.18	.23	9.10	4.00	4.50	9.10	1.00	.44	.49	1.00	1.28
AVERAGE	1.62	16.31	.17	.19	.27	6.32	5.86	5.97	9.43	.77	.65	.65	1.17	1.44
				.21			6.05							
STANDARD DEVIATION	2.09		.01	.03	.08	2.75	2.54	3.97	2.71					
				.06 **			3.16 **							

** STANDARD DEVIATION FOR ENTIRE T(P) AND F(P) GROUPS

TABLE XII

3 PARACHUTE CLUSTER, L(R) = 8.4 D(0) + INTERNAL PARACHUTE , 0.2 D(0)

DROP DISTANCE = 26.0FT   M* = 2.33

TEST	DOWN TIME (SEC)	VELOCITY (FT/SEC)	T(P) (SEC) 1	T(P) 2	T(P) 3	F(P) (LB) 1	F(P) 2	F(P) 3	F(MAX) (LB)	F(P1)/F(MAX)	F(P2)/F(MAX)	F(P3)/F(MAX)	T(P2)/T(P1)	T(P3)/T(P1)
1	2.22	11.71	.17	.26	.26	7.30	2.30	7.30	7.30	1.00	.32	1.00	1.53	1.53
2	1.60	16.25	.15	.24	.33	4.10	3.00	4.50	4.50	.91	.67	1.00	1.60	2.20
3	1.60	16.25	.22	.24	.35	2.40	4.00	6.50	6.50	.37	.62	1.00	1.09	1.59
4	1.29	20.16	.16	.24	.32	3.00	4.30	6.90	6.90	.43	.62	1.00	1.50	2.00
5	1.71	15.20	.21	.21	.26	4.20	2.60	9.90	9.90	.42	.26	1.00	1.00	1.24
6	1.86	13.98	.17	.19	.28	5.00	5.00	8.50	8.50	.59	.59	1.00	1.12	1.65
7	2.20	11.82	.17	.20	.21	6.20	4.00	7.00	7.00	.89	.57	1.00	1.18	1.24
8	1.93	13.47	.15	.16	.17	11.00	4.00	4.50	11.00	1.00	.36	.41	1.07	1.13
9	2.30	11.30	.16	.17	.24	5.40	5.00	9.00	9.00	.60	.56	1.00	1.06	1.50
10	1.81	14.36	.17	.17	.19	7.40	10.70	4.60	10.70	.60	1.00	.43	1.00	1.12
AVERAGE	1.85	14.45	.17	.21	.26	5.60	4.49	6.87	9.13	.69	.56	.88	1.27	1.52
				.21			5.65							
STANDARD DEVIATION		2.55	.02	.03	.06	2.39	2.25	1.82	1.95					
				.05 **			2.37 **							

** STANDARD DEVIATION FOR ENTIRE T(P) AND F(P) GROUPS

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TABLE XIII

2 PARACHUTE CLUSTER L(R) = 0.2 D(O)

DROP DISTANCE = 27.0FT   Mo = 1.57

TEST	DOWN TIME (SEC)	VELOCITY (FT/SEC)	T(P) (SEC) 1	2	3	F(P) (LB) 1	2	3	F(MAX) (LB)	$\frac{F(P1)}{F(MAX)}$	$\frac{F(P2)}{F(MAX)}$	$\frac{F(P3)}{F(MAX)}$	$\frac{T(P2)}{T(P1)}$	$\frac{T(P3)}{T(P1)}$
1	1.33	20.24	.19	.21		12.00	11.80		12.00	1.00	.98		1.09	
2	1.20	22.50	.15	.16		13.80	8.80		13.80	1.00	.64		1.03	
3	1.18	22.86	.17	.22		6.60	10.80		10.80	.61	1.00		1.34	
4	1.44	18.82	.20	.21		11.10	10.90		11.10	1.00	.98		1.02	
5	1.52	17.82	.21	.24		9.20	11.50		11.50	.80	1.00		1.17	
6	1.24	21.77	.19	.26		11.20	9.80		11.20	1.00	.88		1.34	
7	1.15	23.48	.22	.23		7.00	12.50		12.50	.56	1.00		1.05	
8	1.37	19.74	.17	.17		9.20	6.60		9.20	1.00	.72		1.03	
9	1.26	21.48	.20	.21		10.00	9.50		10.00	1.00	.95		1.05	
10	1.36	19.90	.17	.22		11.00	11.00		11.00	1.00	1.00		1.34	
AVERAGE	1.30	20.86	.19	.21	.20	10.11	10.32	10.21	11.31	.96	.91		1.14	
STANDARD DEVIATION		1.75	.02	.03	.03 **	2.09	1.63	1.88 **	1.21					

** STANDARD DEVIATION FOR ENTIRE T(P) AND F(P) GROUPS

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TABLE XIV

SINGLE PARACHUTE   NO MODIFICATIONS

DROP DISTANCE = 28.0FT   4ο = 2.33

TEST	DOWN TIME (SEC)	VELOCITY (FT/SEC)	T(P) (SEC)			F(P) (LB)			F(MAX) (LB)	F(P1)/F(MAX)	F(P2)/F(MAX)	F(P3)/F(MAX)	T(P2)/T(P1)	T(P3)/T(P1)
			1	2	3	1	2	3						
1			.24			9.80								
2			.19			4.60								
3			.16			6.00								
4			.17			8.70								
5			.27			5.90								
6			.23			8.30								
7			.17			7.70								
8			.16			7.80								
9			.15			6.90								
10			.18			7.50								
AVERAGE			.19			7.32								
STANDARD DEVIATION			.04			1.44								

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TABLE XV

SINGLE PARACHUTE NO MODIFICATIONS

DROP DISTANCE = 28.0FT   M* = 1.57

TEST	DOWN TIME (SEC)	VELOCITY (FT/SEC)	T(P) (SEC) 1	2	3	F(P) (LB) 1	2	3	F(MAX) (LB)	F(P1)/F(MAX)	F(P2)/F(MAX)	F(P3)/F(MAX)	T(P2)/T(P1)	T(P3)/T(P1)
1			.17			10.30								
2			.17			10.30								
3			.20			16.50								
4			.21			14.20								
5			.22			7.80								
6			.24			10.50								
7			.17			12.80								
8			.20			15.50								
9			.22			12.00								
10			.22			13.50								
AVERAGE			.20			12.34								
STANDARD DEVIATION			.02			2.54								

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TABLE XVI

SINGLE PARACHUTE $C_{(C)}$ = 0.97 D(0)

DROP DISTANCE = 28.0FT   N* = 7.33

TEST	DOWN TIME (SEC)	VELOCITY (FT/SEC)	T(P) (SEC)			F(P) (LB)			F(MAX) (LB)	$\frac{F(P1)}{F(MAX)}$	$\frac{F(P2)}{F(MAX)}$	$\frac{F(P3)}{F(MAX)}$	$\frac{T(P2)}{T(P1)}$	$\frac{T(P3)}{T(P1)}$
			1	2	3	1	2	3						
1			.18			9.50								
2			.24			9.00								
3			.23			14.80								
4			.16			12.00								
5			.25			10.80								
AVERAGE			.21			11.22								
STANDARD DEVIATION			.03			2.07								

TABLE XVII

SINGLE PARACHUTE L(R) = 6.6 D(0)

DROP DISTANCE = 26.0FT   W0 = 7.33

TEST	DOWN TIME (SEC)	VELOCITY (FT/SEC)	T(P) (SEC) 1	2	3	F(P) (LB) 1	2	3	F(MAX) (LB)	$\frac{F(P1)}{F(MAX)}$	$\frac{F(P2)}{F(MAX)}$	$\frac{F(P3)}{F(MAX)}$	$\frac{T(P2)}{T(P1)}$	$\frac{T(P3)}{T(P1)}$
1			.17			8.10								
2			.17			11.00								
3			.23			10.90								
4			.17			8.20								
5			.18			8.40								
AVERAGE			.19			9.32								
STANDARD DEVIATION			.02			1.33								

TABLE XVIII

SINGLE PARACHUTE L(R) = 0.4 D(O) • L(C) = 0.97 D(O)

DROP DISTANCE = 26.0FT   M• = 2.33

TEST	DOWN TIME (SEC)	VELOCITY (FT/SEC)	T(P) (SEC) 1	2	3	F(P) (LB) 1	2	3	F(MAX) (LB)	$\frac{F(P1)}{F(MAX)}$	$\frac{F(P2)}{F(MAX)}$	$\frac{F(P3)}{F(MAX)}$	$\frac{T(P2)}{T(P1)}$	$\frac{T(P3)}{T(P1)}$
1			.20			12.50								
2			.19			10.40								
3			.26			7.00								
4			.18			12.30								
5			.19			14.50								
AVERAGE			.20			11.34								
STANDARD DEVIATION			.03			2.53								

TABLE XIX

SINGLE PARACHUTE L(R) = 0.4 D(O) + L(C) = 0.88 D(O)

DROP DISTANCE = 26.0FT   W* = 7.33

TEST	DOWN TIME (SEC)	VELOCITY (FT/SEC)	T(P) (SEC) 1	2	3	F(P) (LB) 1	2	3	F(MAX) (LB)	$\frac{F(P1)}{F(MAX)}$	$\frac{F(P2)}{F(MAX)}$	$\frac{F(P3)}{F(MAX)}$	$\frac{T(P2)}{T(P1)}$	$\frac{T(P3)}{T(P1)}$
1			.24			11.80								
2			.20			14.60								
3			.25			6.20								
4			.28			9.50								
5			.22			11.30								
AVERAGE			.24			10.68								
STANDARD DEVIATION			.03			2.77								

TABLE XX

SINGLE PARACHUTE L(R) = 0.4 D(O) + INTERNAL PARACHUTE, 0.2 D(O)

DROP DISTANCE = 26.0FT   M0 = 7.33

TEST	DOWN TIME (SEC)	VELOCITY (FT/SEC)	T(P) (SEC) 1	2	3	F(P) (LB) 1	2	3	F(MAX) (LB)	$\frac{F(P)1}{F(MAX)}$	$\frac{F(P2)}{F(MAX)}$	$\frac{F(P3)}{F(MAX)}$	$\frac{T(P2)}{T(P)1}$	$\frac{T(P3)}{T(P)1}$
1			.17			16.00								
2			.18			6.80								
3			.16			8.50								
4			.16			10.80								
5			.17			14.30								
AVERAGE			.17			11.28								
STANDARD DEVIATION			.01			3.45								

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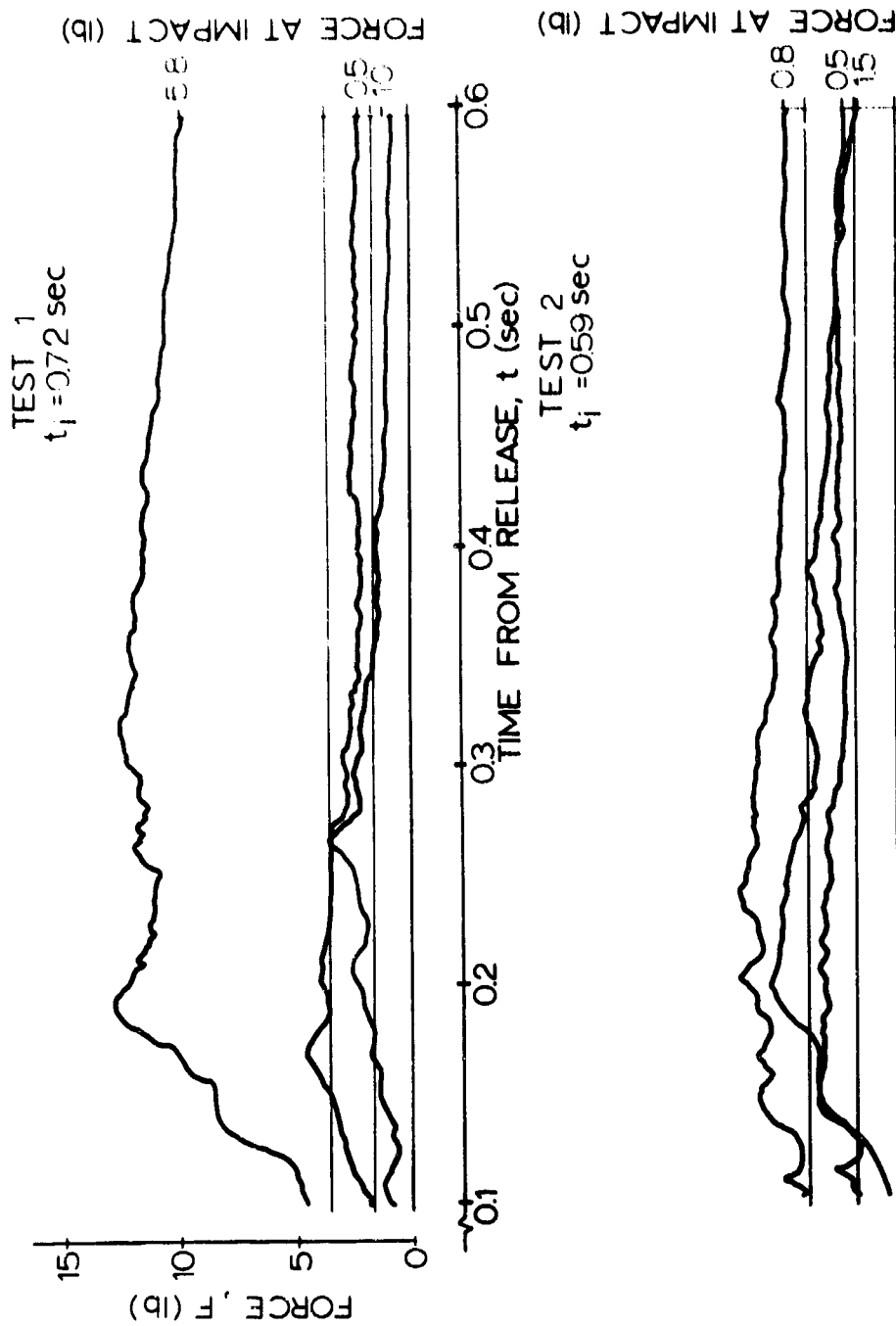
Fig 24   3 Parachute Cluster, Standard Parachute

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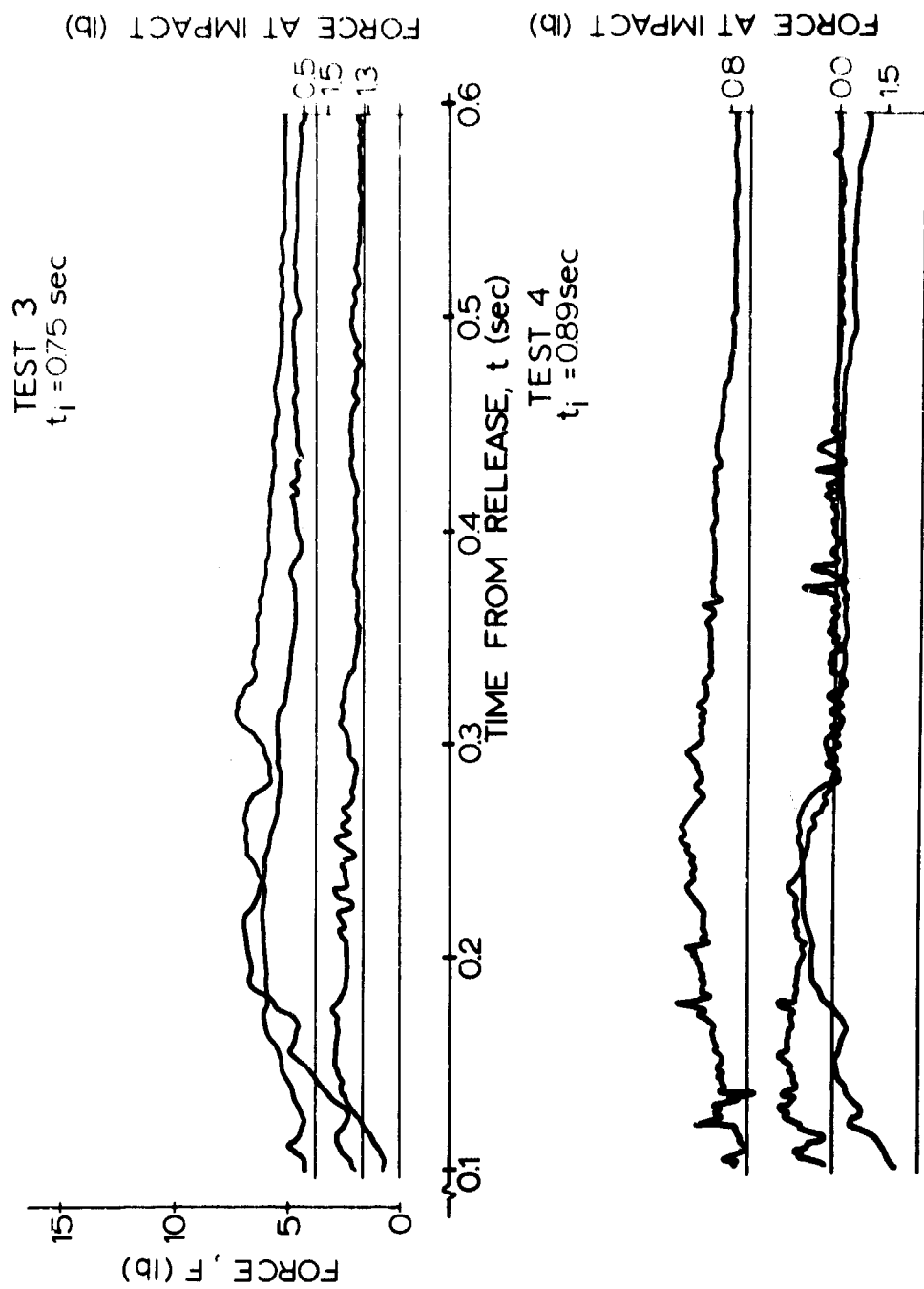
Fig 25 3 Parachute Cluster, Standard Parachute

68
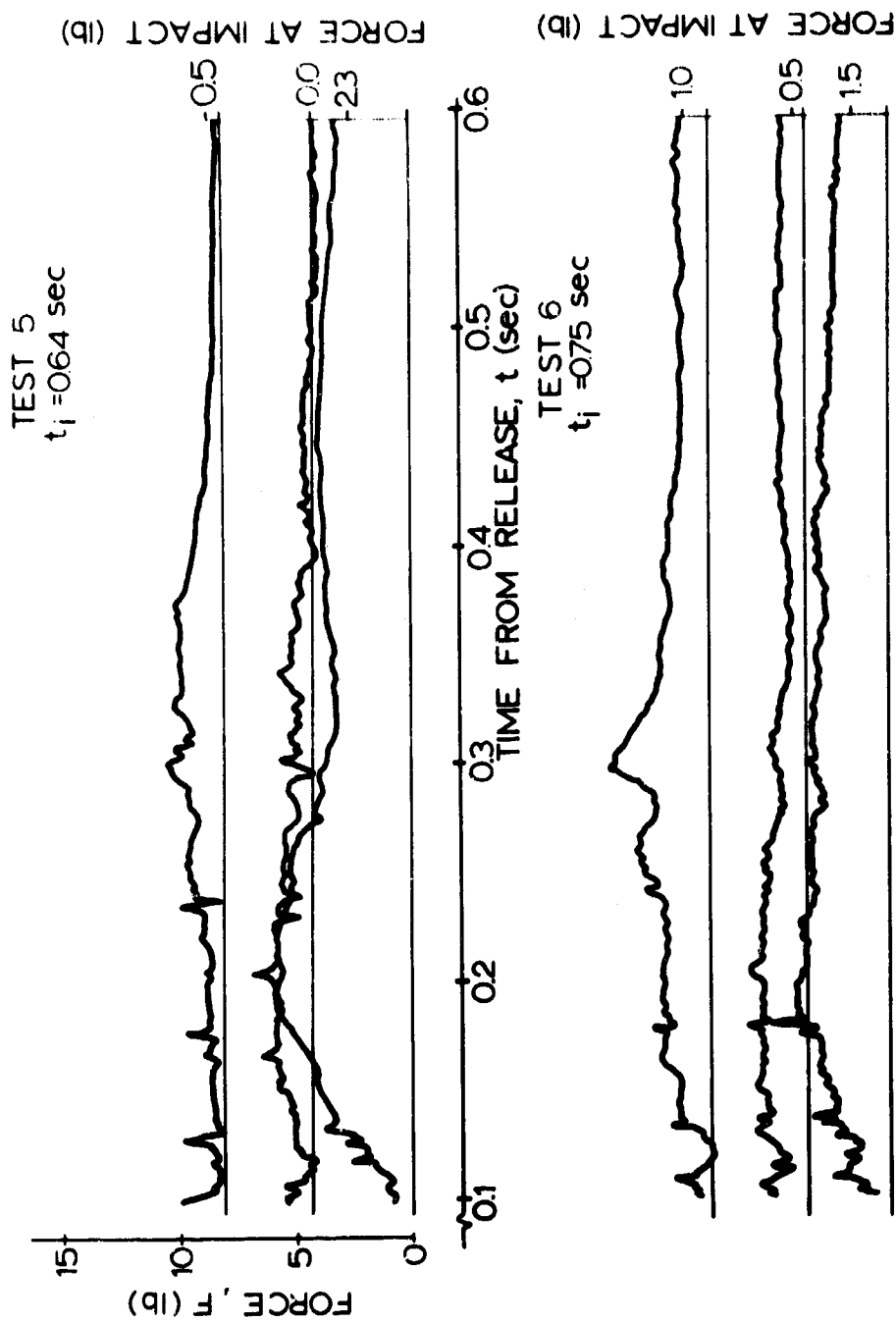
Fig 26   3 Parachute Cluster, Standard Parachute
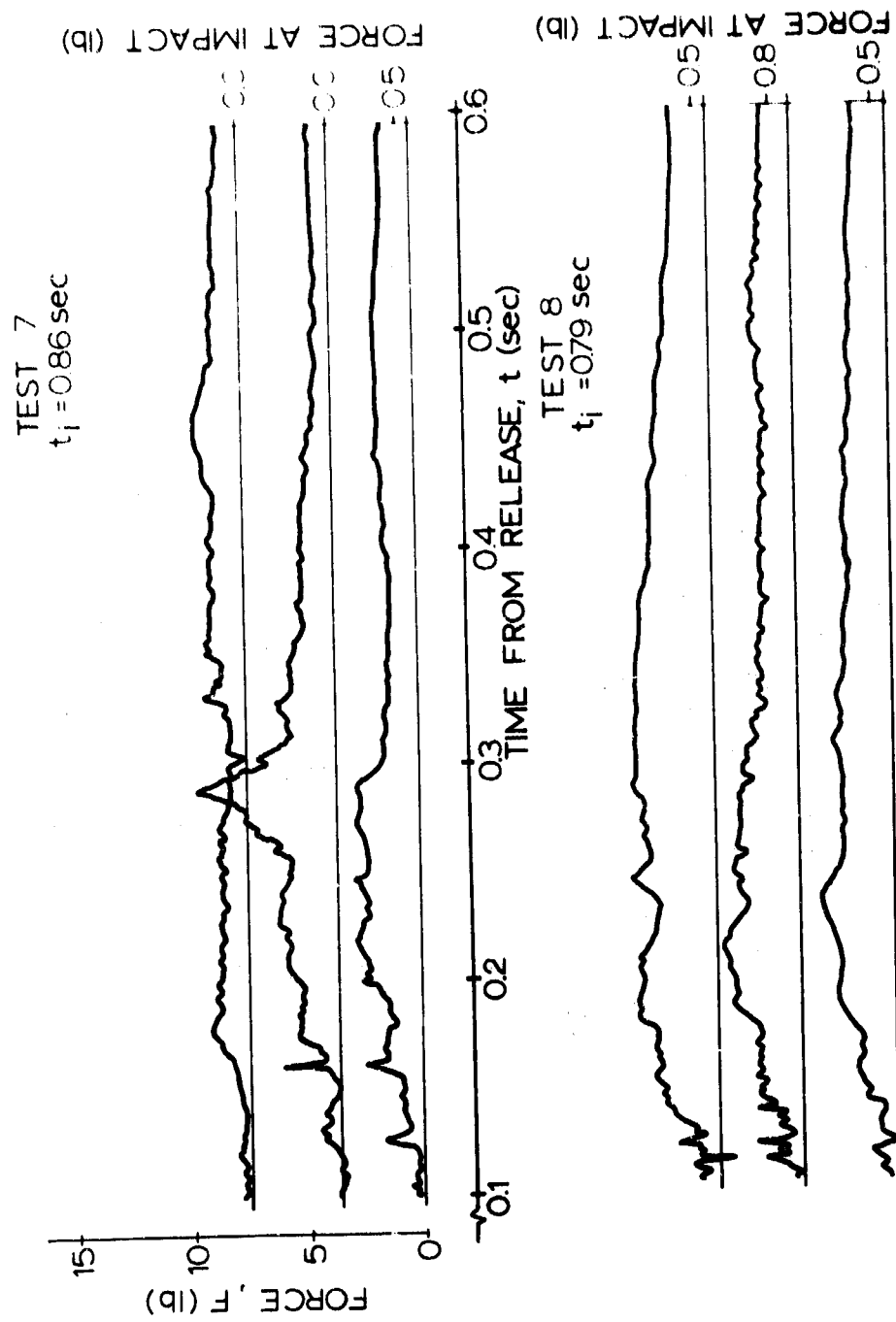
Fig 27 3 Parachute Cluster, Standard Parachute
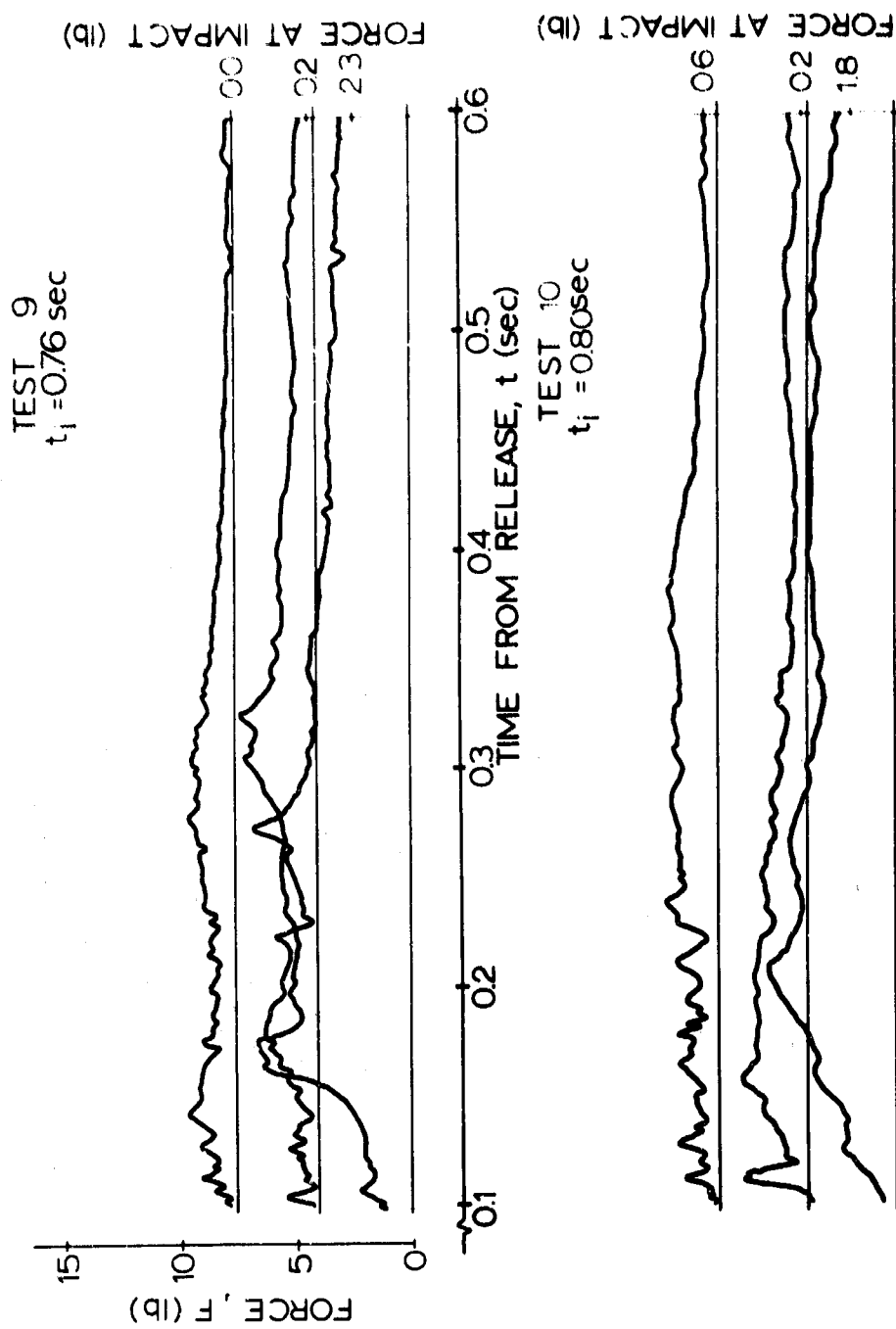
Fig 28   3 Parachute Cluster, Standard Parachute

71
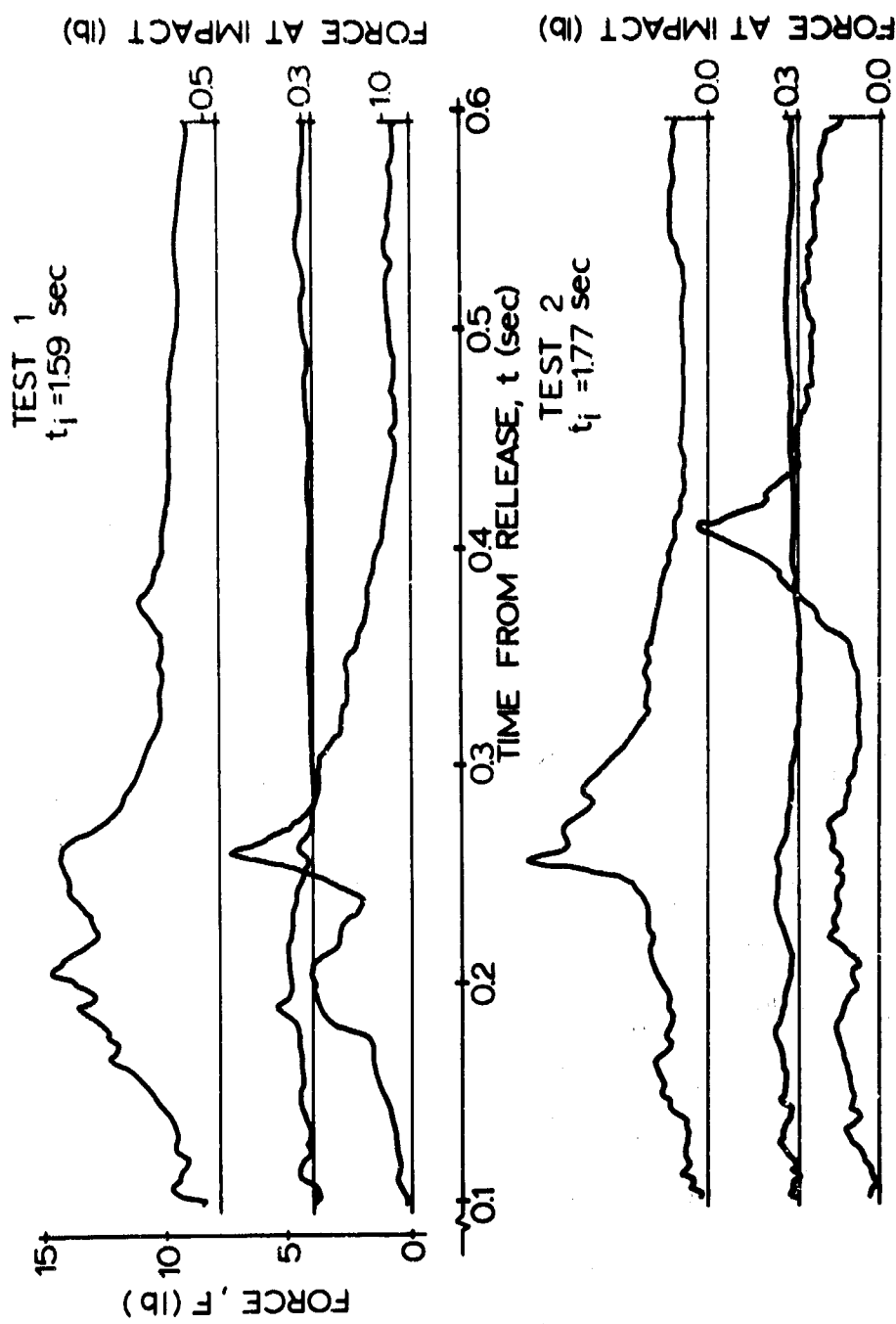
Fig 29   3 Parachute Cluster, $L_c = 0.97$ D_o

72
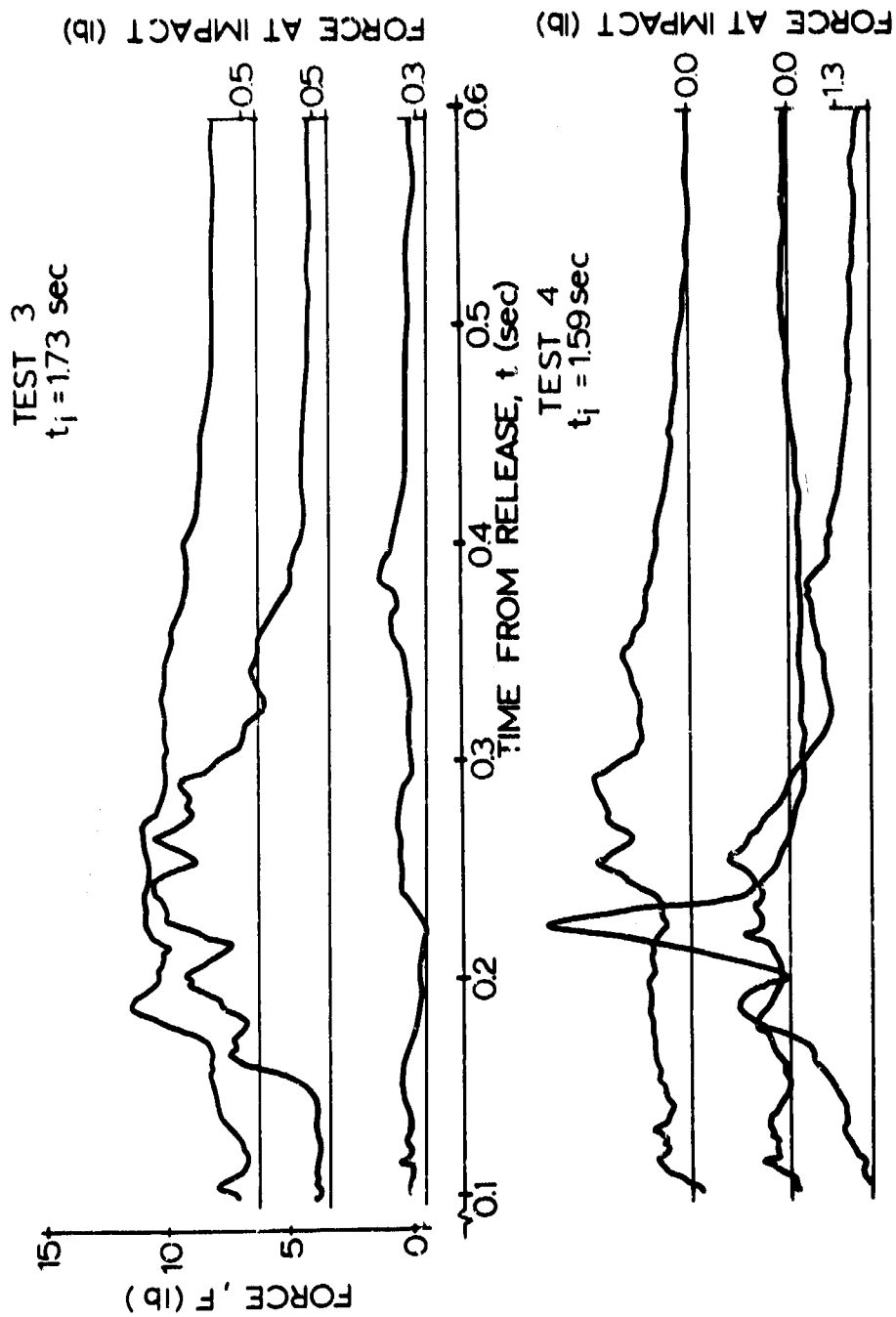
Fig 30   3 Parachute Cluster, $L_c = 0.97 \, D_0$

73
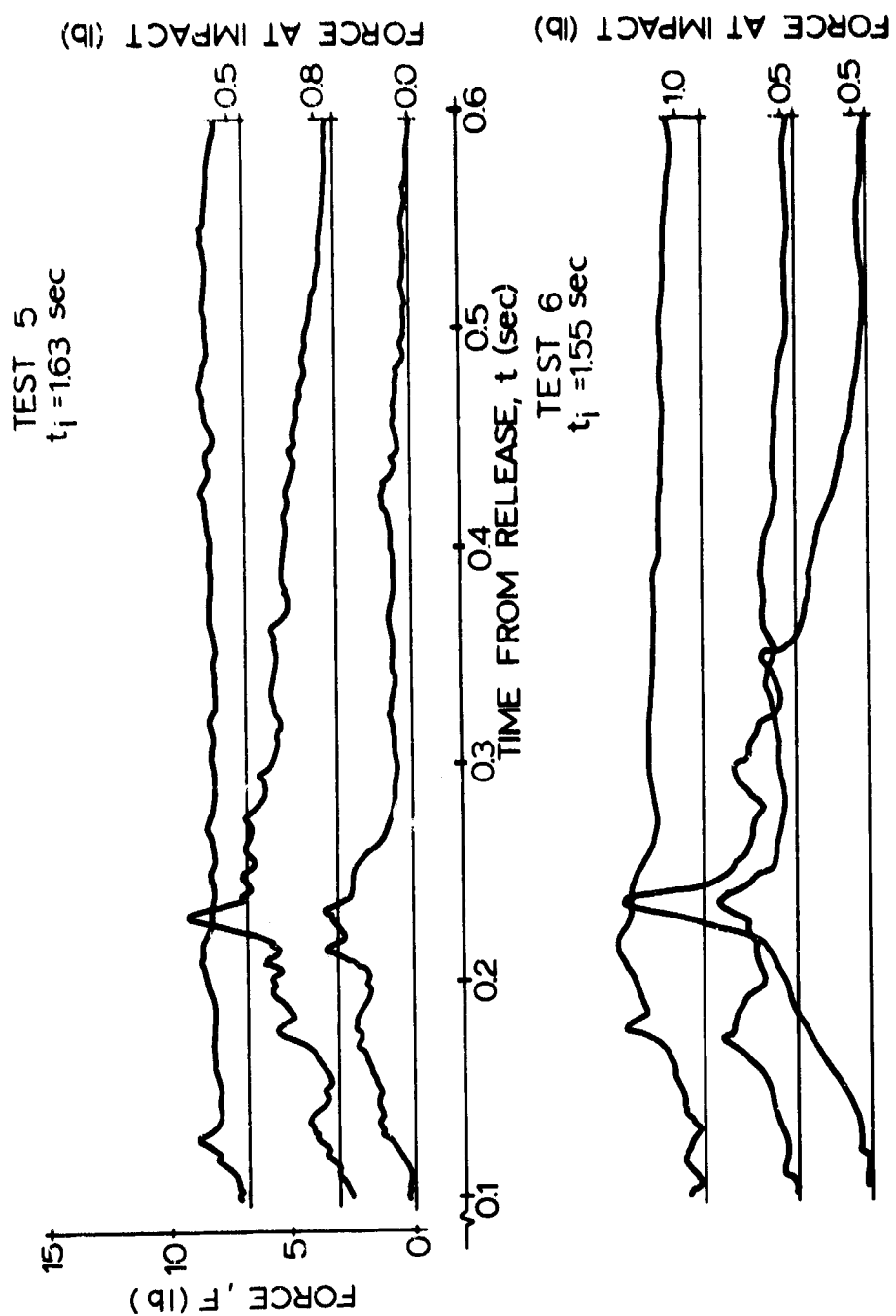
Fig 31   3 Parachute Cluster, L_c = 0.97 D_o

74
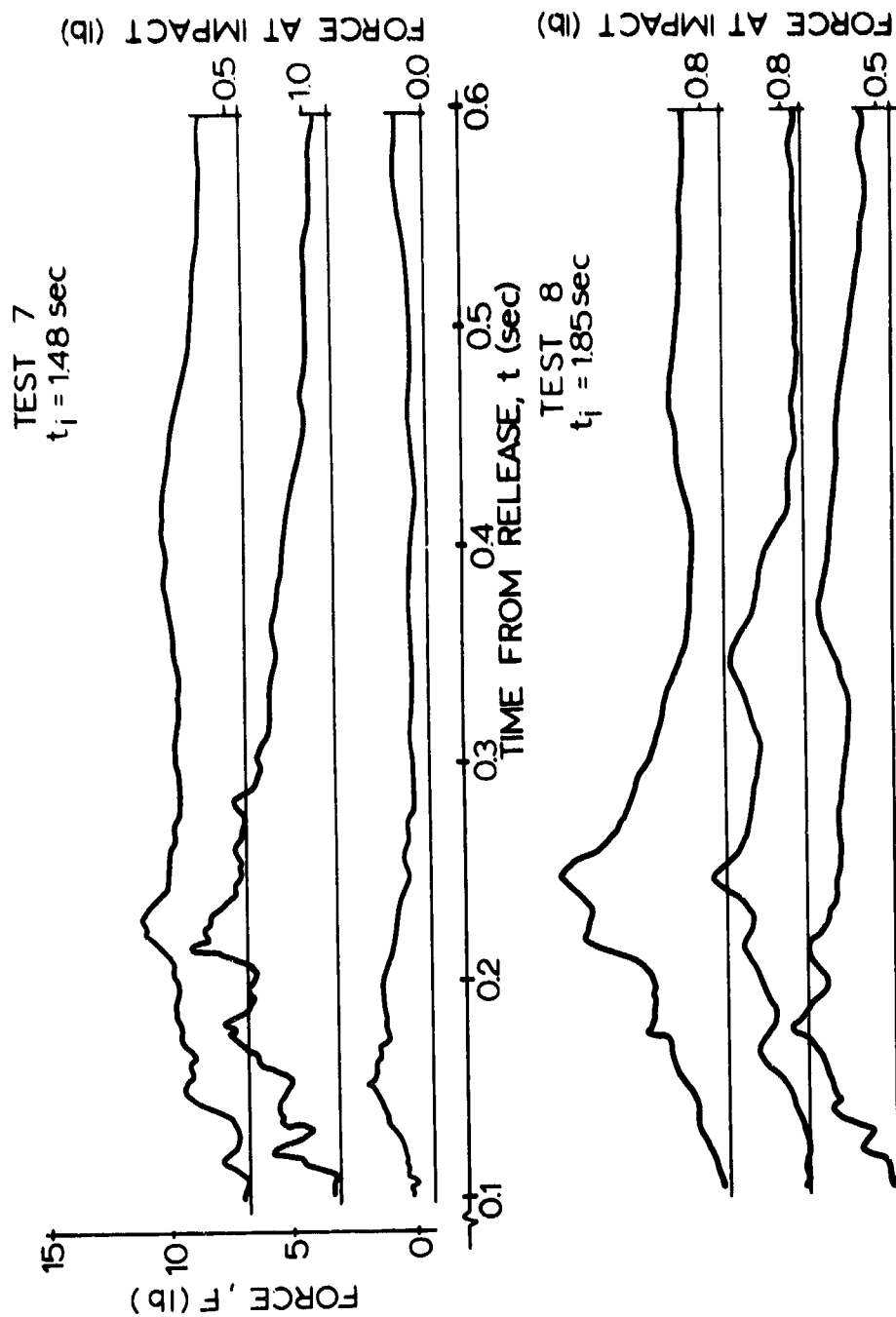
Fig 32   3 Parachute Cluster, $L_c = 0.97 D_o$
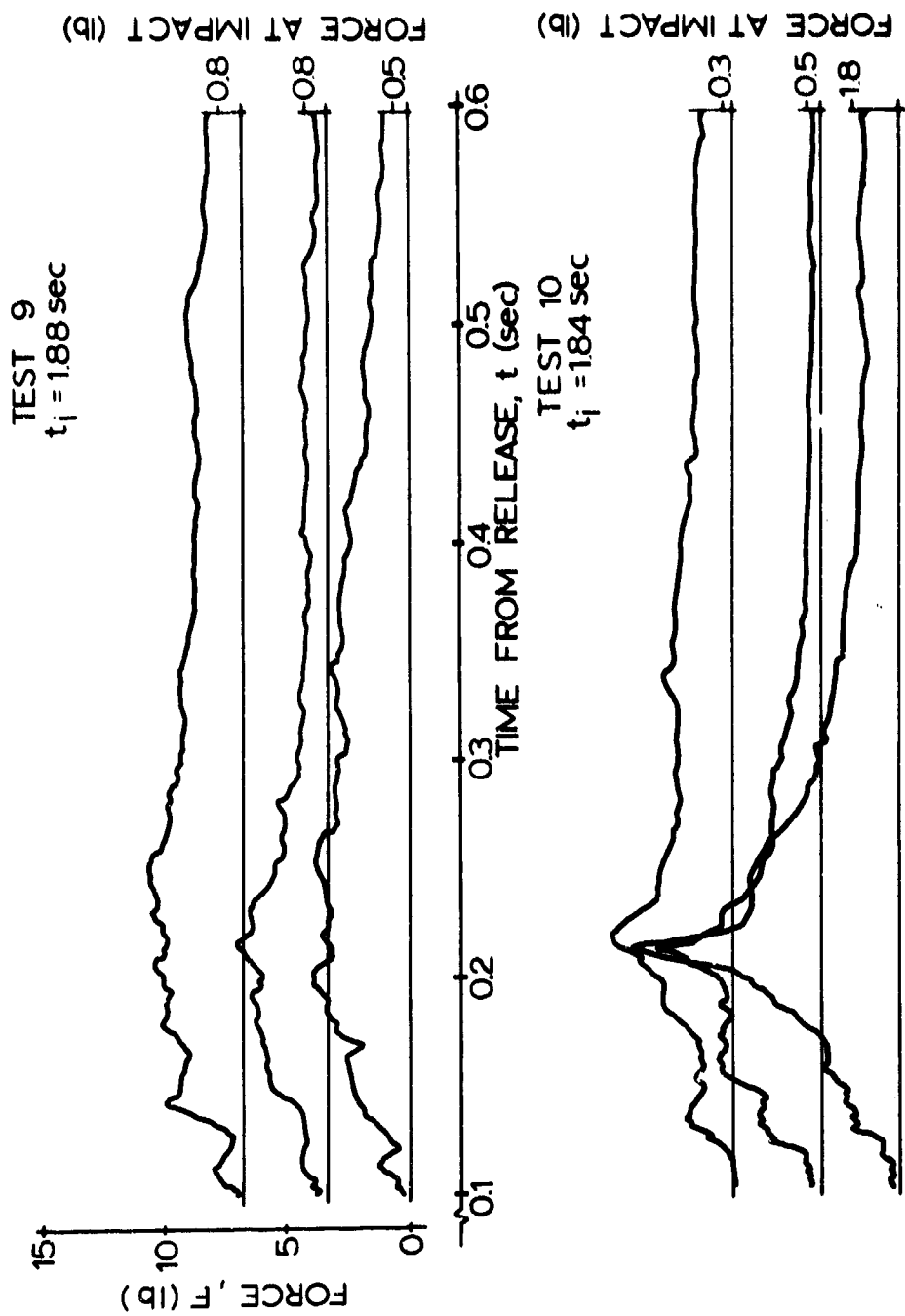
Fig 33   3 Parachute Cluster, $L_c = 0.97 \ D_o$

76
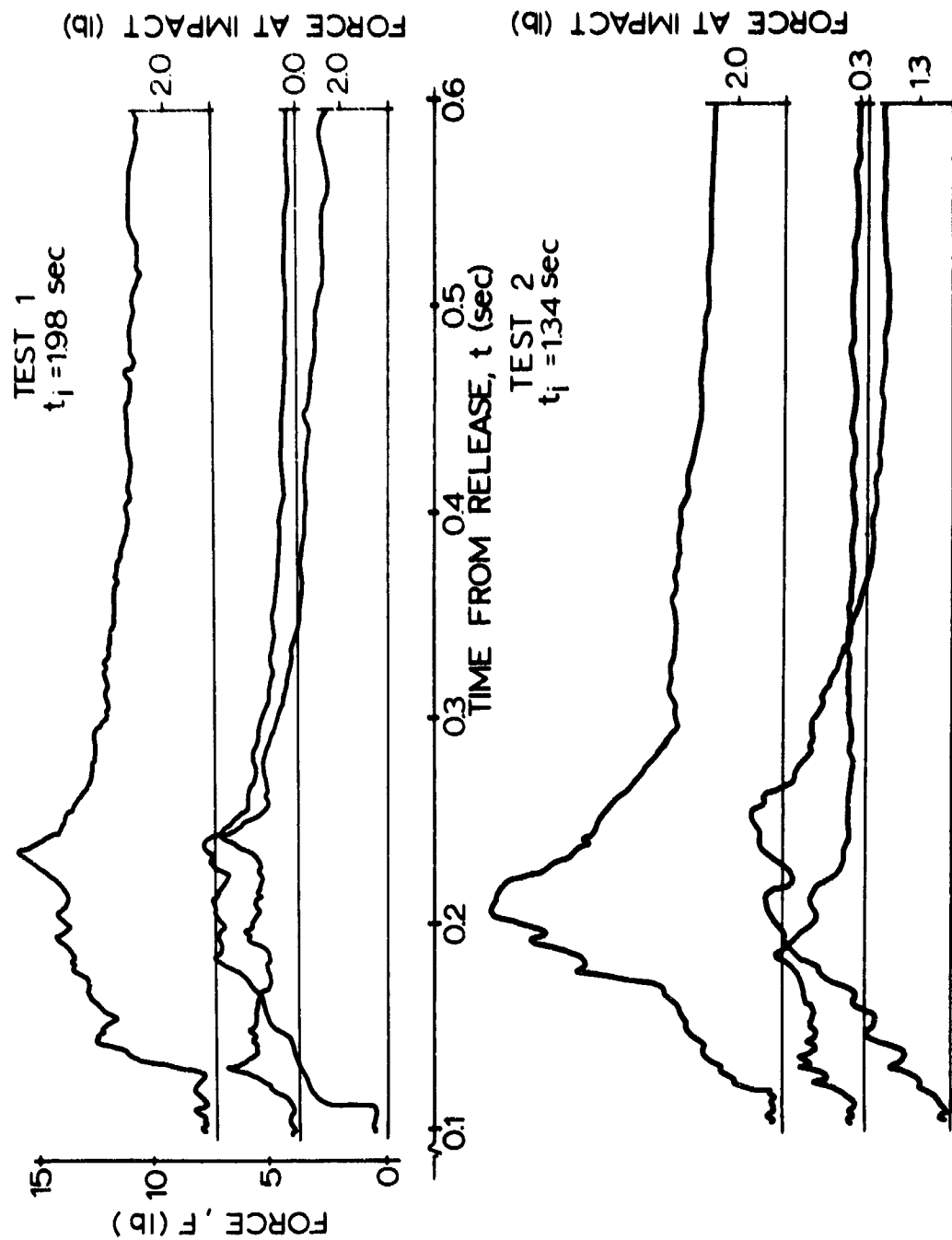
Fig 34   3 Parachute Cluster, $L_c = 0.88$ D_o

77
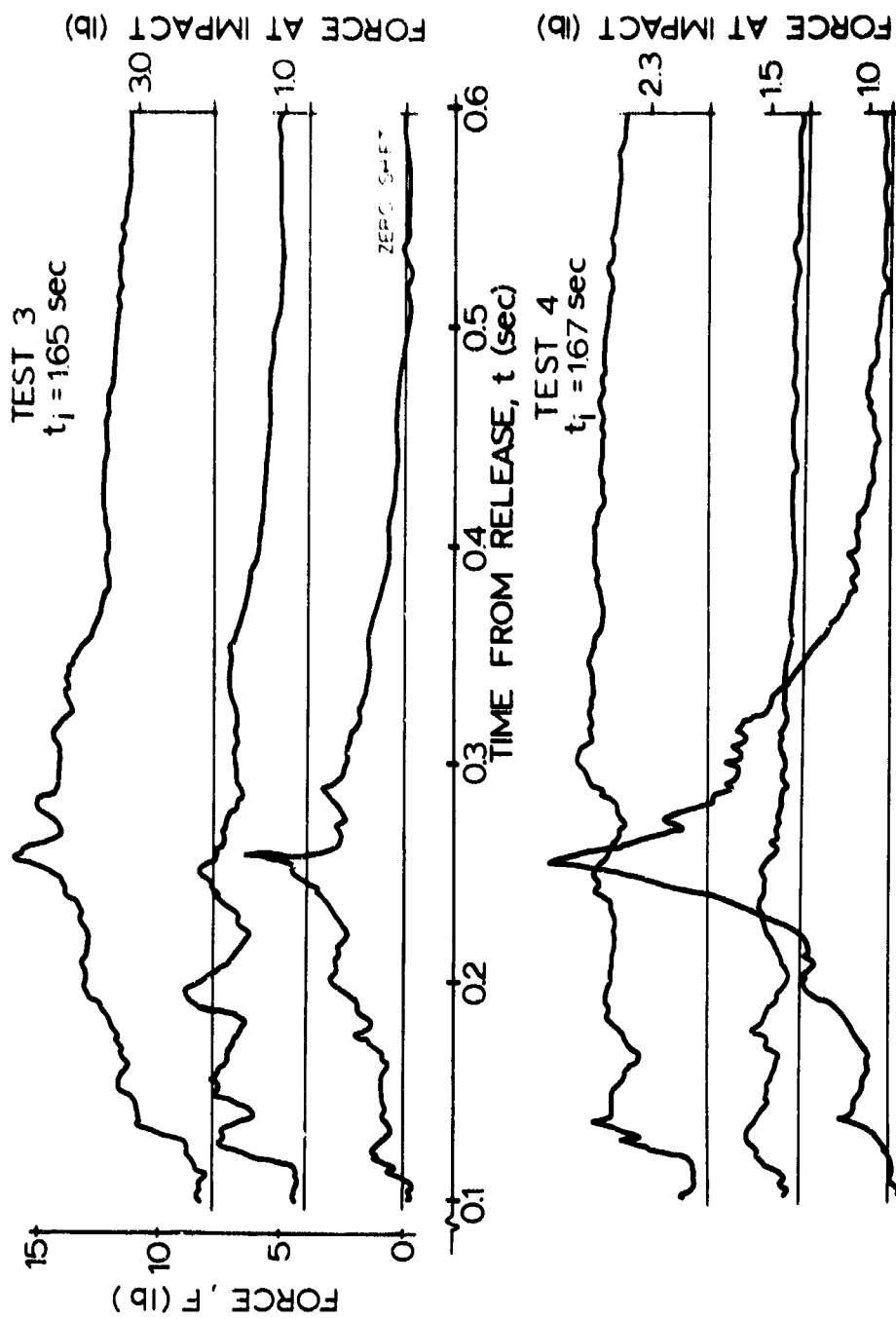
Fig 35 3 Parachute Cluster, $L_c = 0.88 \, D_o$

78
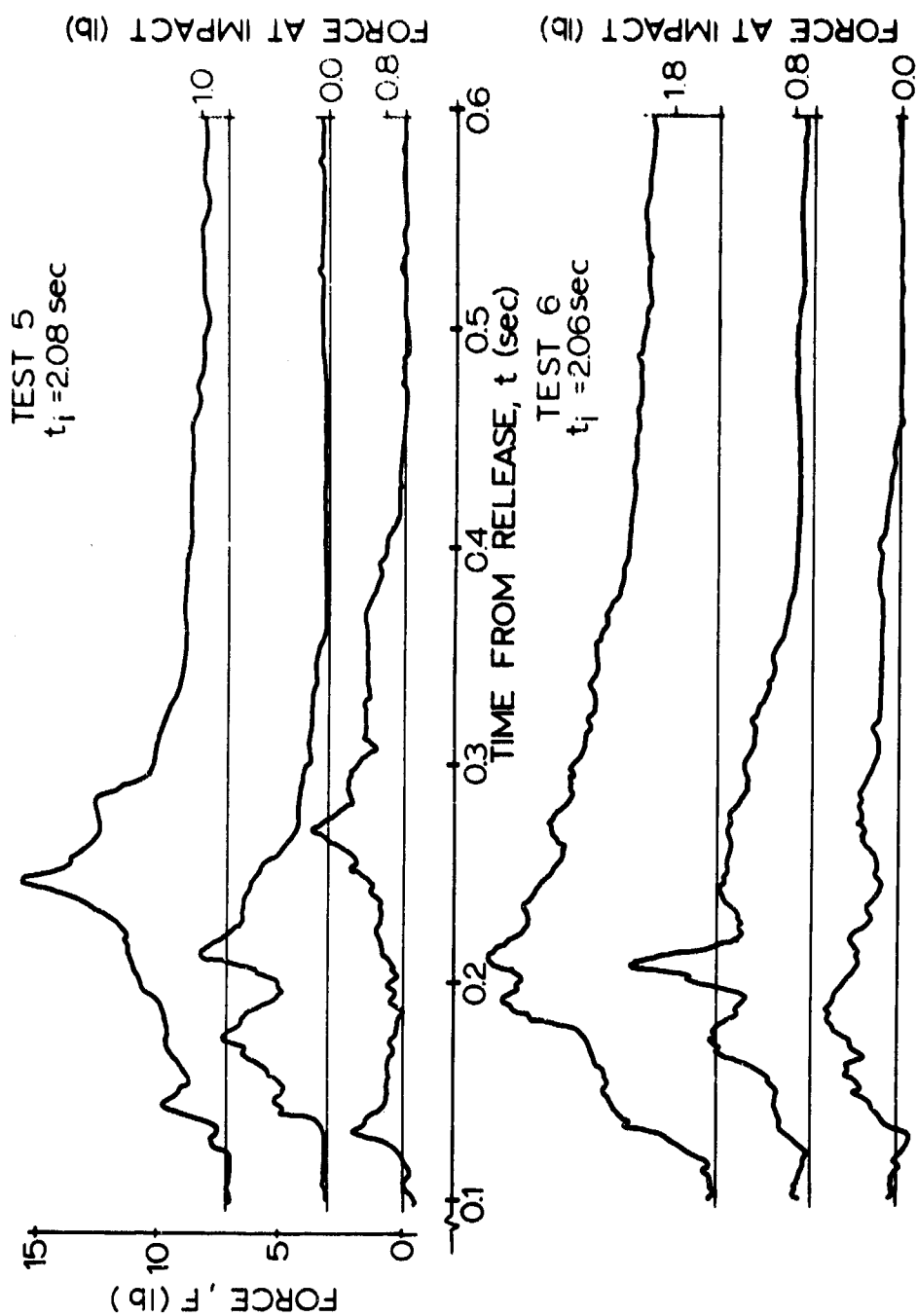
Fig 36 3 Parachute Cluster, $L_c = 0.88 \ D_o$

79
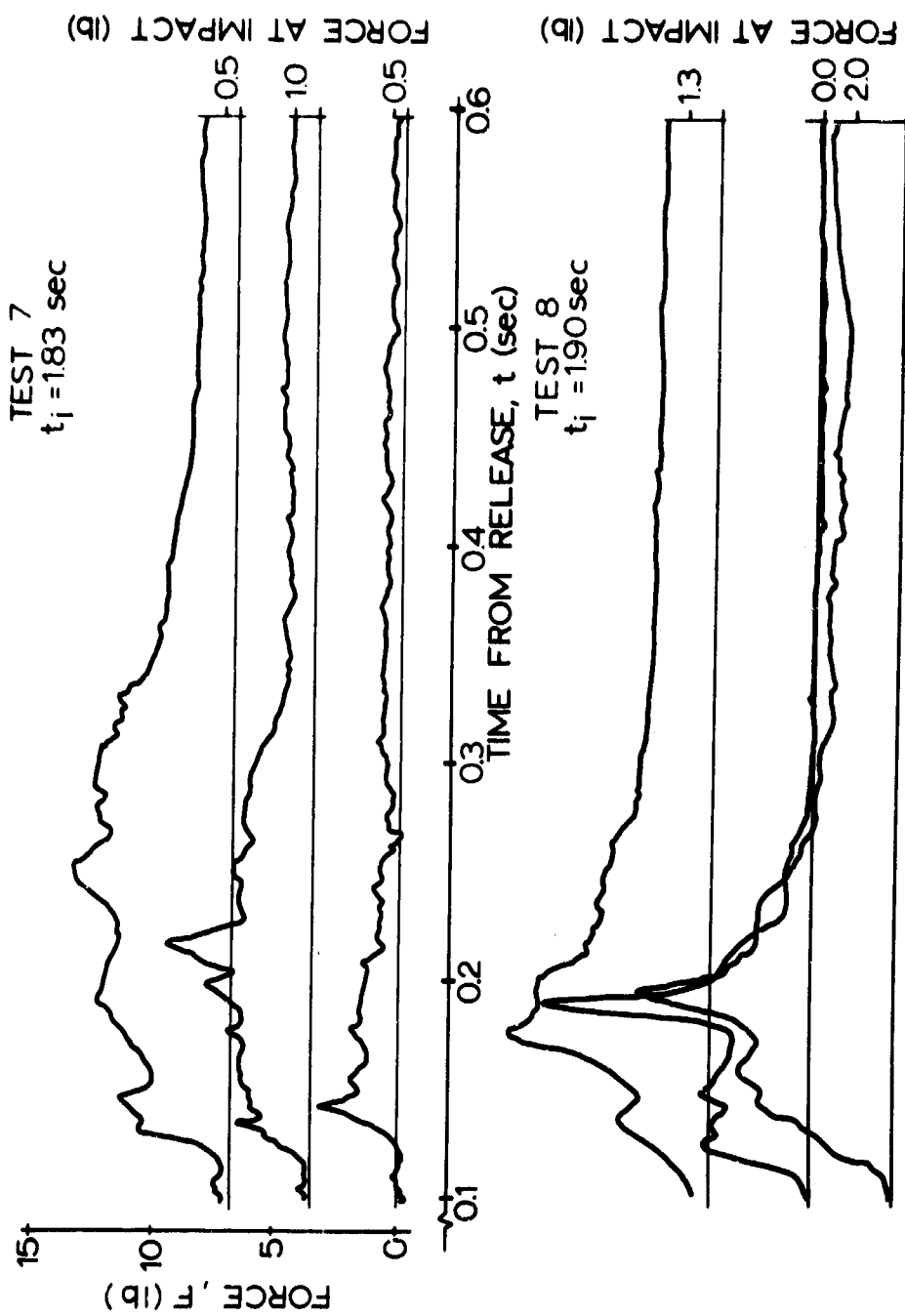
Fig 37   3 Parachute Cluster, $L_c = 0.88 \ D_o$

80
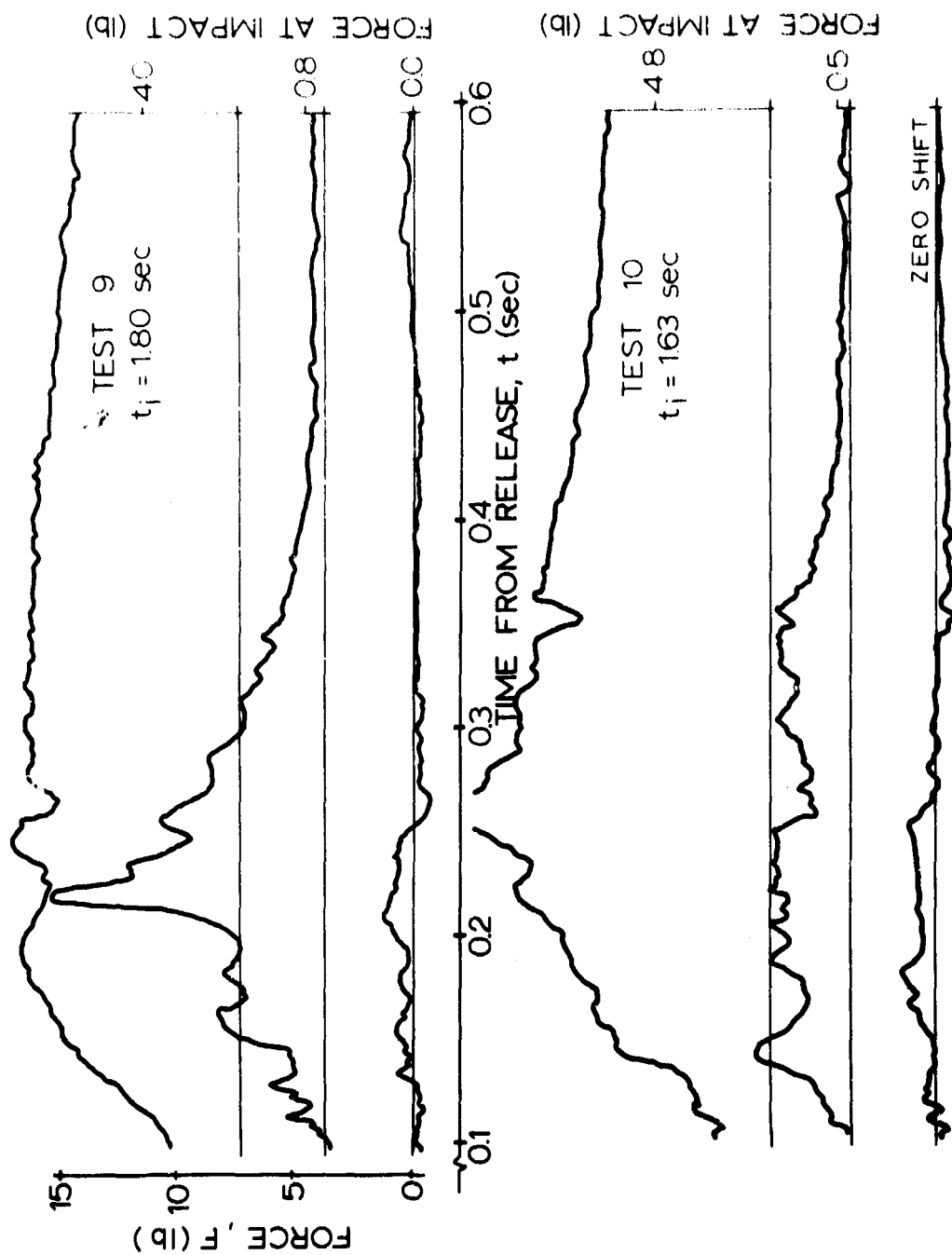
Fig 58 3 Parachute Cluster, $L_c = 0.88\ D_o$
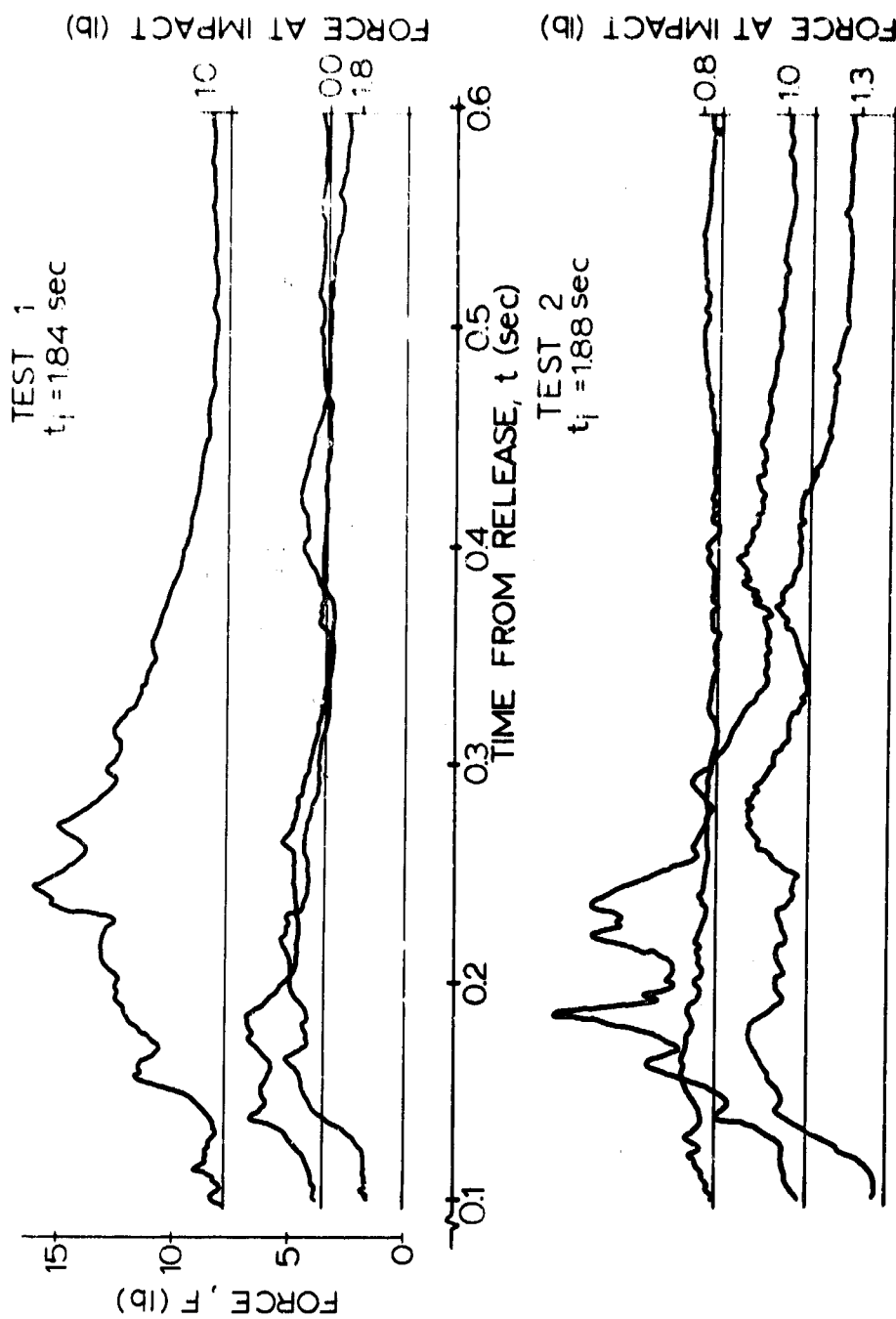
Fig 39 3 Parachute Cluster , Internal Parachute, Q2 D_o

82
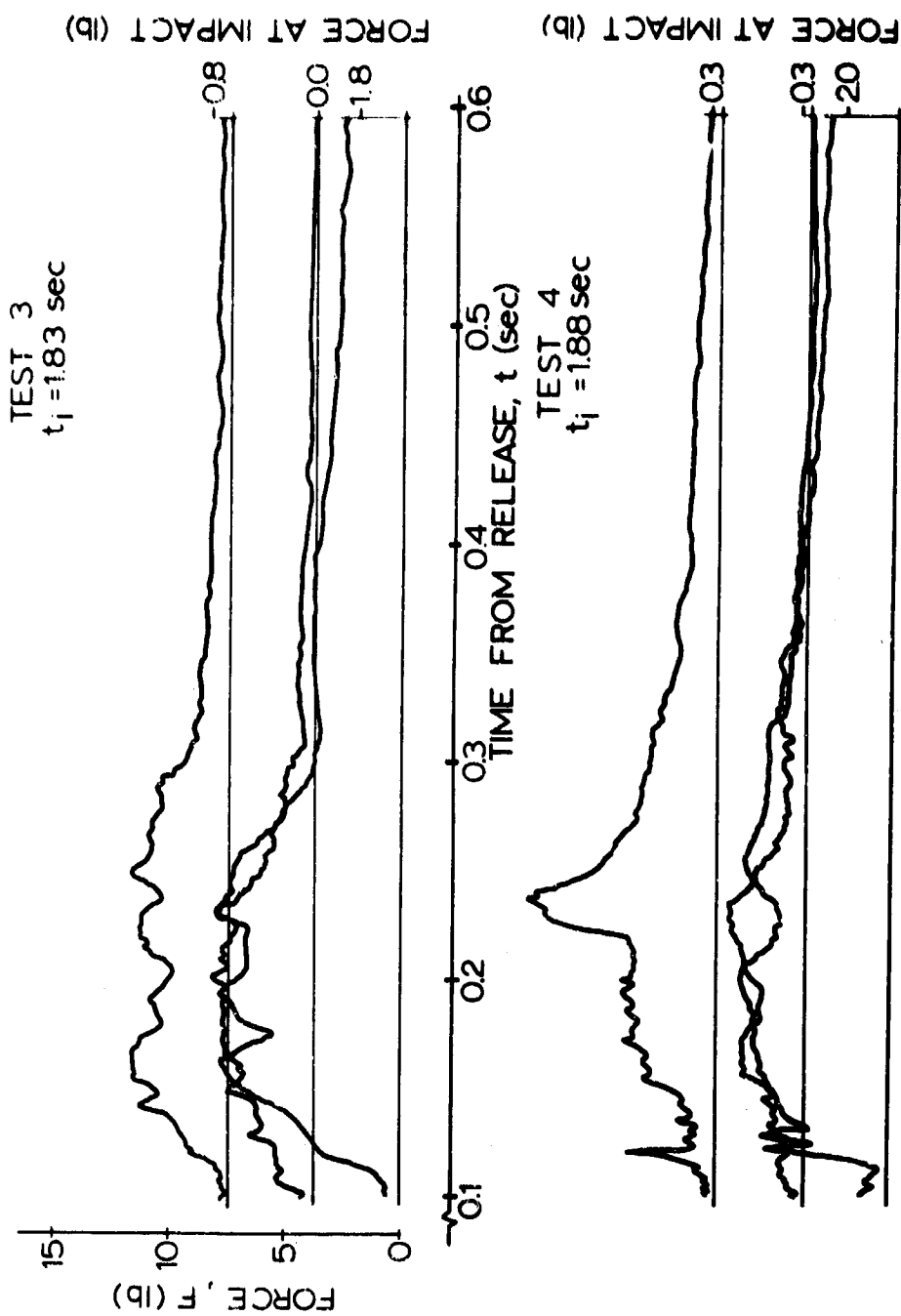
Fig 40   3 Parachute Cluster, Internal Parachute, 0.2 D_o
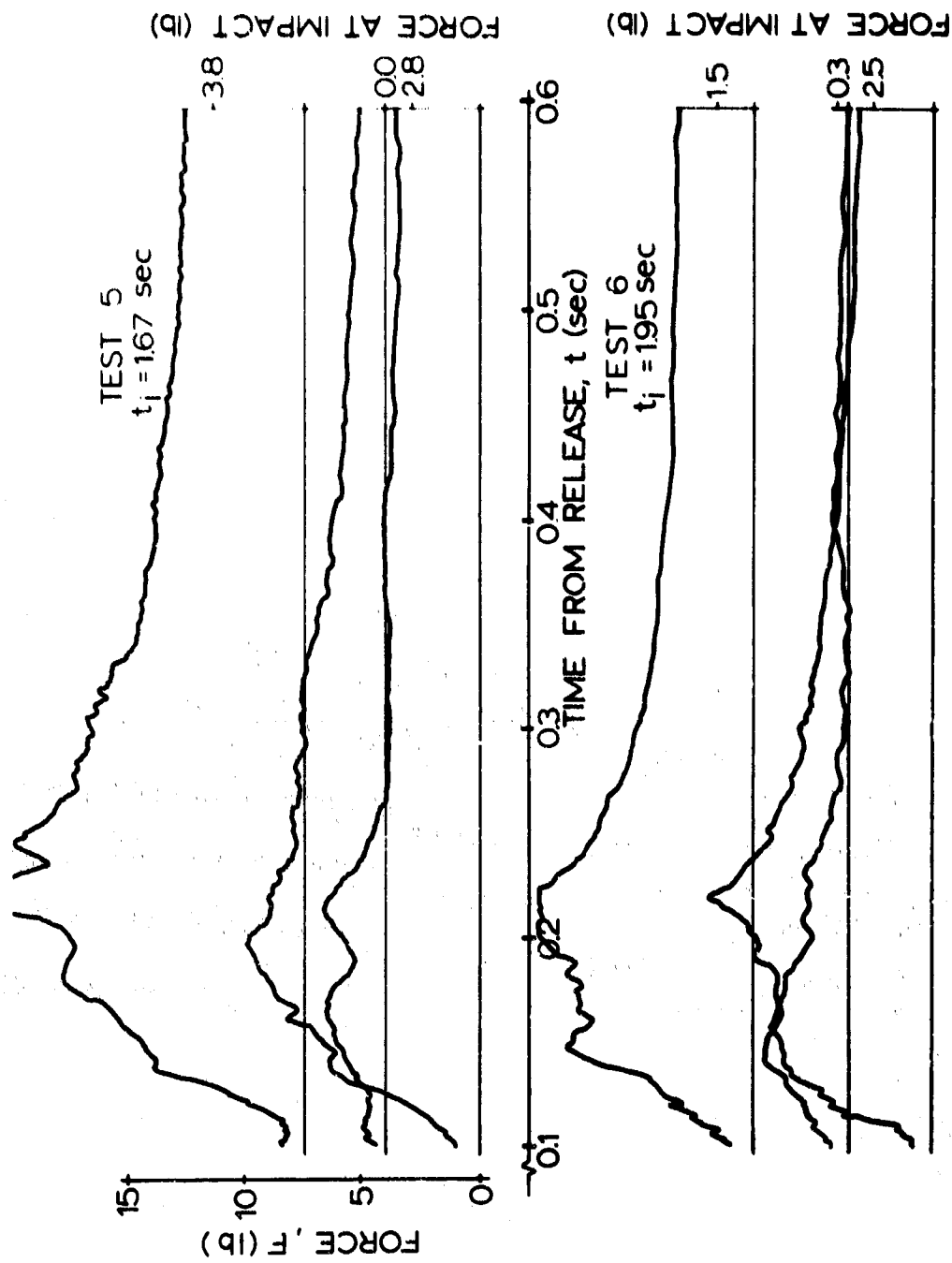
Fig 41   3 Parachute Cluster, Internal Parachute, O2 D_o

84
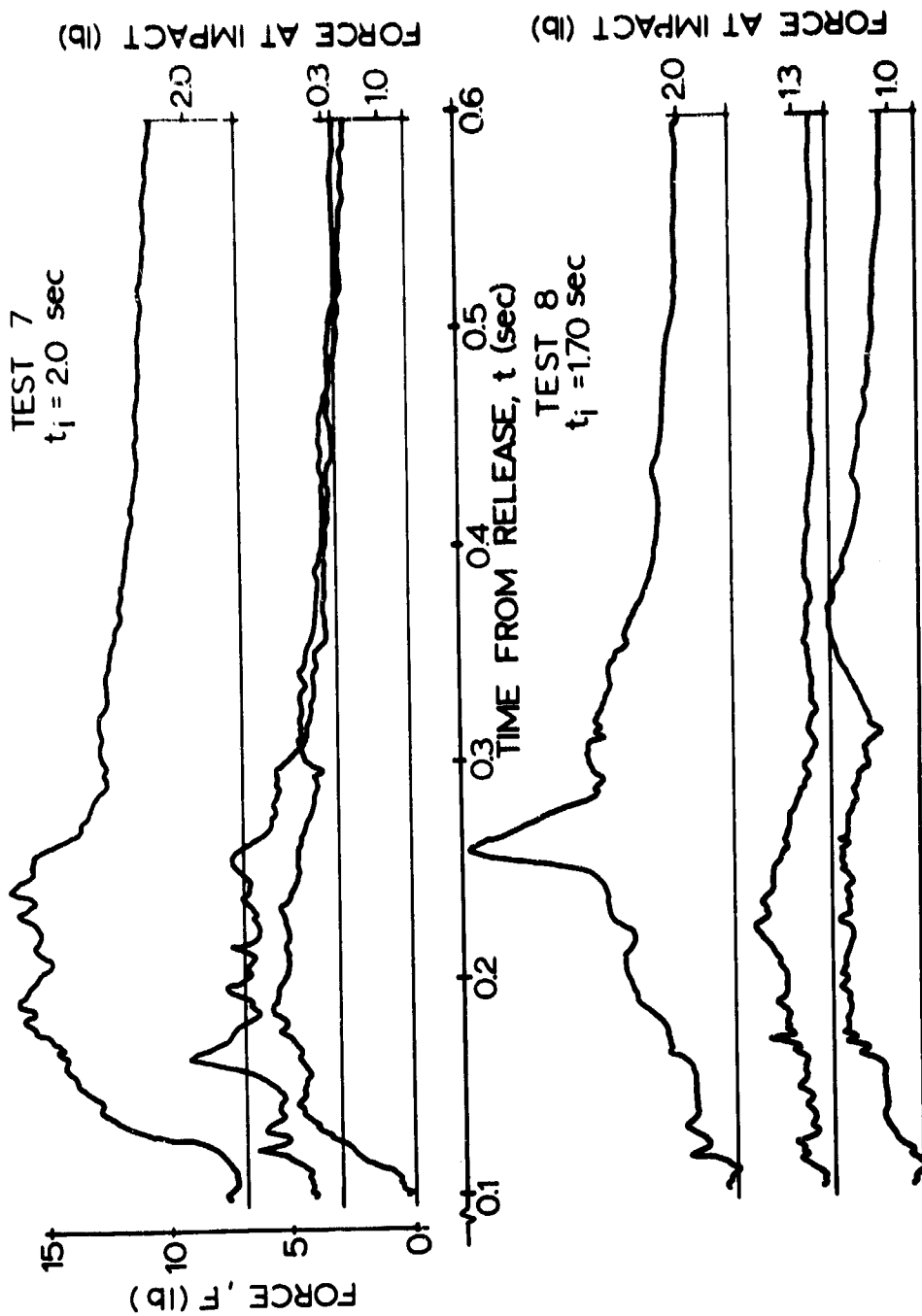
Fig 42 3 Parachute Cluster, Internal Parachute, O2 D₀

85
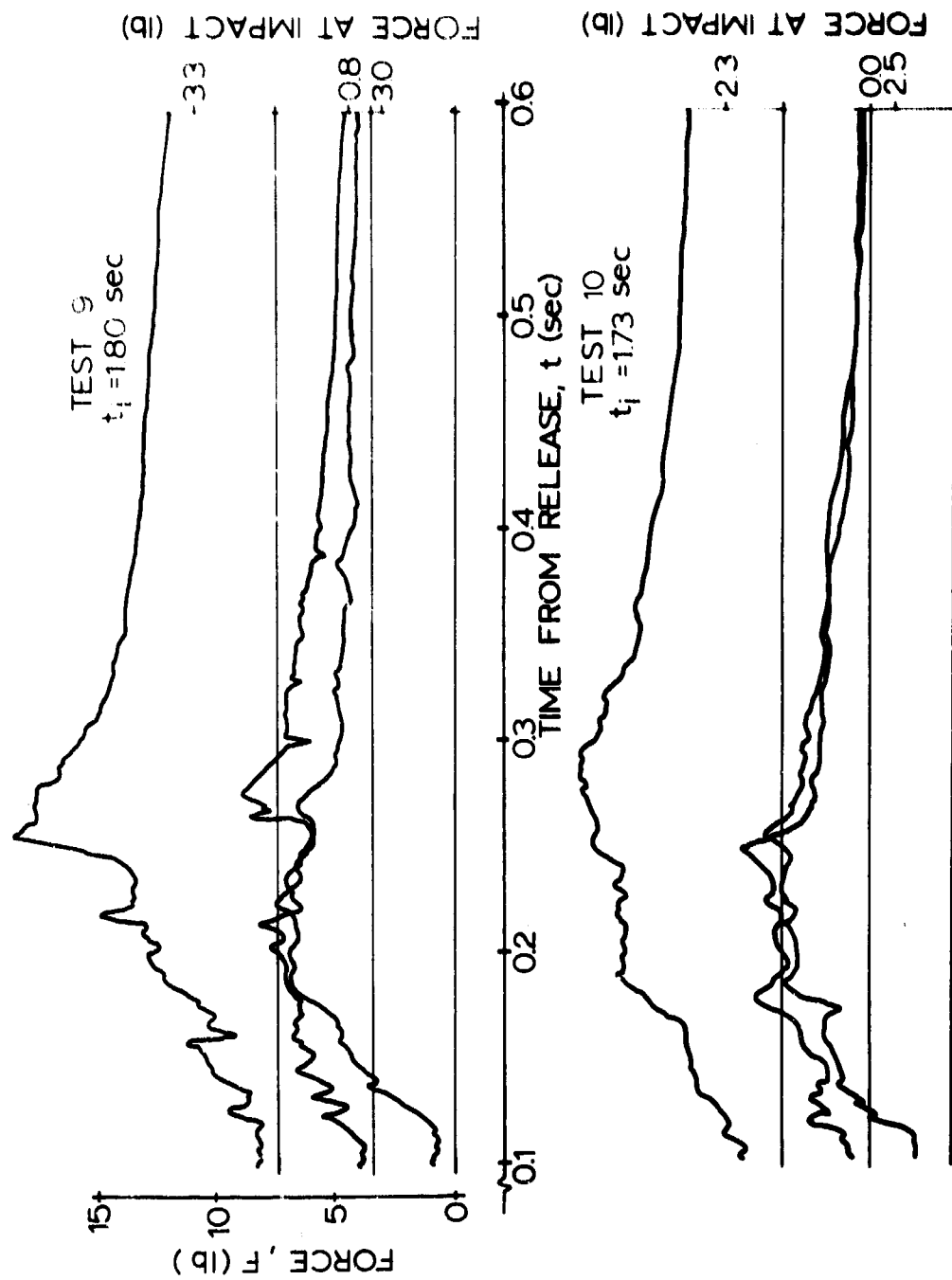
Fig 43 3 Parachute Cluster, Internal Parachute, 02 D_o
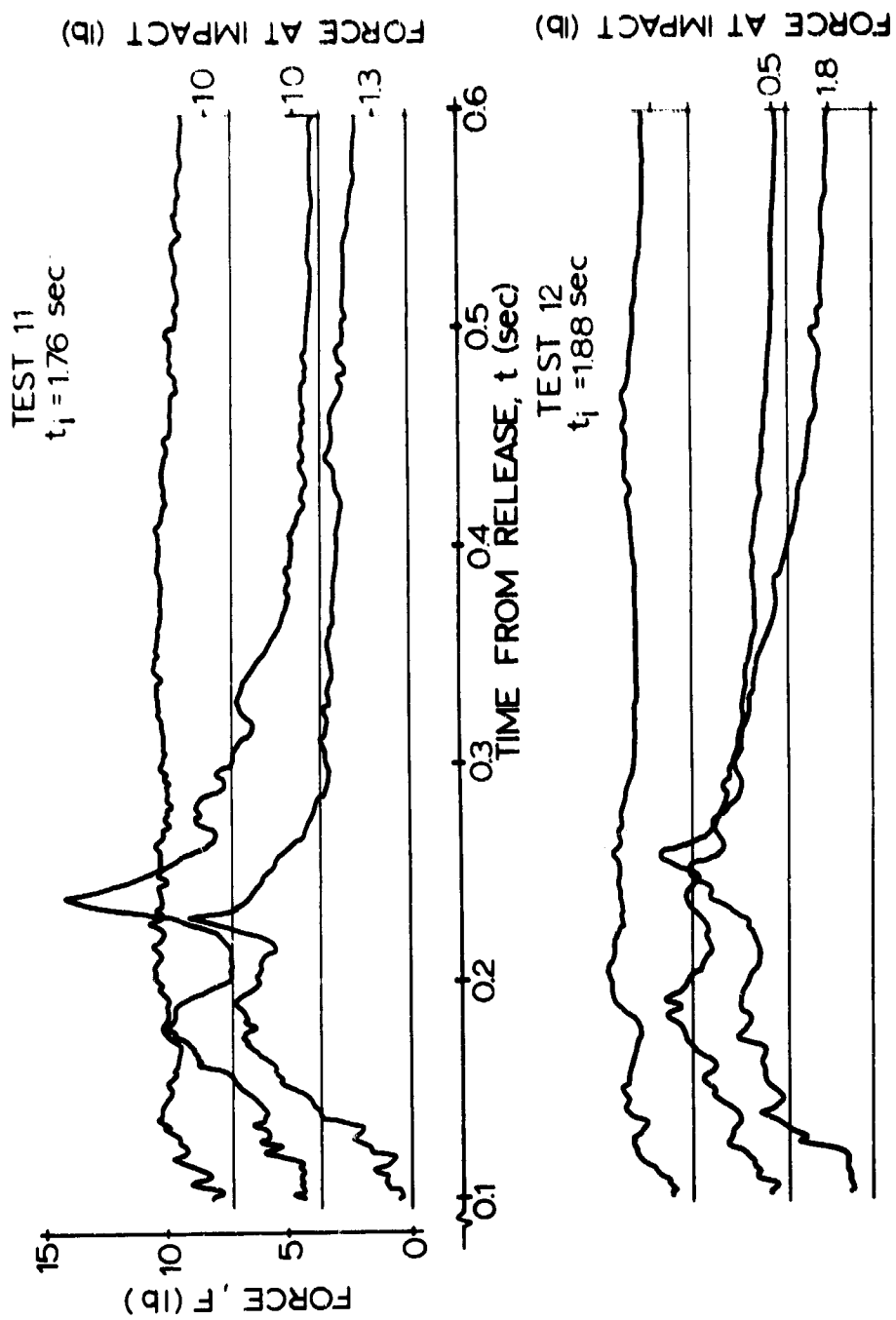
Fig 44 3 Parachute Cluster, Internal Parachute, 02 D_o

87
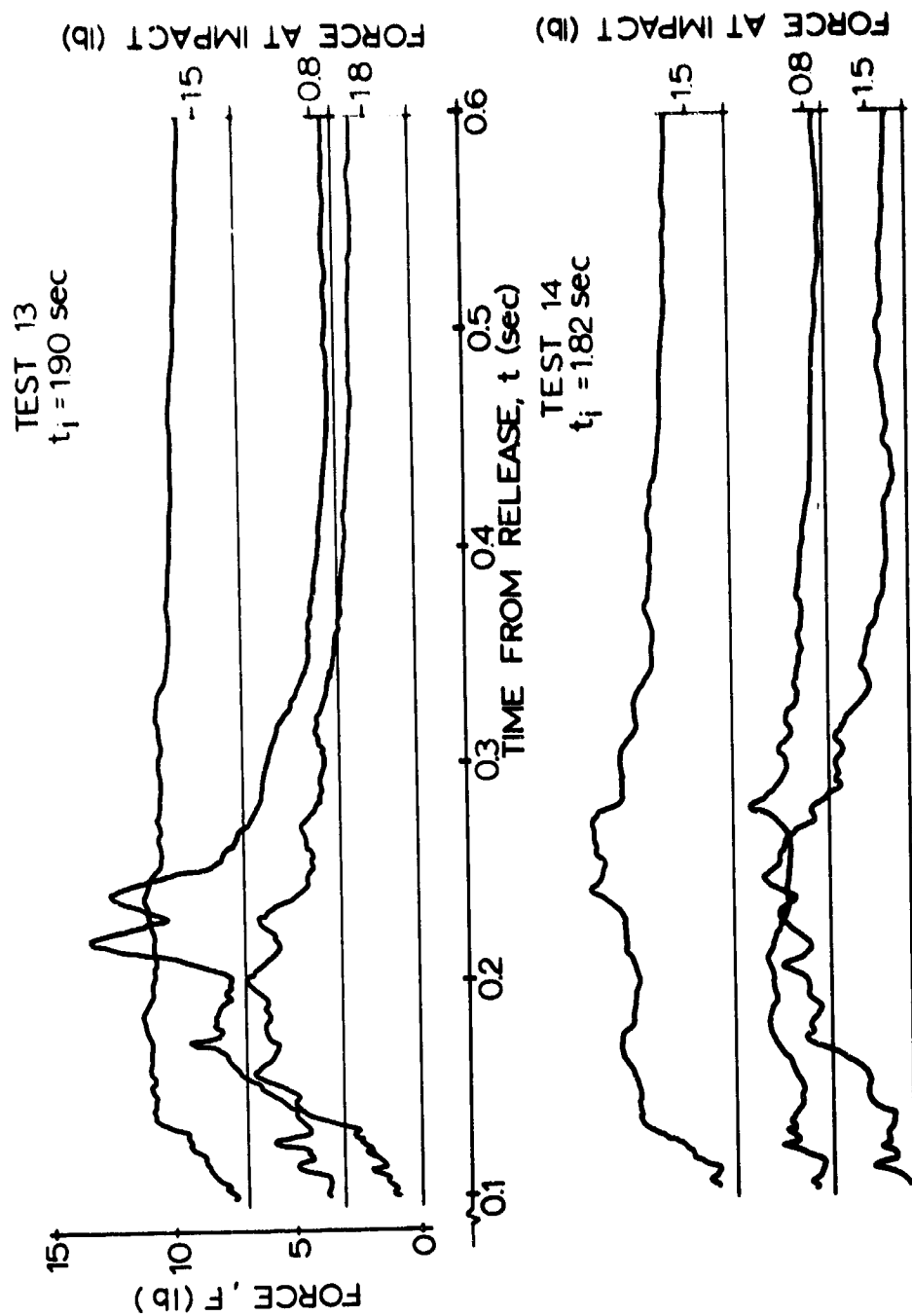
Fig 45   3 Parachute Cluster, Internal Parachute, 02 D_0

88
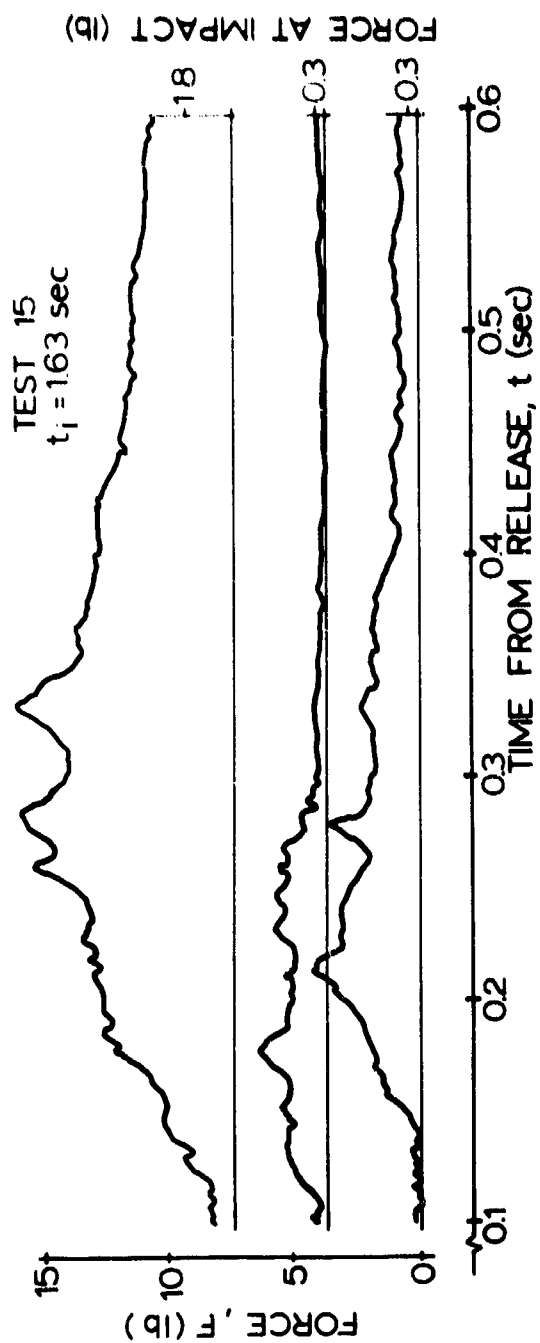
Fig 46 3 Parachute Cluster , Internal Parachute, 0.2 D_o
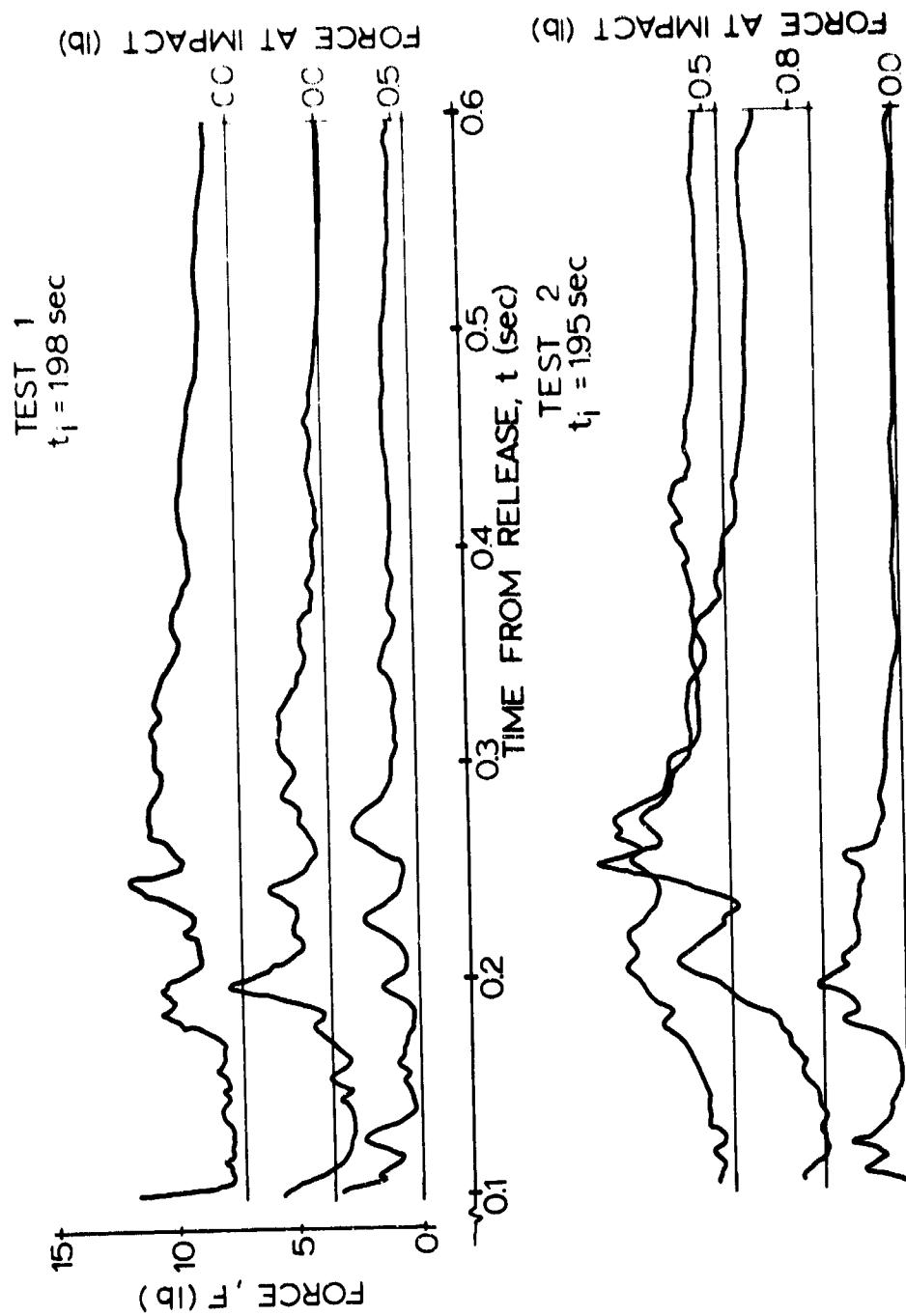
Fig 47 3 Parachute Cluster, $L_r = 0.2 \ D_o$

90
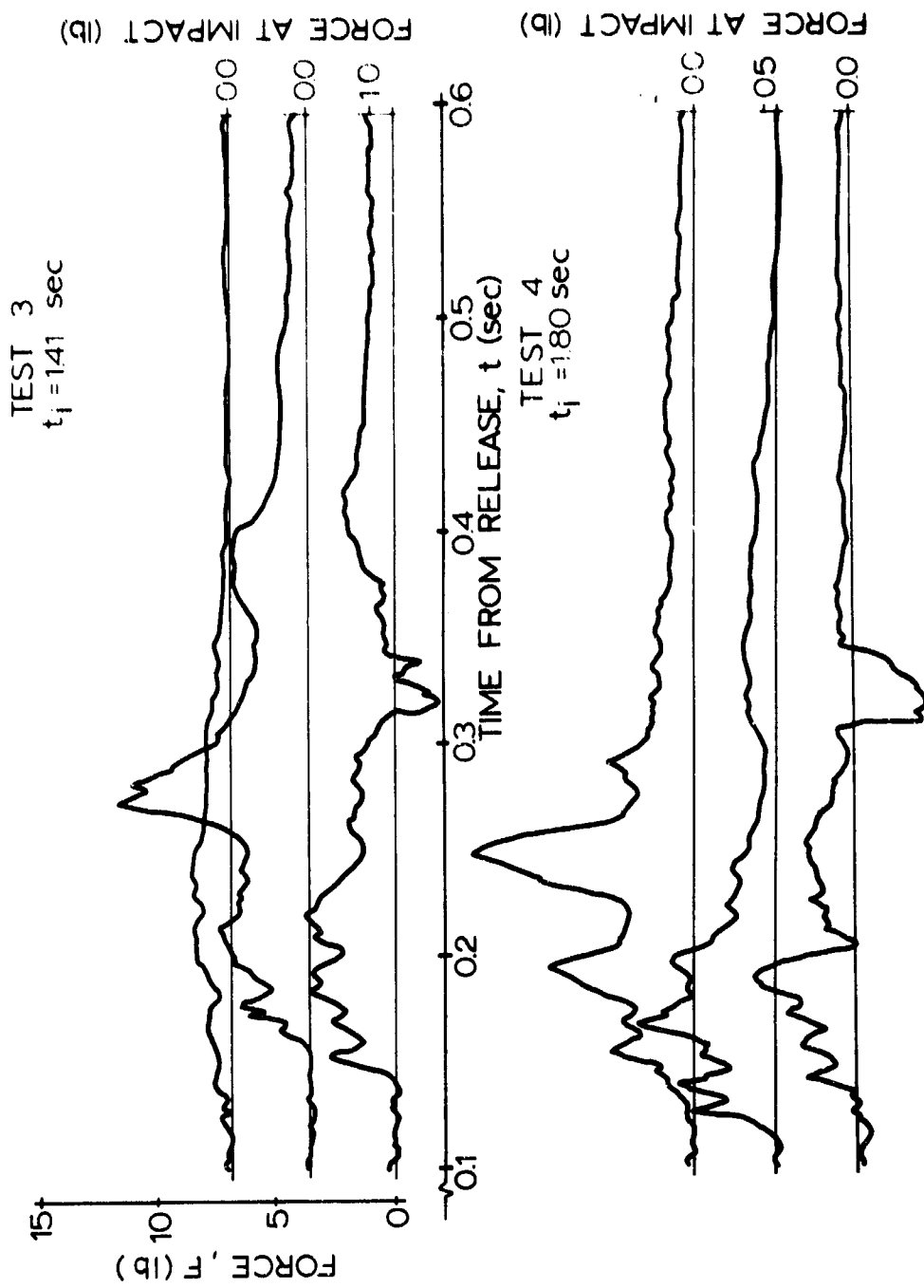
Fig 48 3 Parachute Cluster, $L_r = 0.2 \, D_o$

91
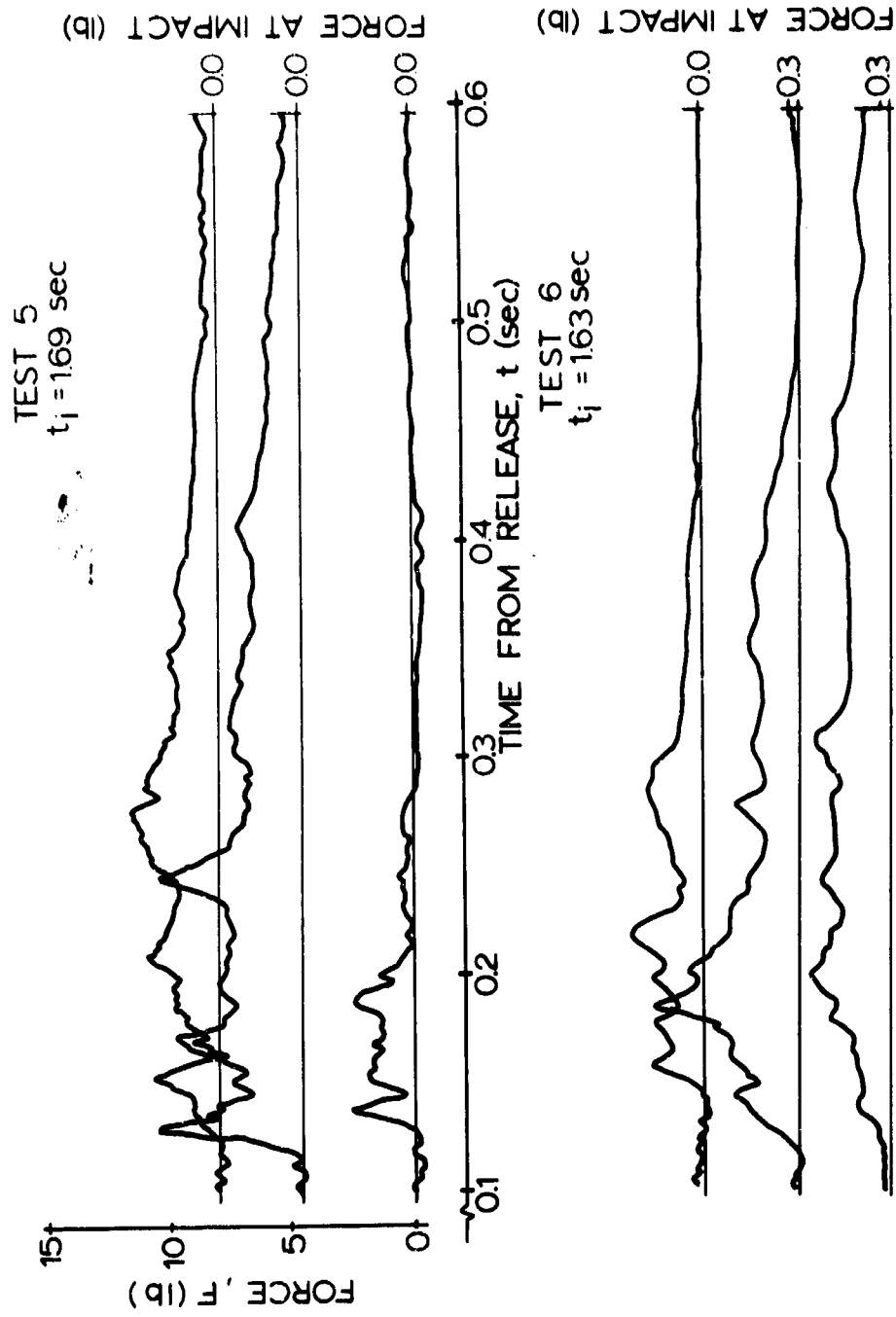
Fig 49 3 Parachute Cluster, $L_r = 0.2\ D_o$

92
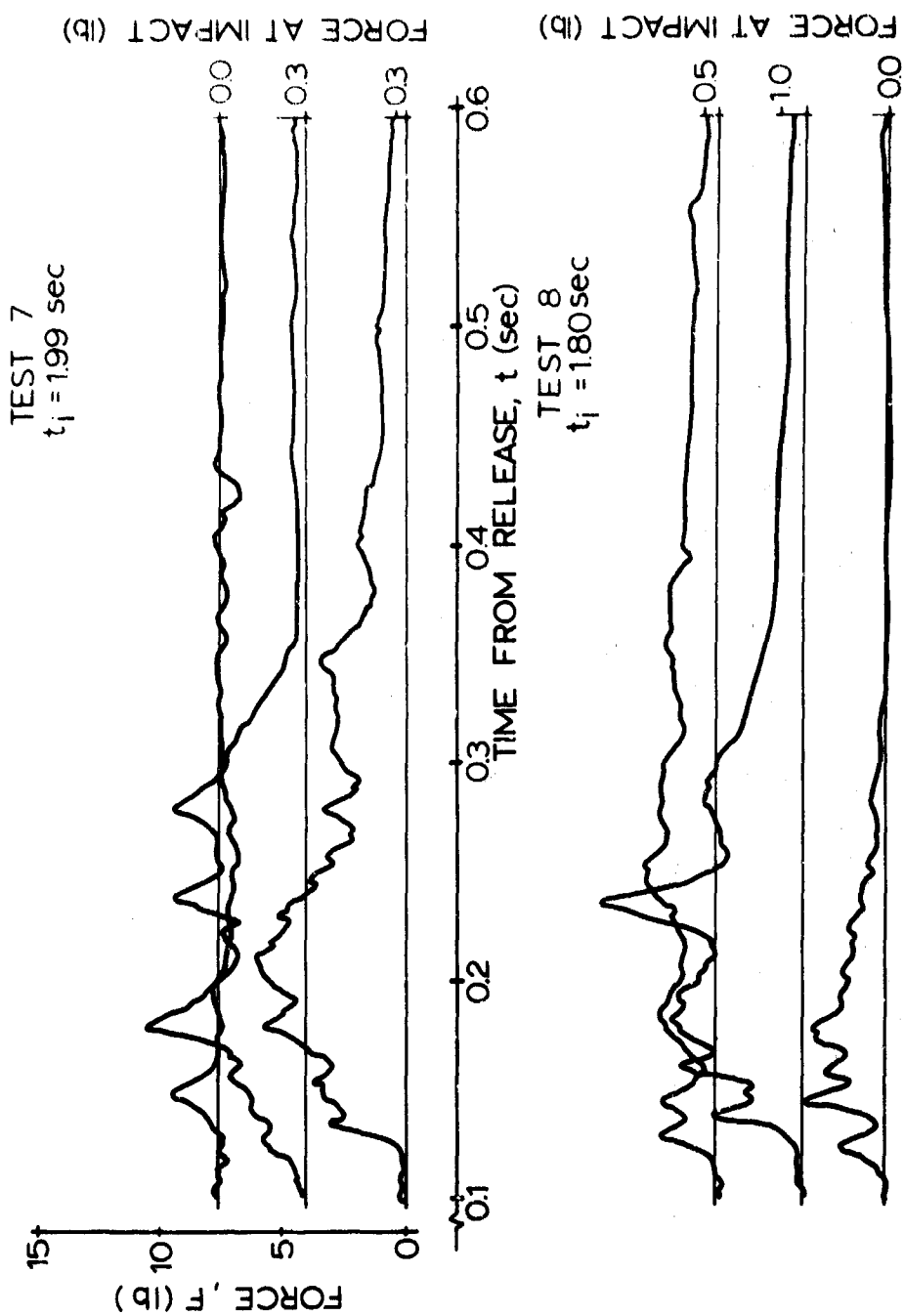
Fig 50   3 Parachute Cluster, $L_r = 0.2\ D_o$

93
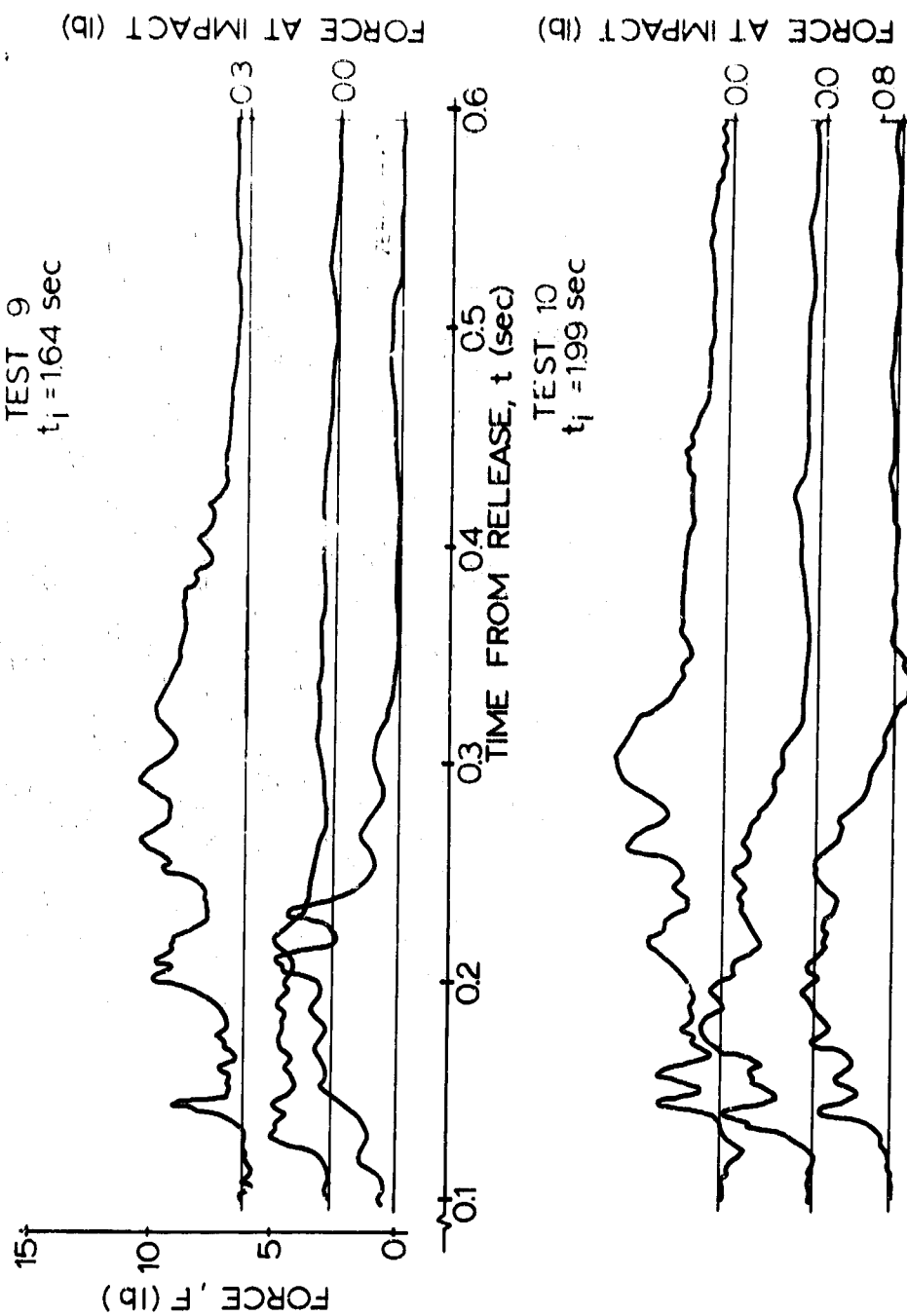
Fig 51   3 Parachute Cluster, $L_r = 0.2 \ D_o$

94
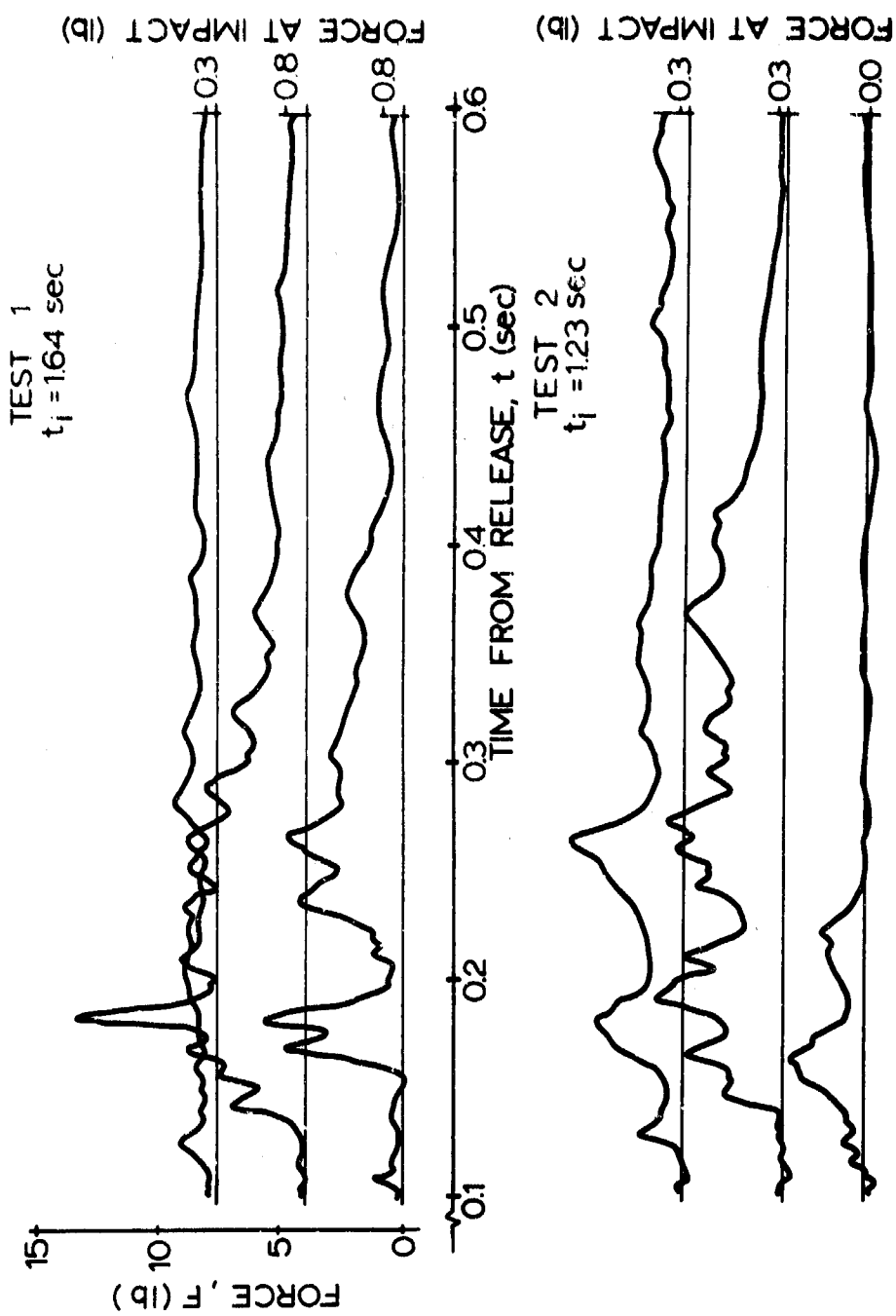
Fig 52   3 Parachute Cluster, $L_r = 0.4 \, D_o$

95
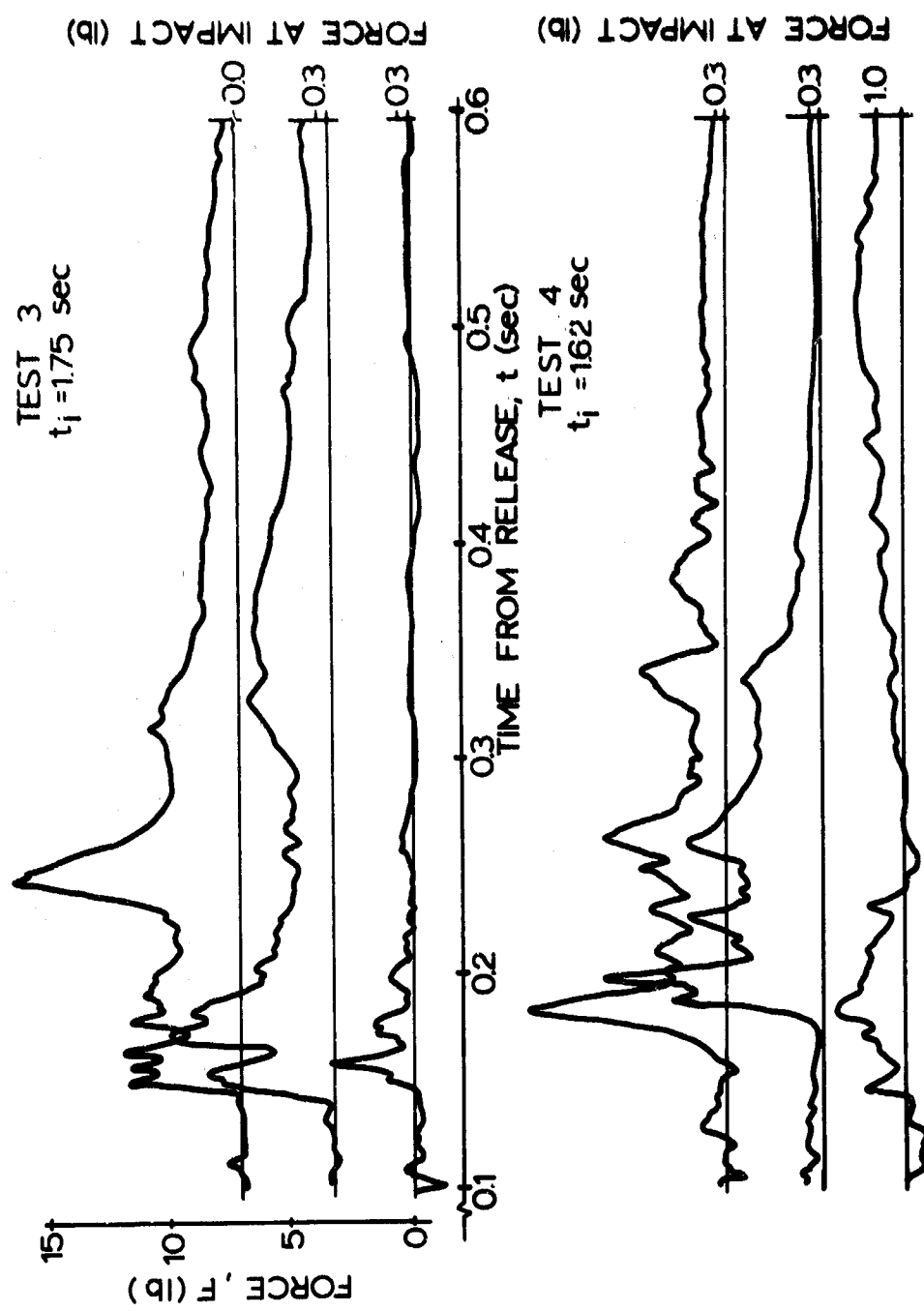
Fig 53   3 Parachute Cluster, $L_r = 0.4 \, D_o$
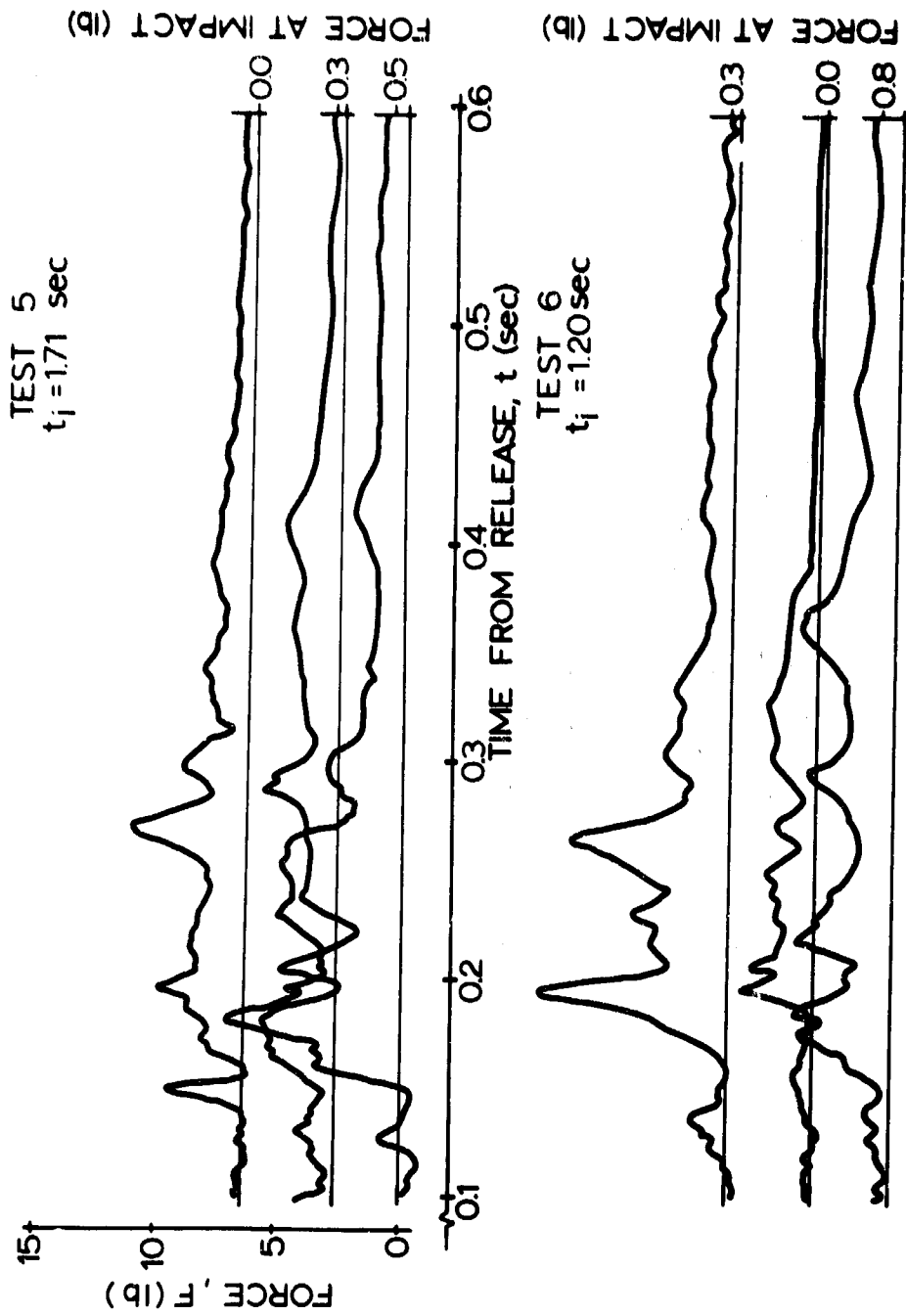
Fig 54 3 Parachute Cluster, $L_r = 0.4 \, D_o$

97
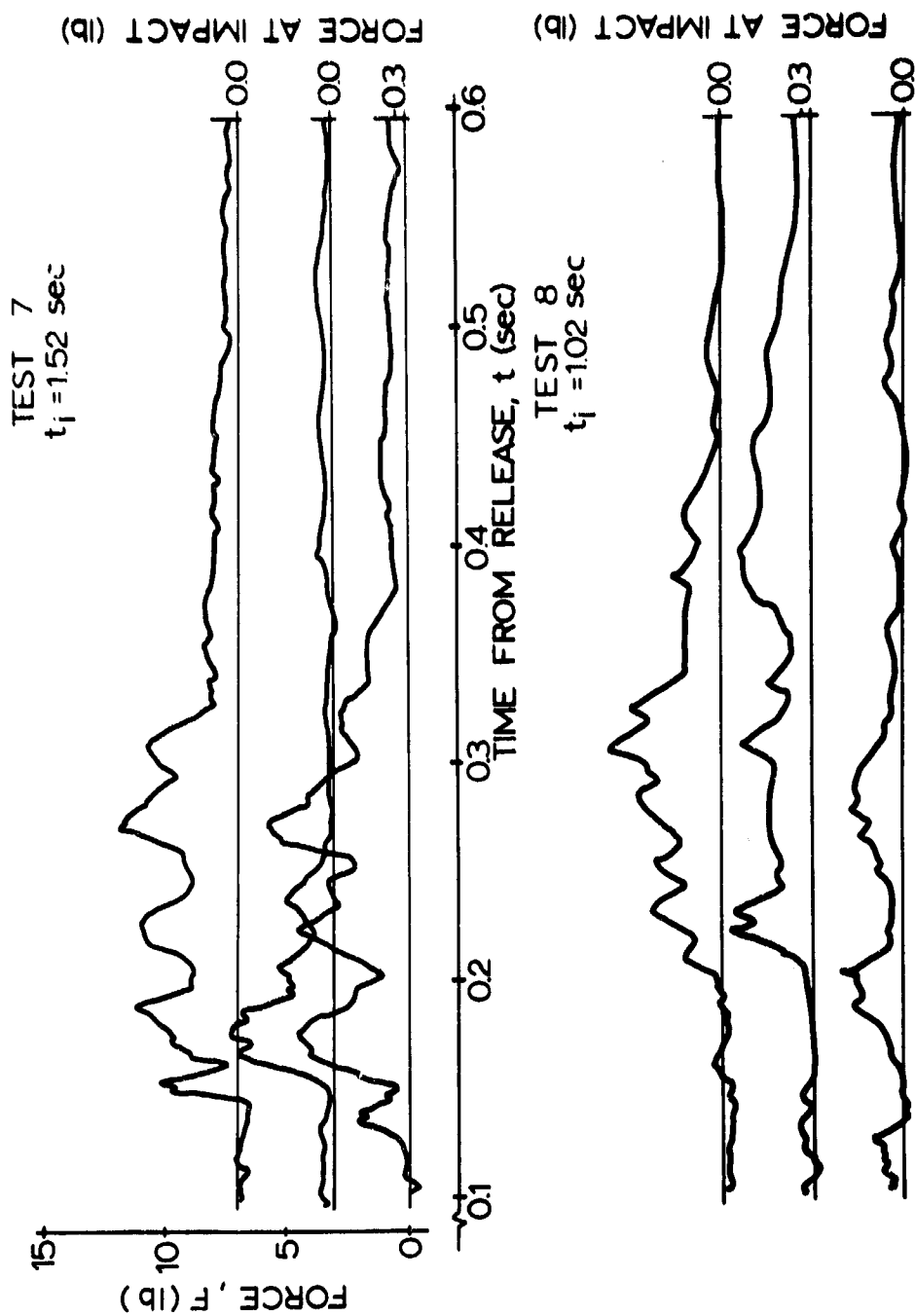
Fig 55 3 Parachute Cluster, $L_r = 0.4$ D_0

98
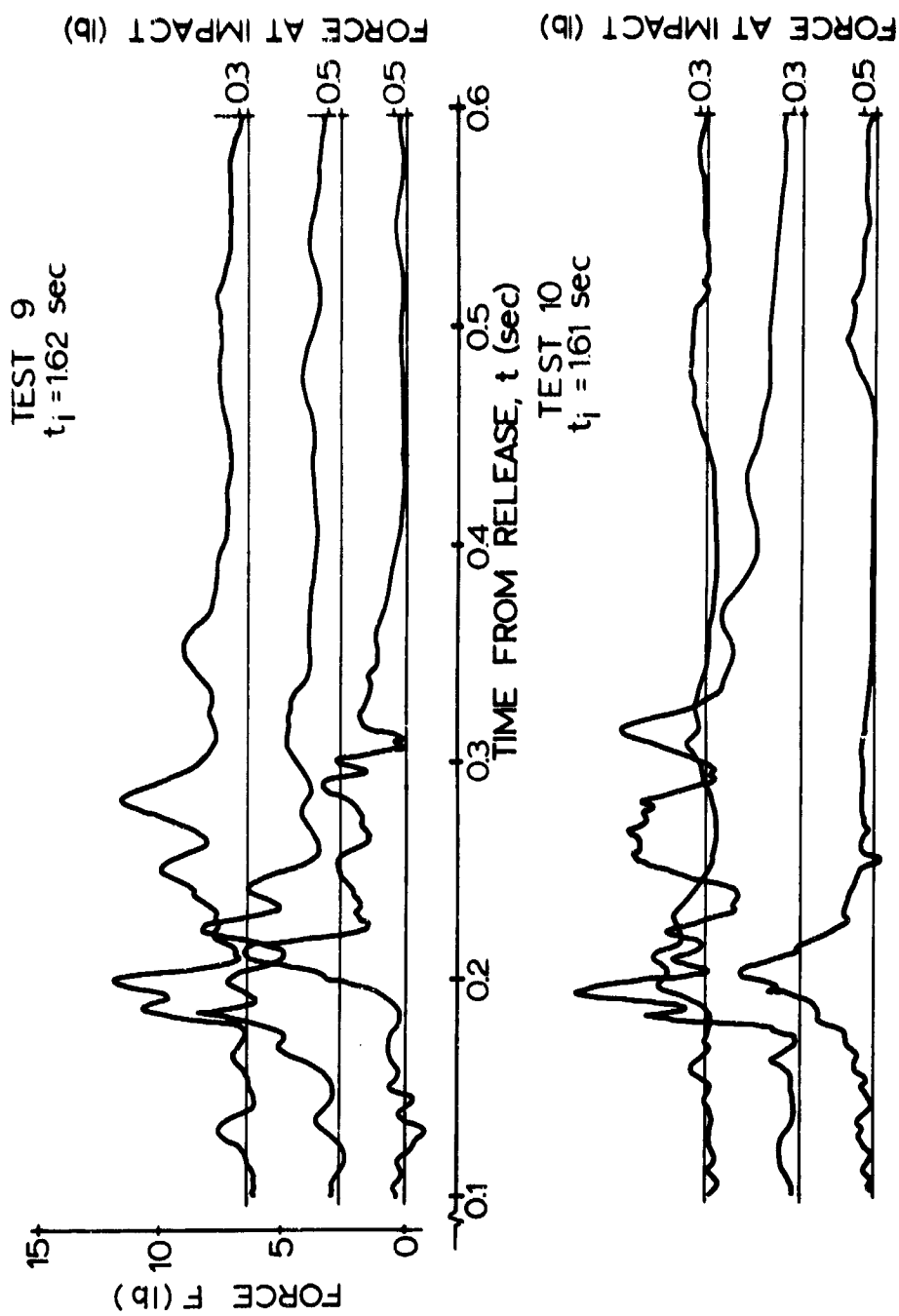
Fig 56 3 Parachute Cluster, $L_r = 0.4 D_o$

99
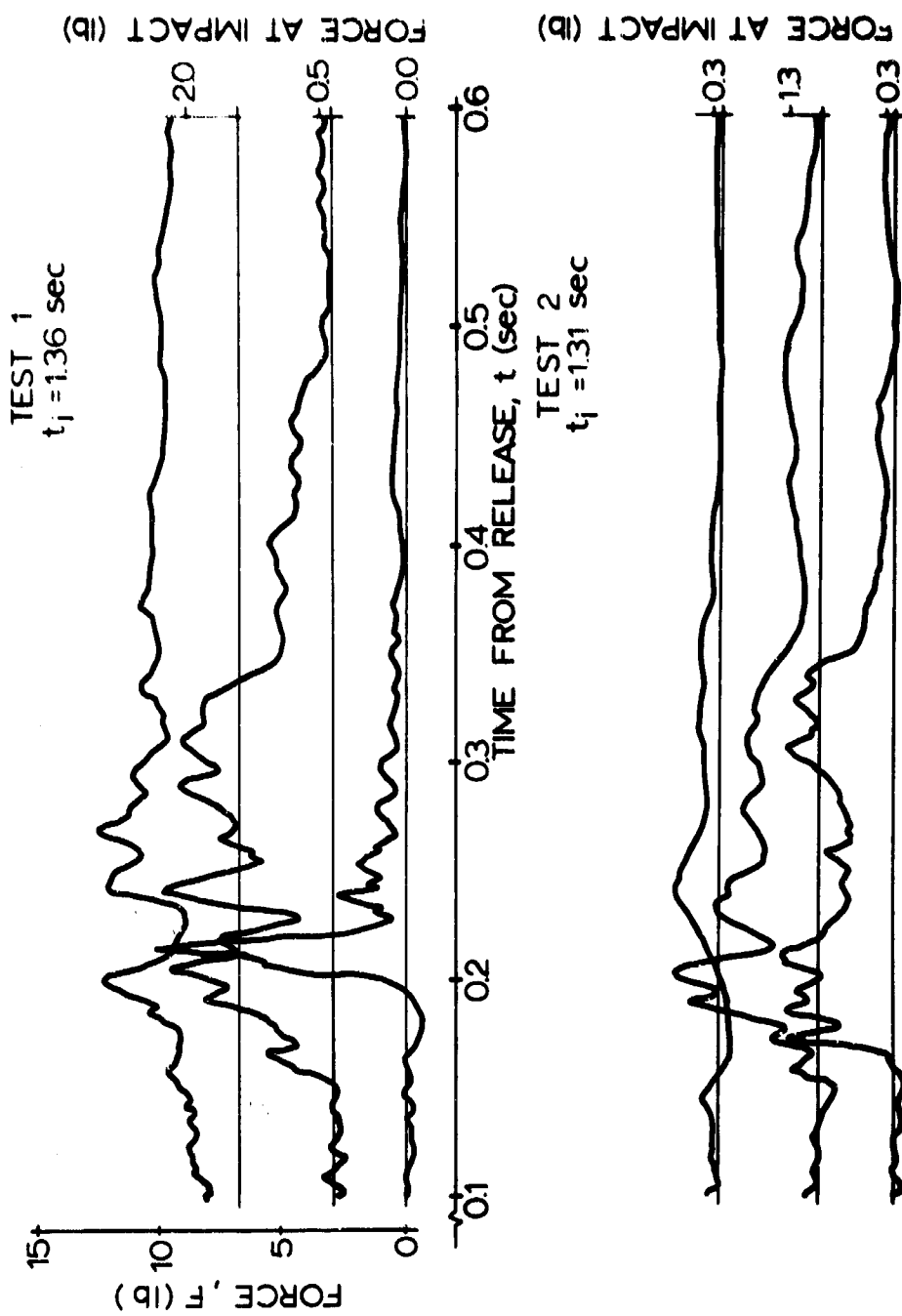
Fig 57   3 Parachute Cluster, $L_r = 0.6 \ D_o$

100

Fig 58 3 Parachute Cluster, L_r = 0.6 D_o

101
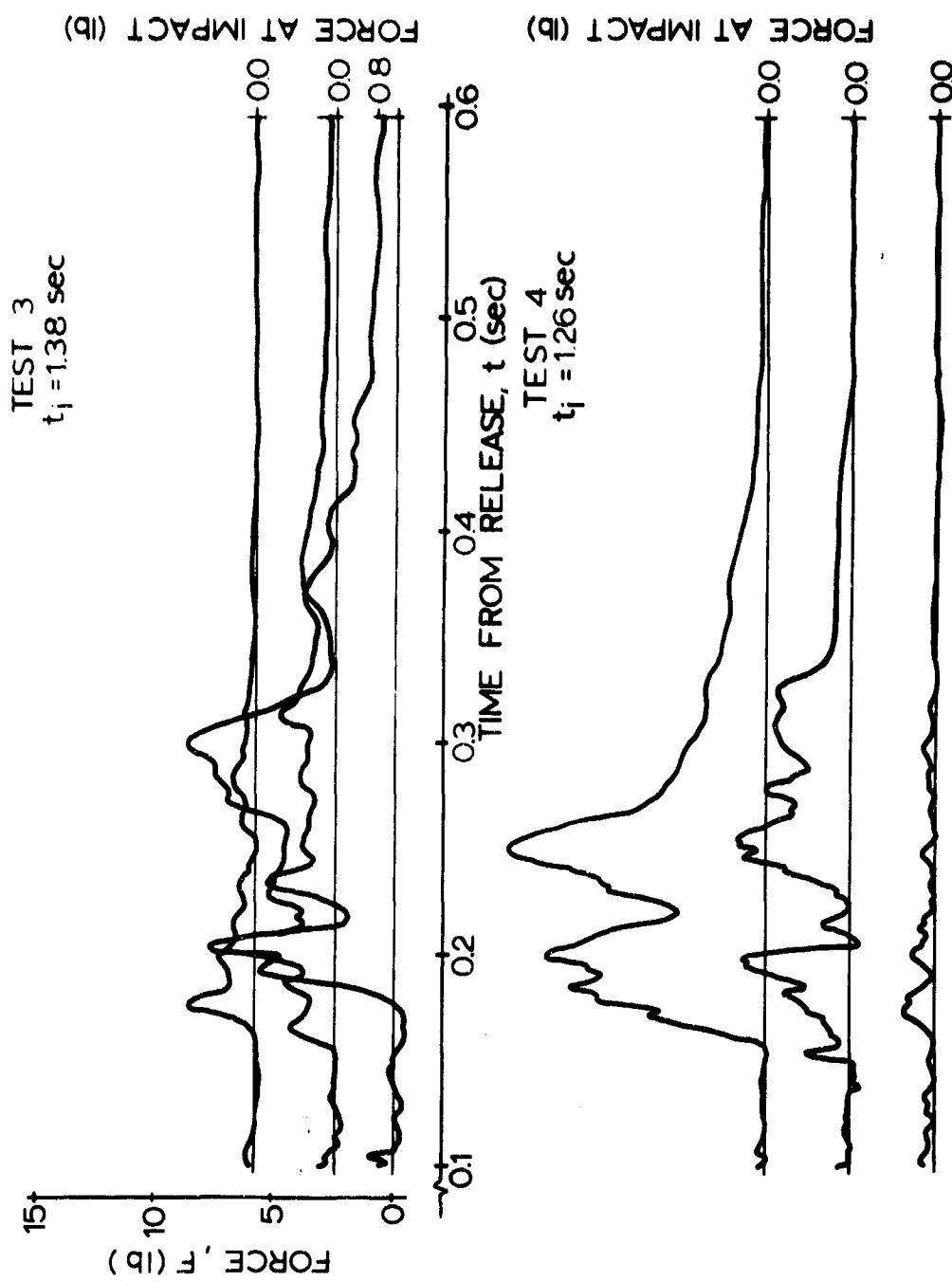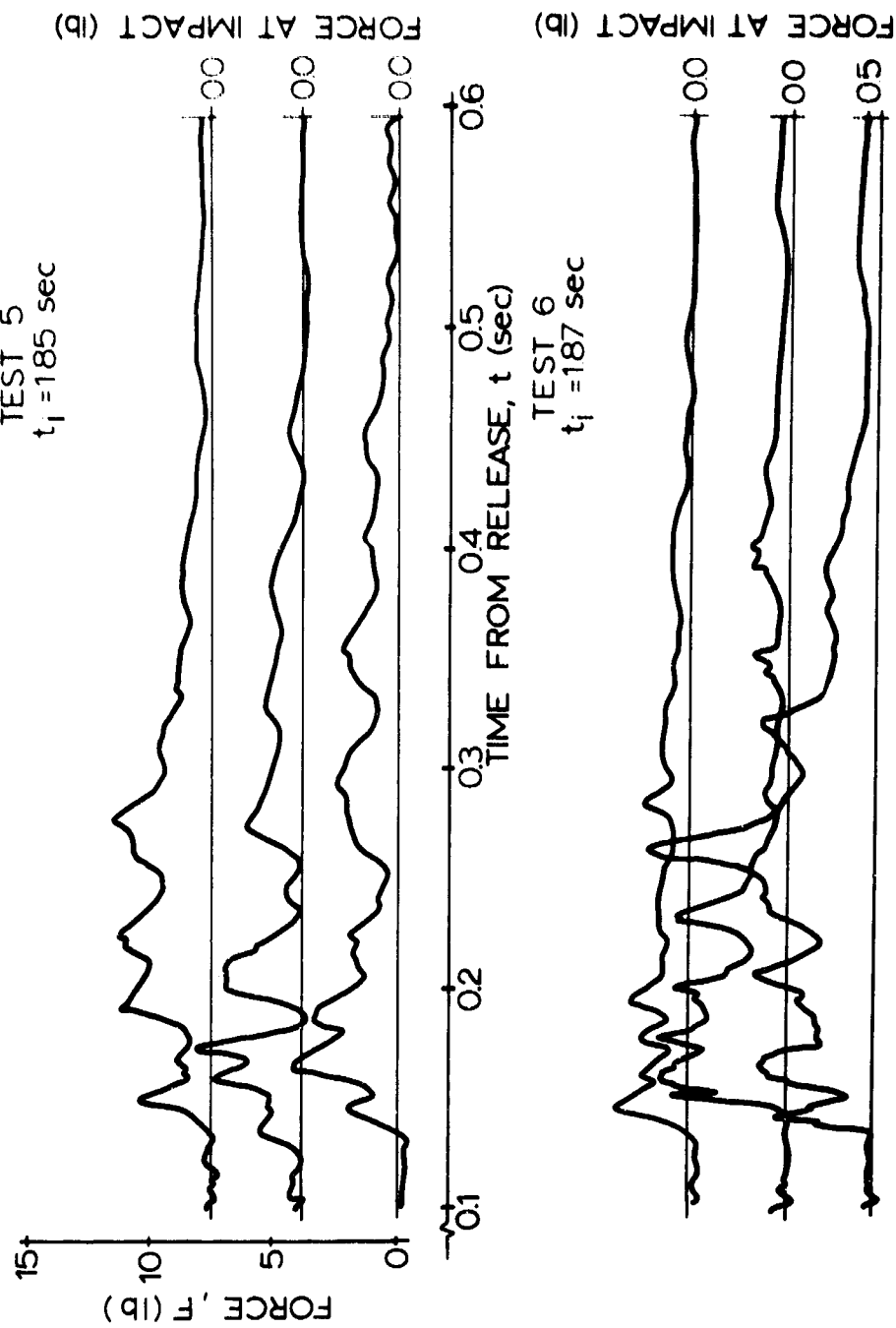
Fig 59 3 Parachute Cluster, $L_r = 0.6\ D_o$
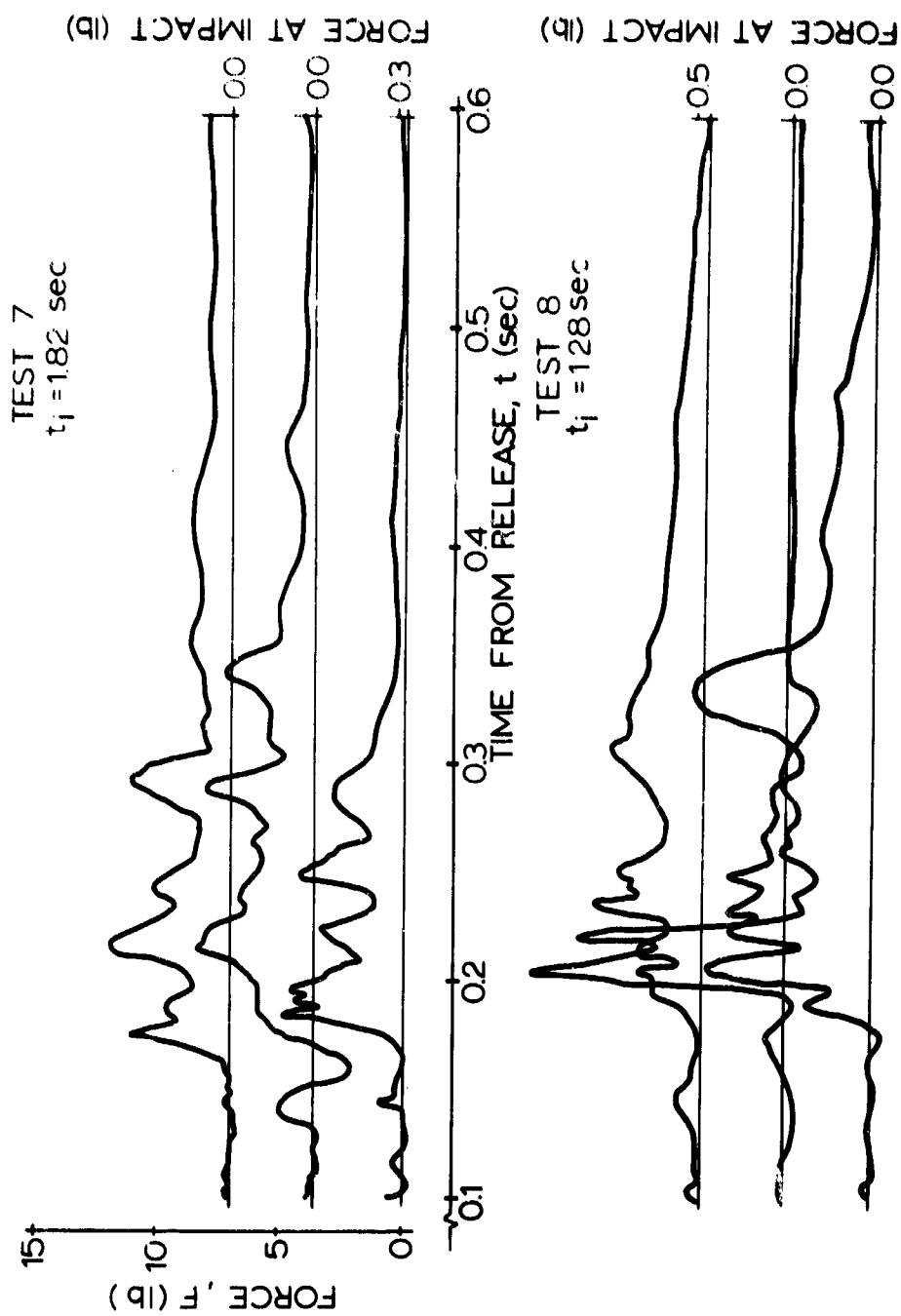
Fig 60 3 Parachute Cluster, $L_r = 0.6\ D_o$

103
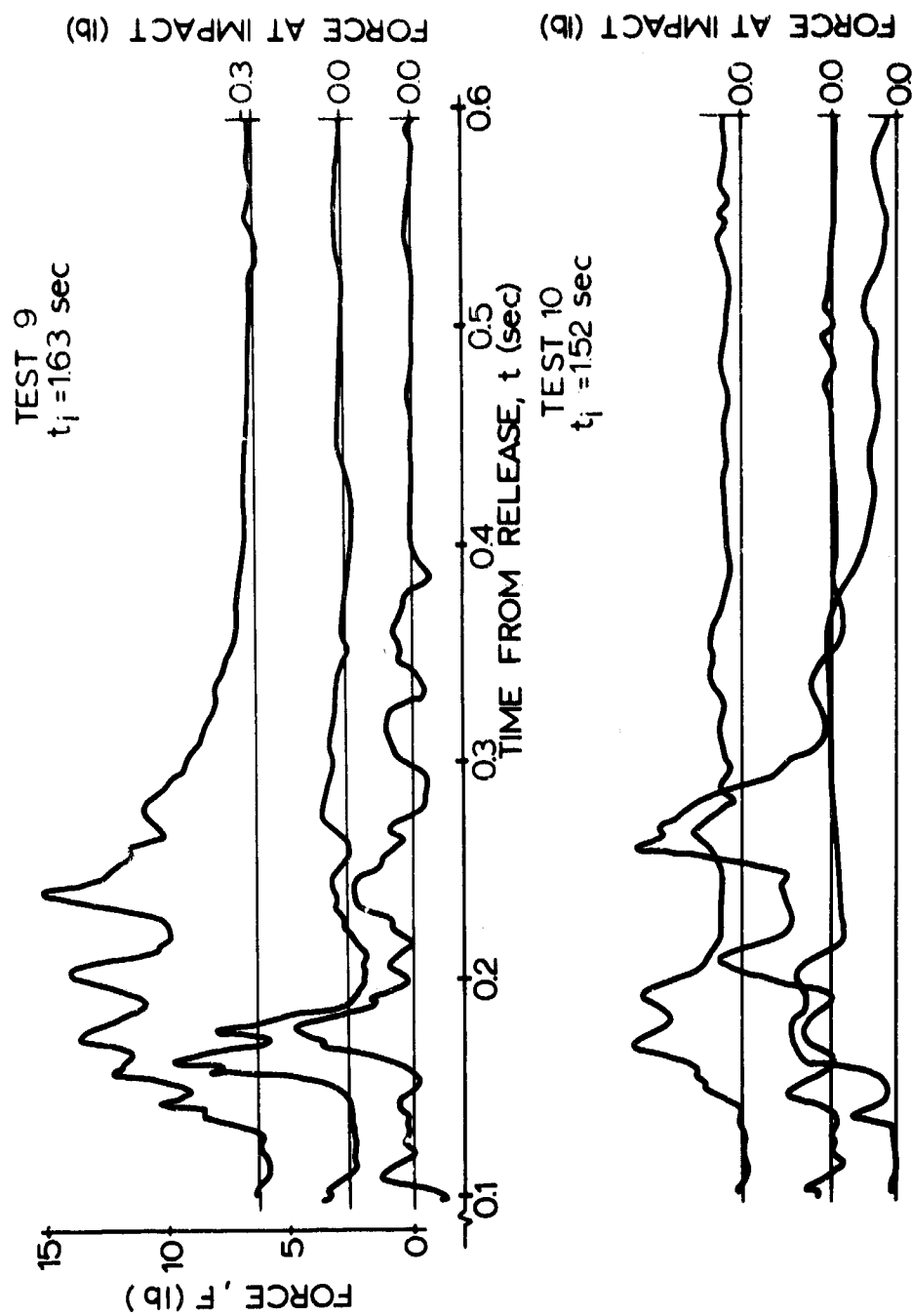
Fig 61   3 Parachute Cluster, L_r = 0.6 D_o
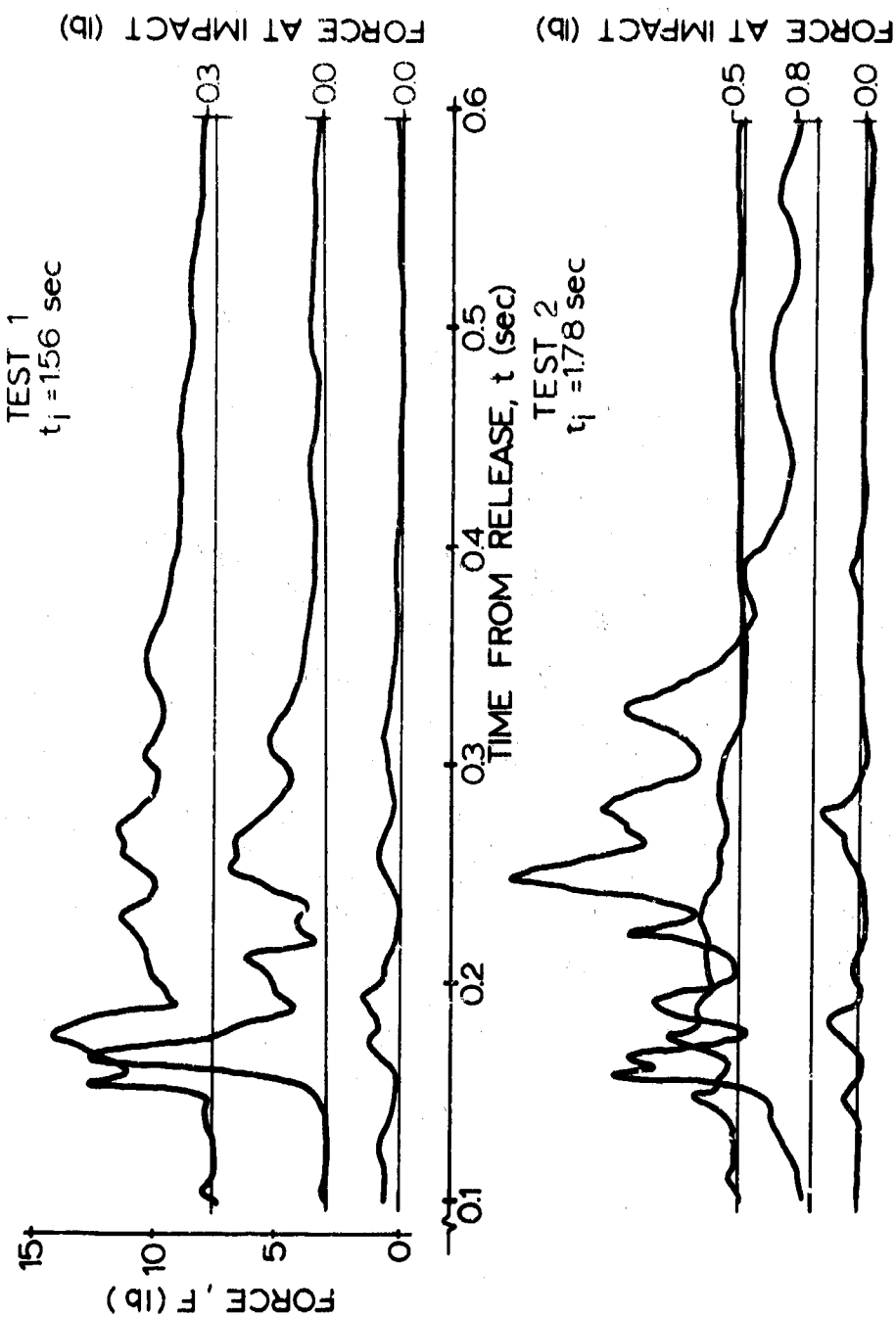
Fig 62   3 Parachute Cluster, $L_r = 0.4\ D_o + L_c = 0.97\ D_o$

105
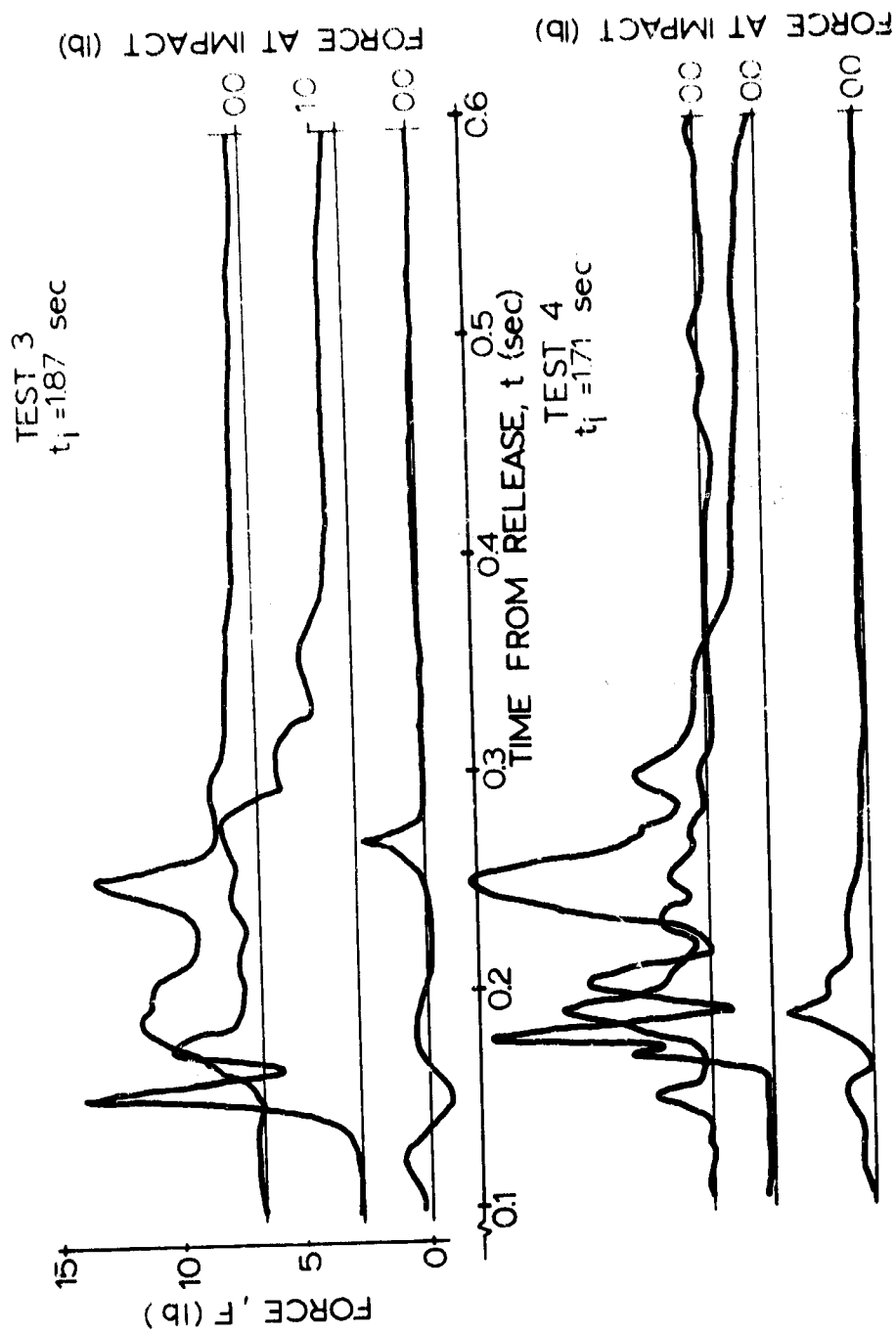
Fig 63 3 Parachute Cluster, $L_r = 0.4\ D_o + L_c = 0.97\ D_o$
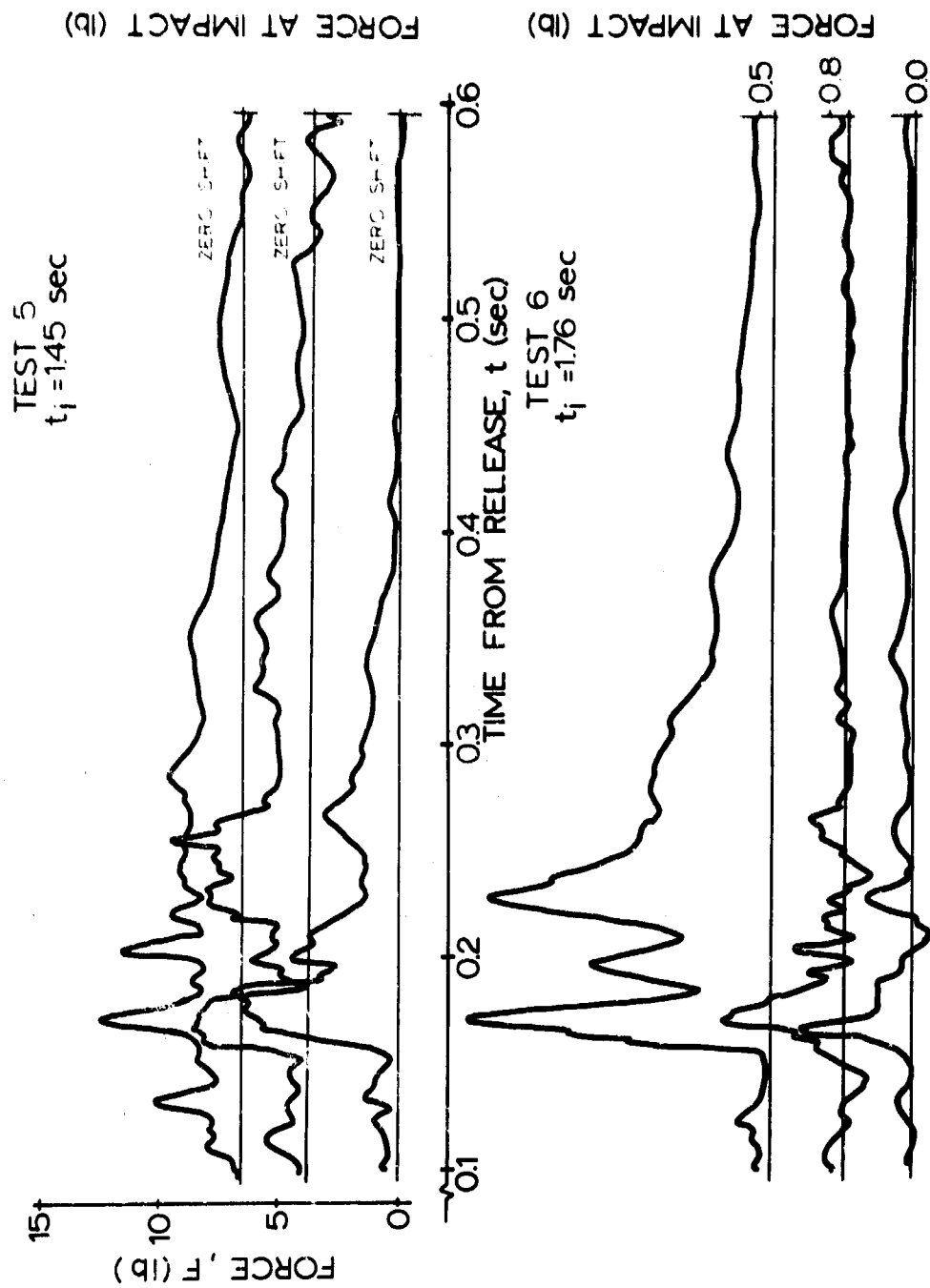
Fig 64   3 Parachute Cluster, $L_r = 0.4\, D_o + L_c = 0.97\, D_o$
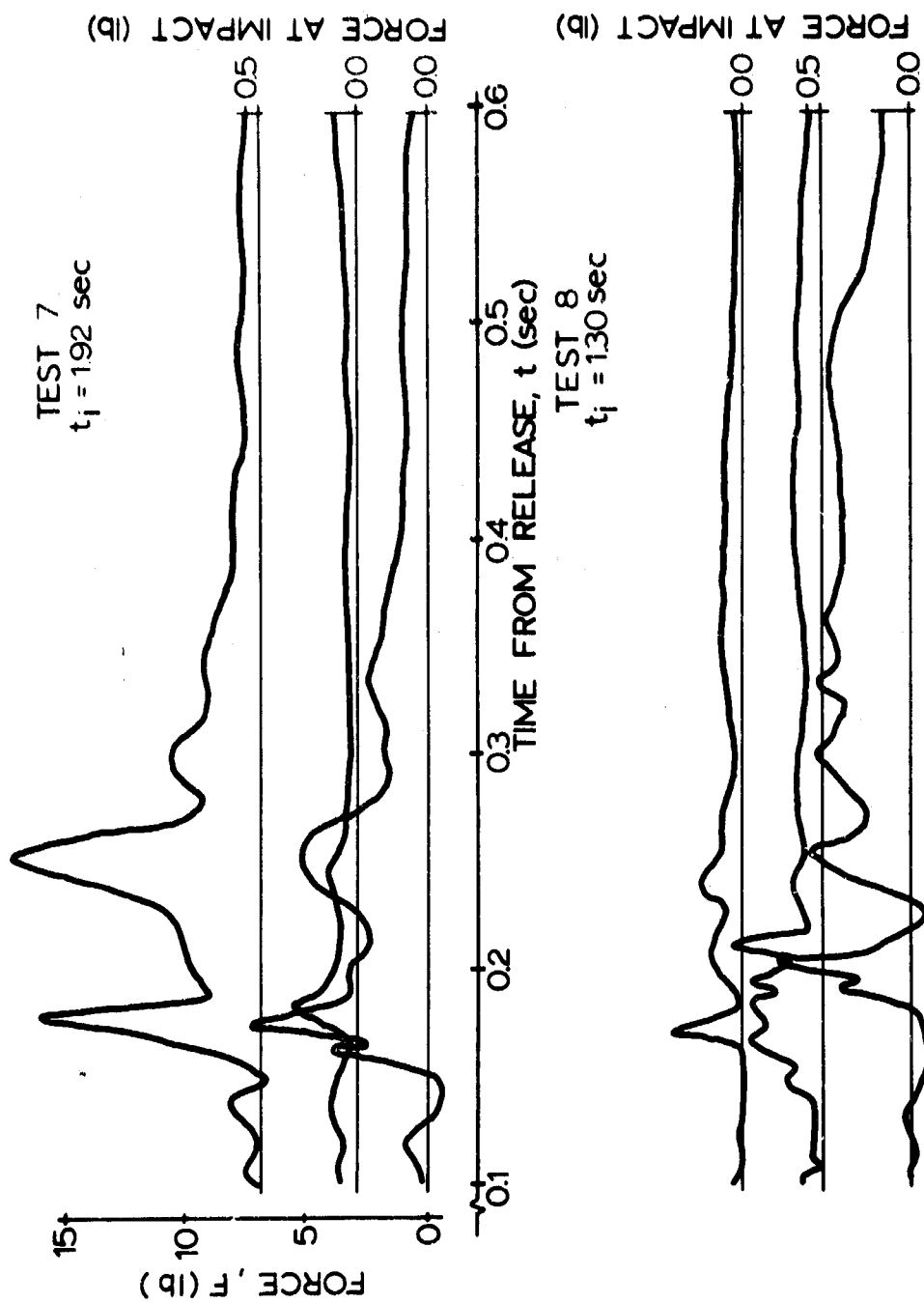
Fig 65   3 Parachute Cluster, $L_r = 0.4\ D_o + L_c = 0.97\ D_o$

108
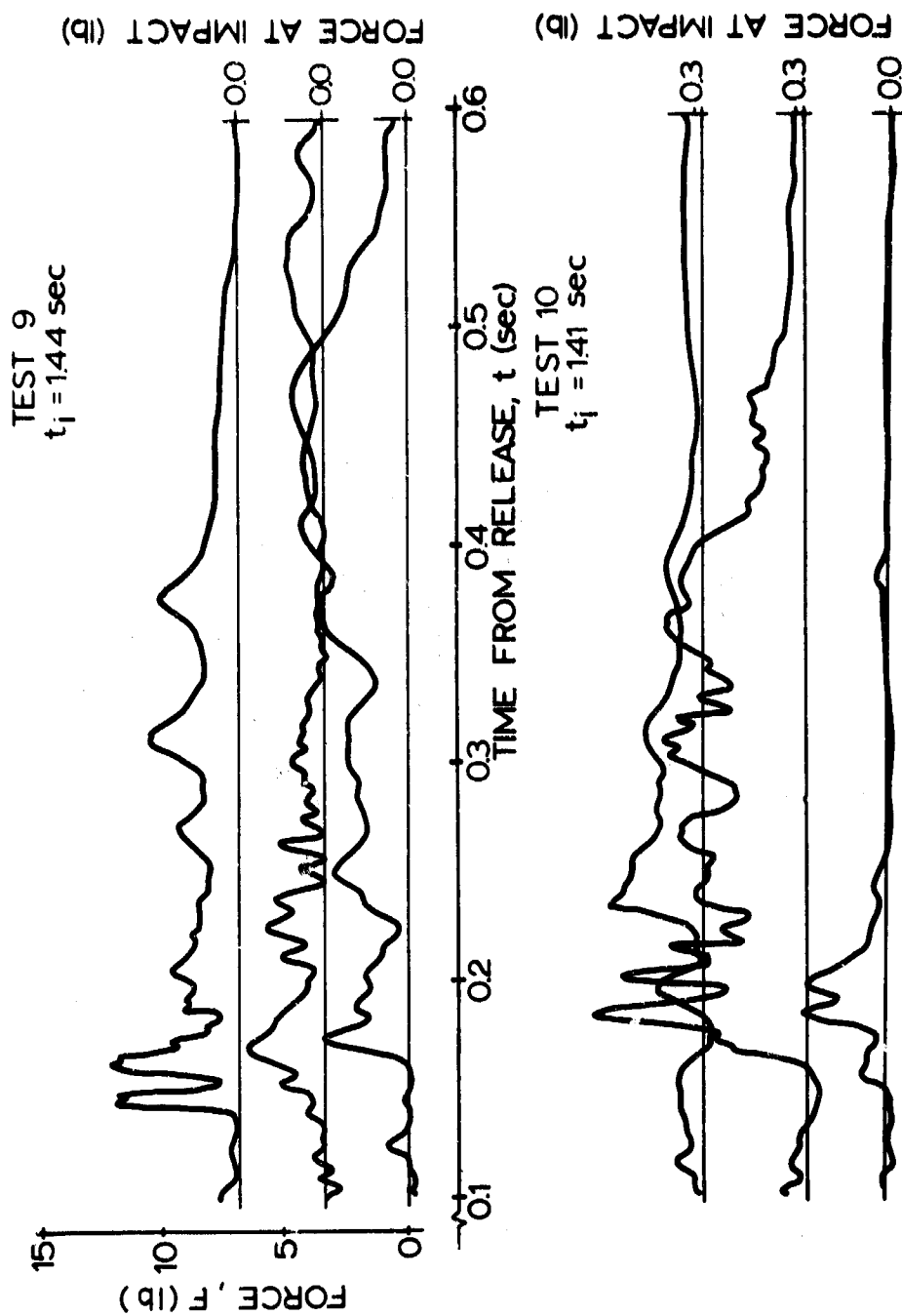
Fig 66   3 Parachute Cluster, $L_r = 0.4\,D_o + L_c = 0.97\,D_o$
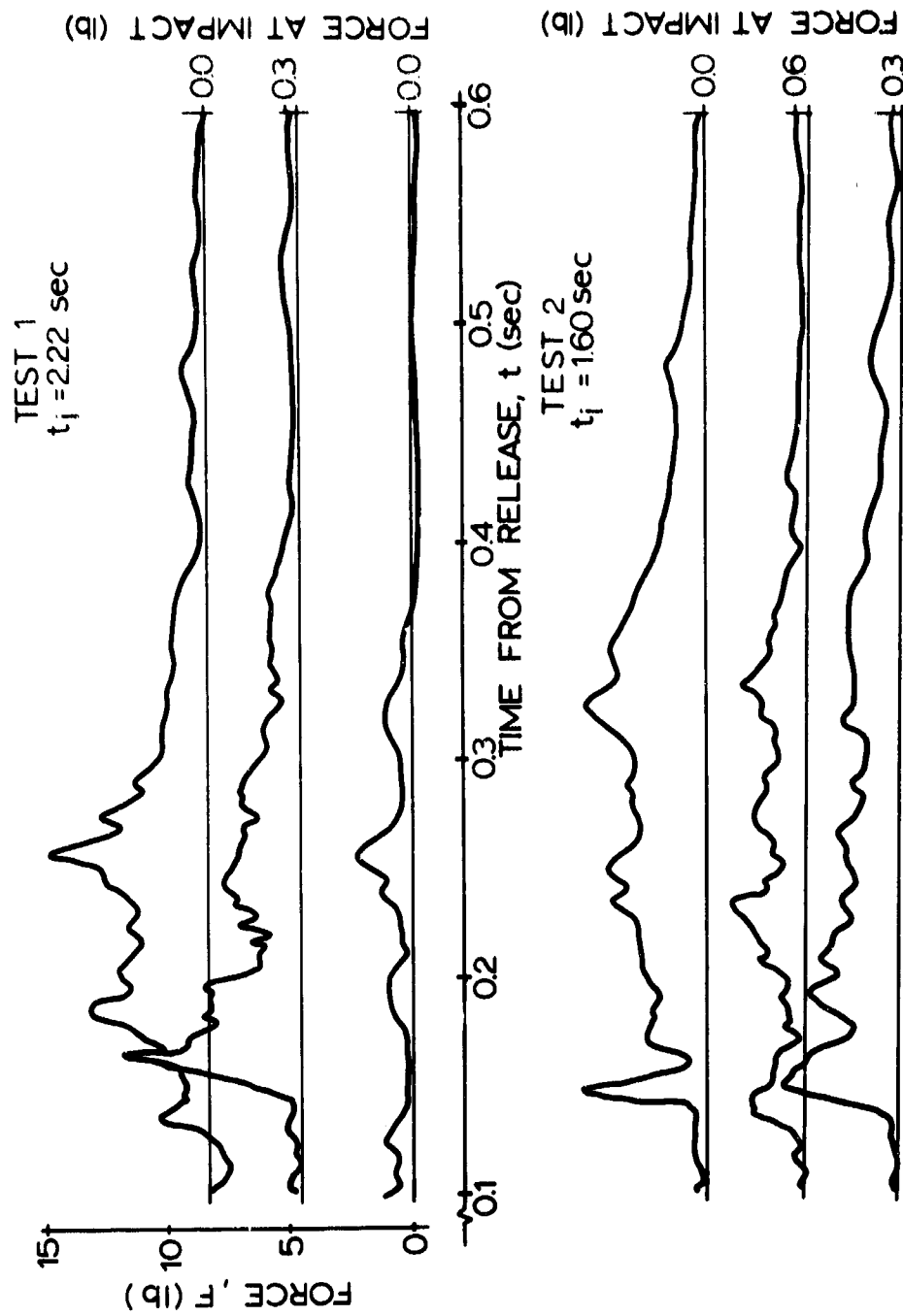
Fig 67   3 Parachute Cluster, $L_r = 0.4\ D_o$ + Internal Parachute, $0.2\ D_o$
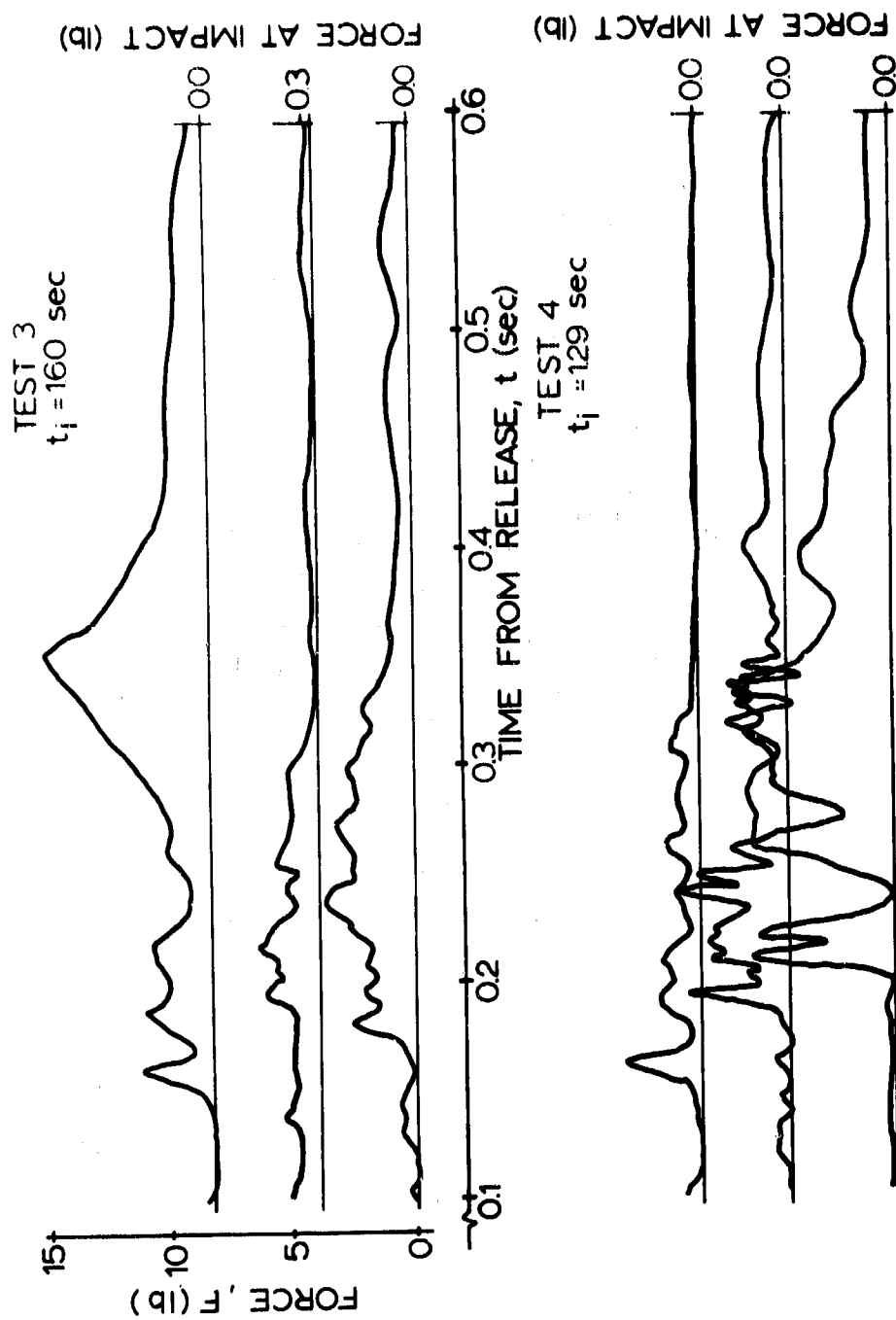
Fig 68 3 Parachute Cluster, $L_r = 0.4 \, D_o$ + Internal Parachute, $0.2 \, D_o$

111
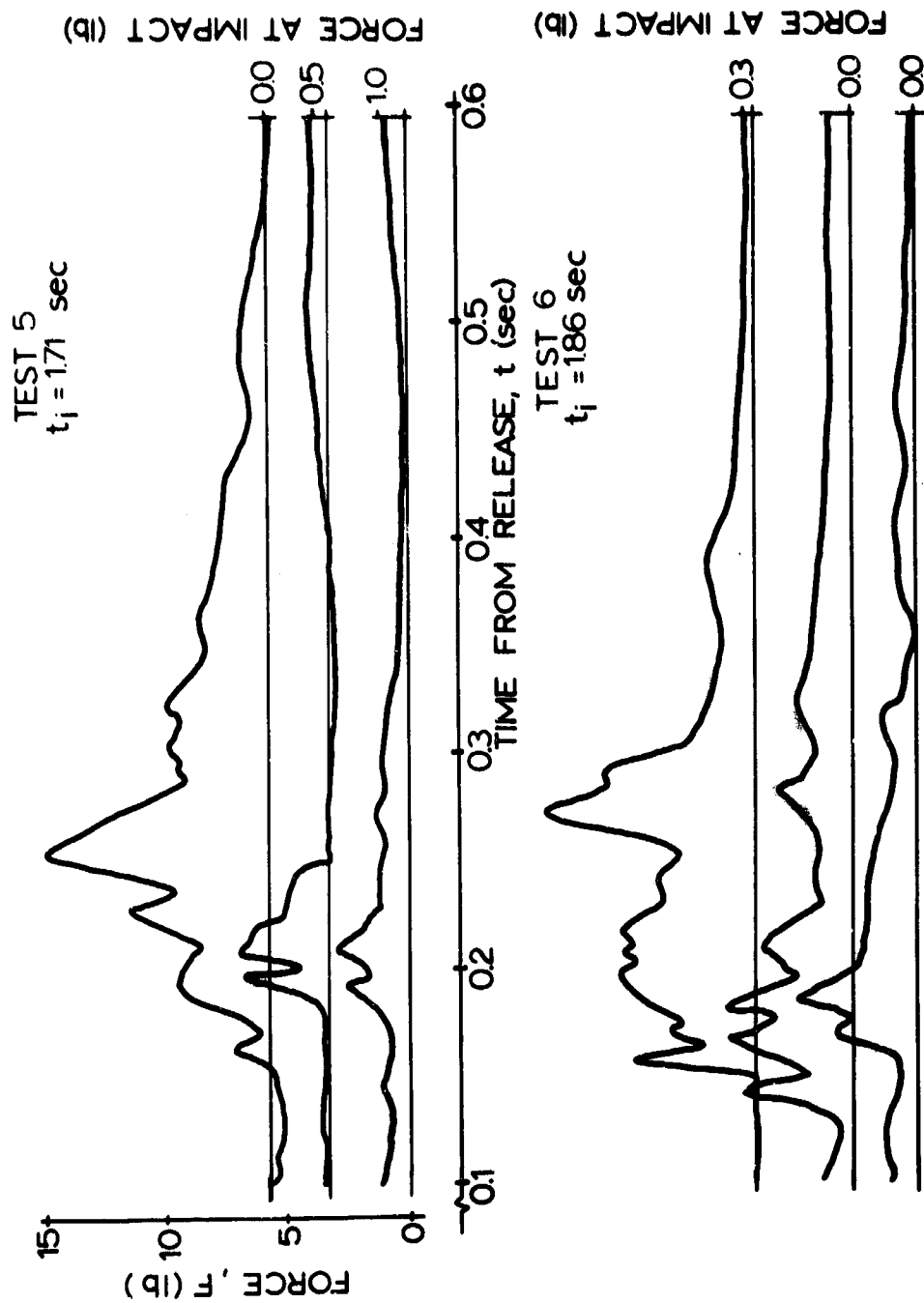
Fig 69 3 Parachute Cluster, $L_r = 0.4\ D_o$ + Internal
Parachute, $0.2\ D_o$
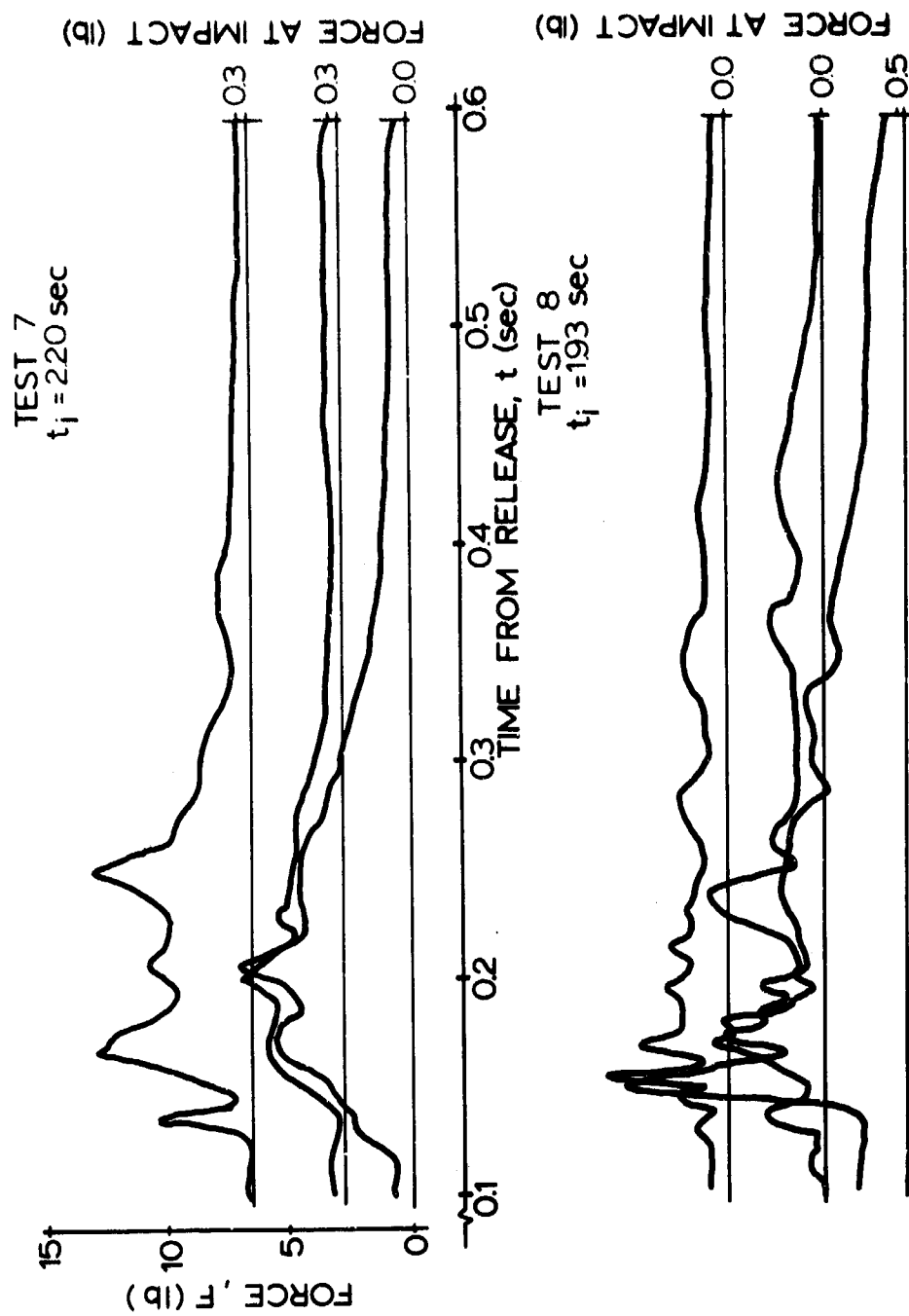
Fig 70 3 Parachute Cluster, $L_r = 0.4 \, D_o$ + Internal Parachute, $0.2 \, D_o$

113

Fig 71   3 Parachute Cluster, $L_r = 0.4\ D_o$ + Internal Parachute, $0.2\ D_o$

114

FORCE AT IMPACT (lb)

FORCE AT IMPACT (lb)

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$t_i = 1.33$ sec

TEST 2
$t_i = 1.20$ sec

TIME FROM RELEASE, t (sec)

FORCE F (lb)
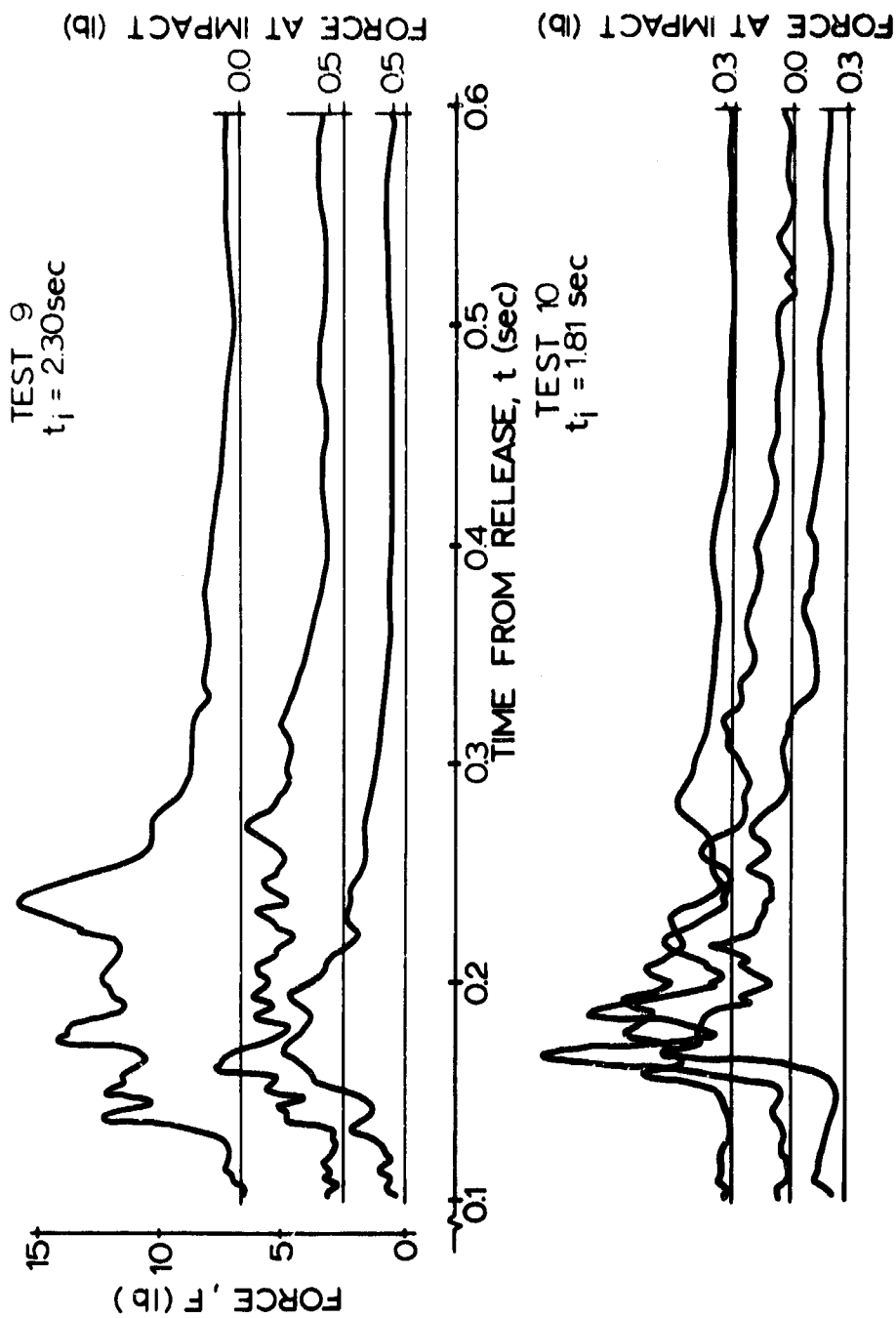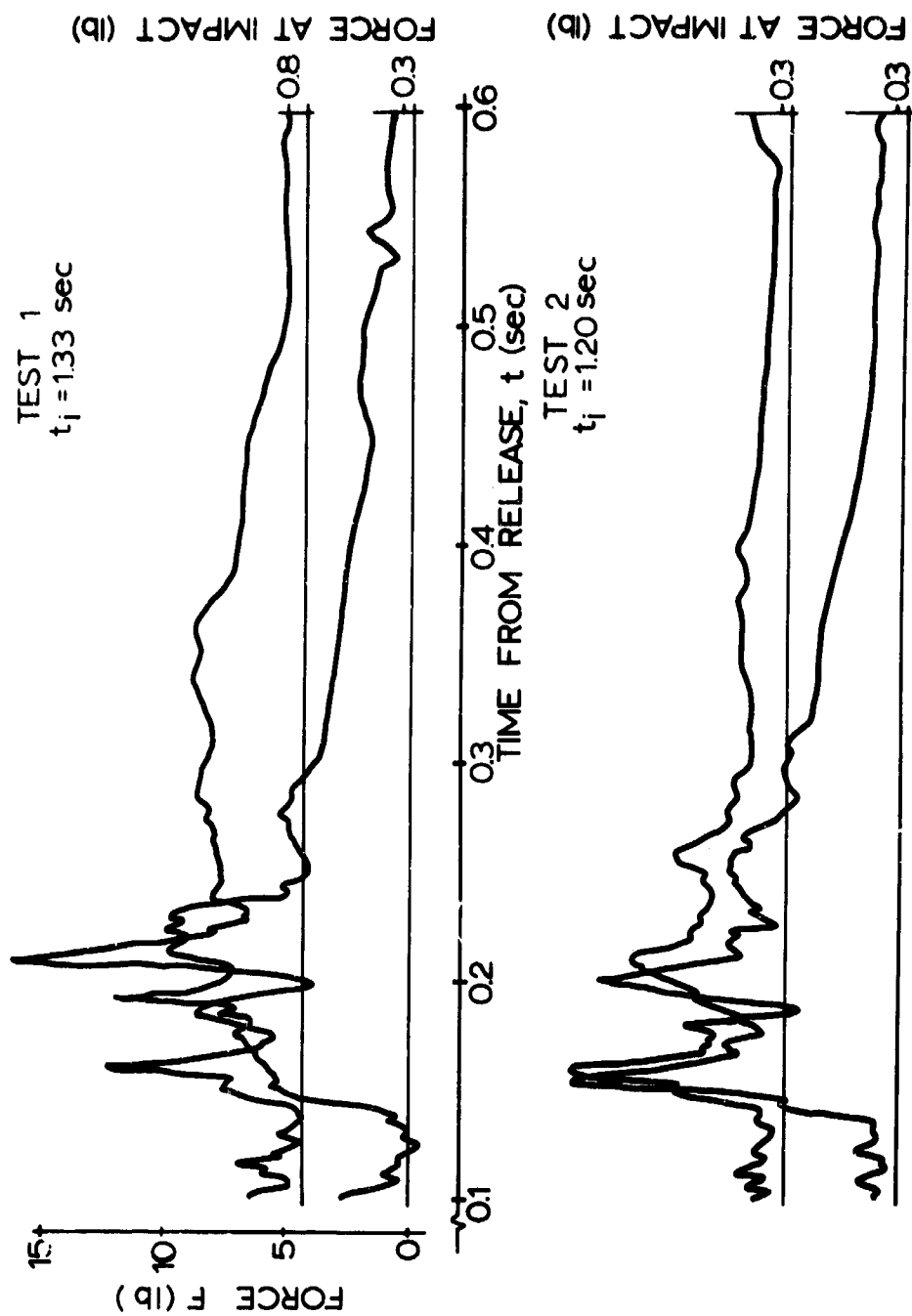
Fig 72   2 Parachute Cluster, $L_r = 0.2\ D_o$

115
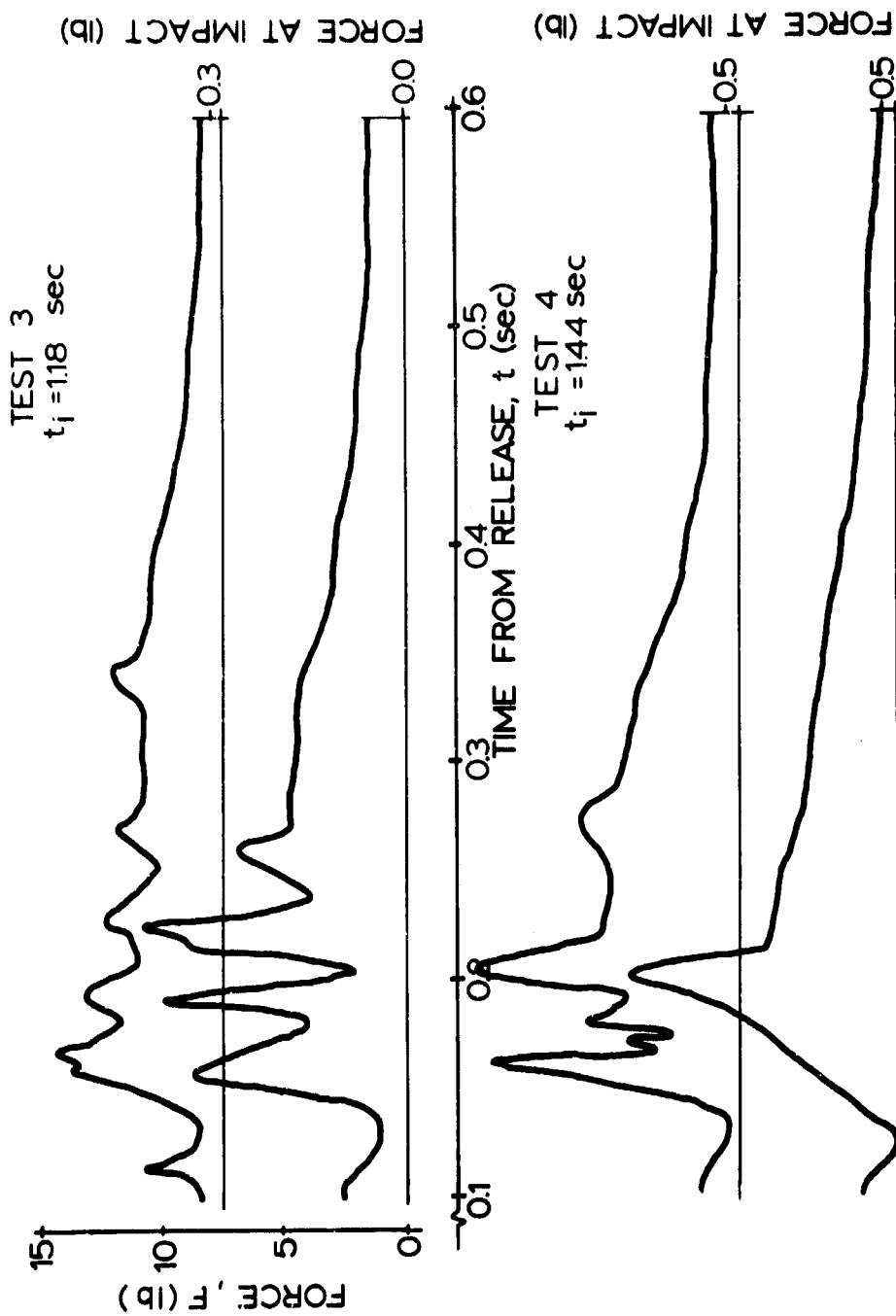
Fig 73 2 Parachute Cluster, L_r = 0.2 D_o

116
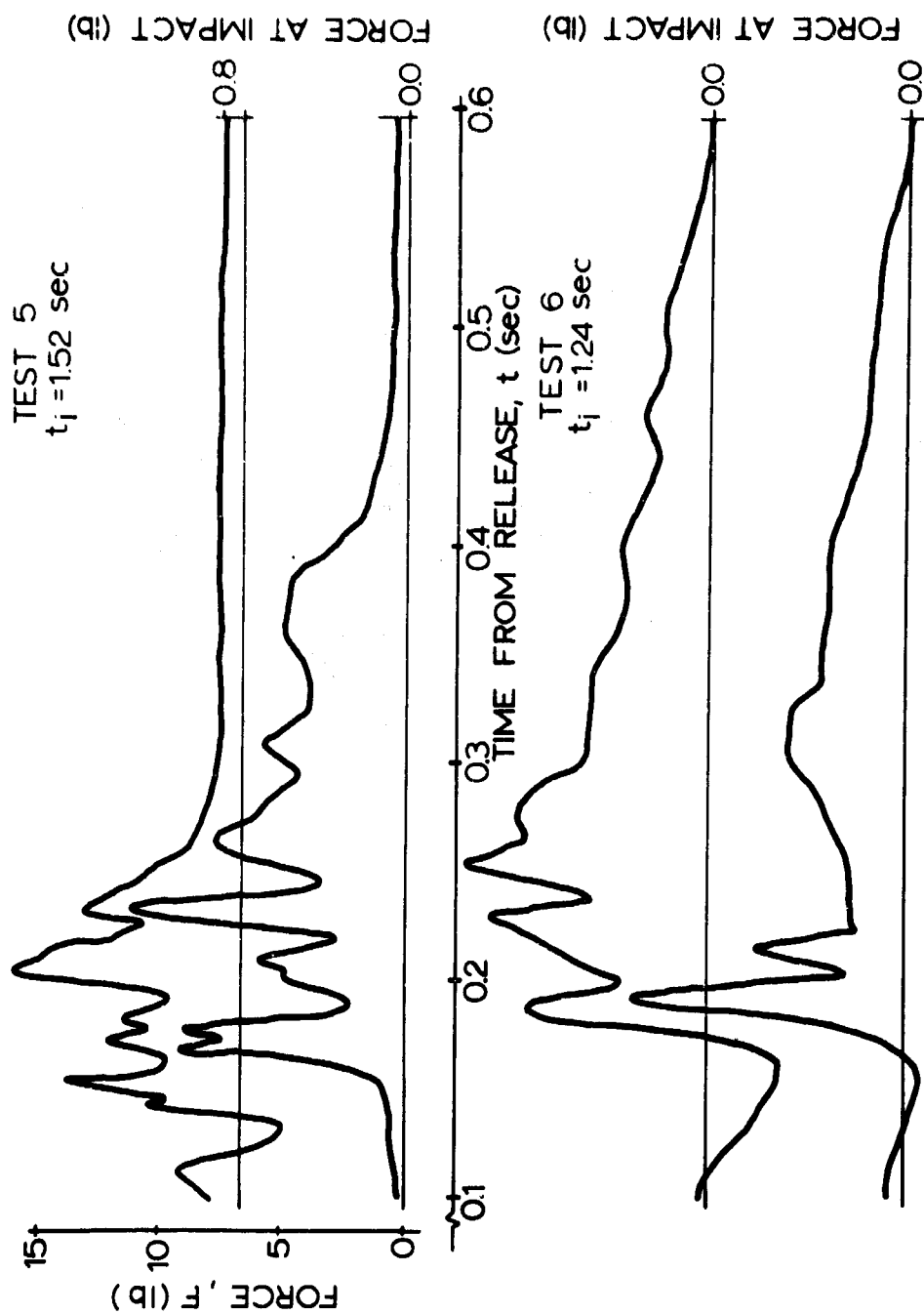
Fig 74 2 Parachute Cluster, $L_r = 0.2 \ D_o$

117
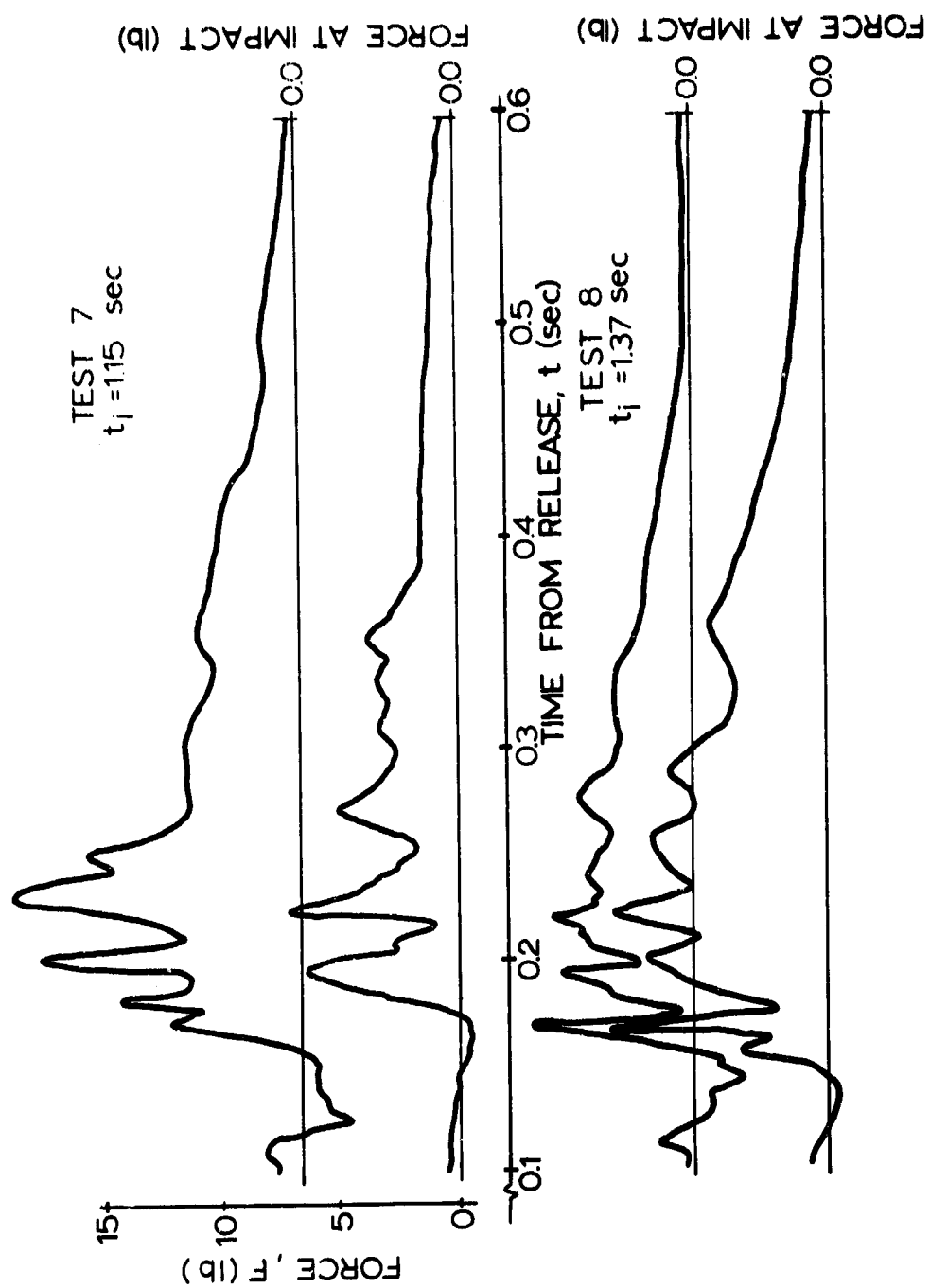
Fig 75 2 Parachute Cluster, $L_r = 0.2$ D_o

118
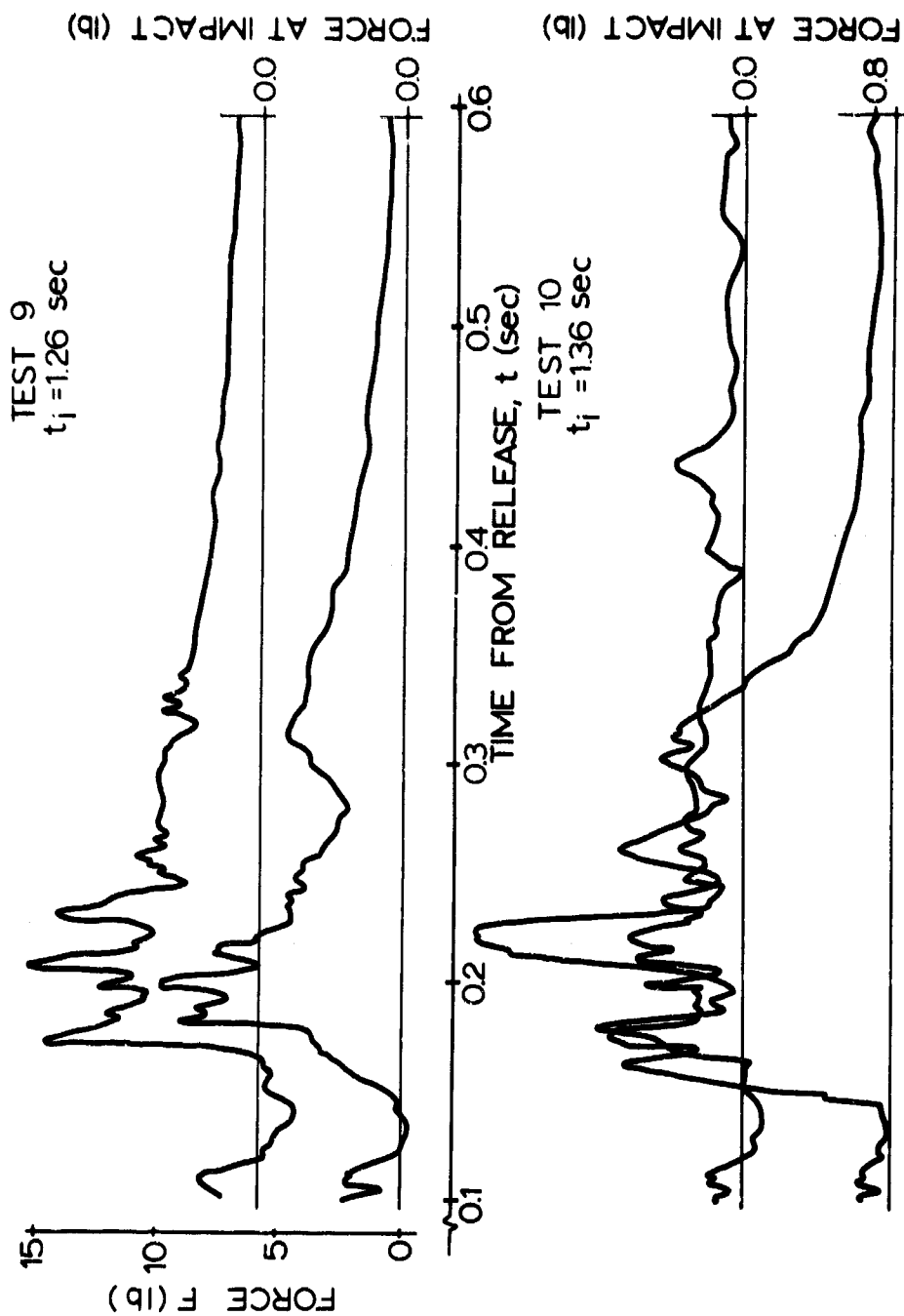
Fig 76   2 Parachute Cluster, $L_r = 0.2\ D_o$
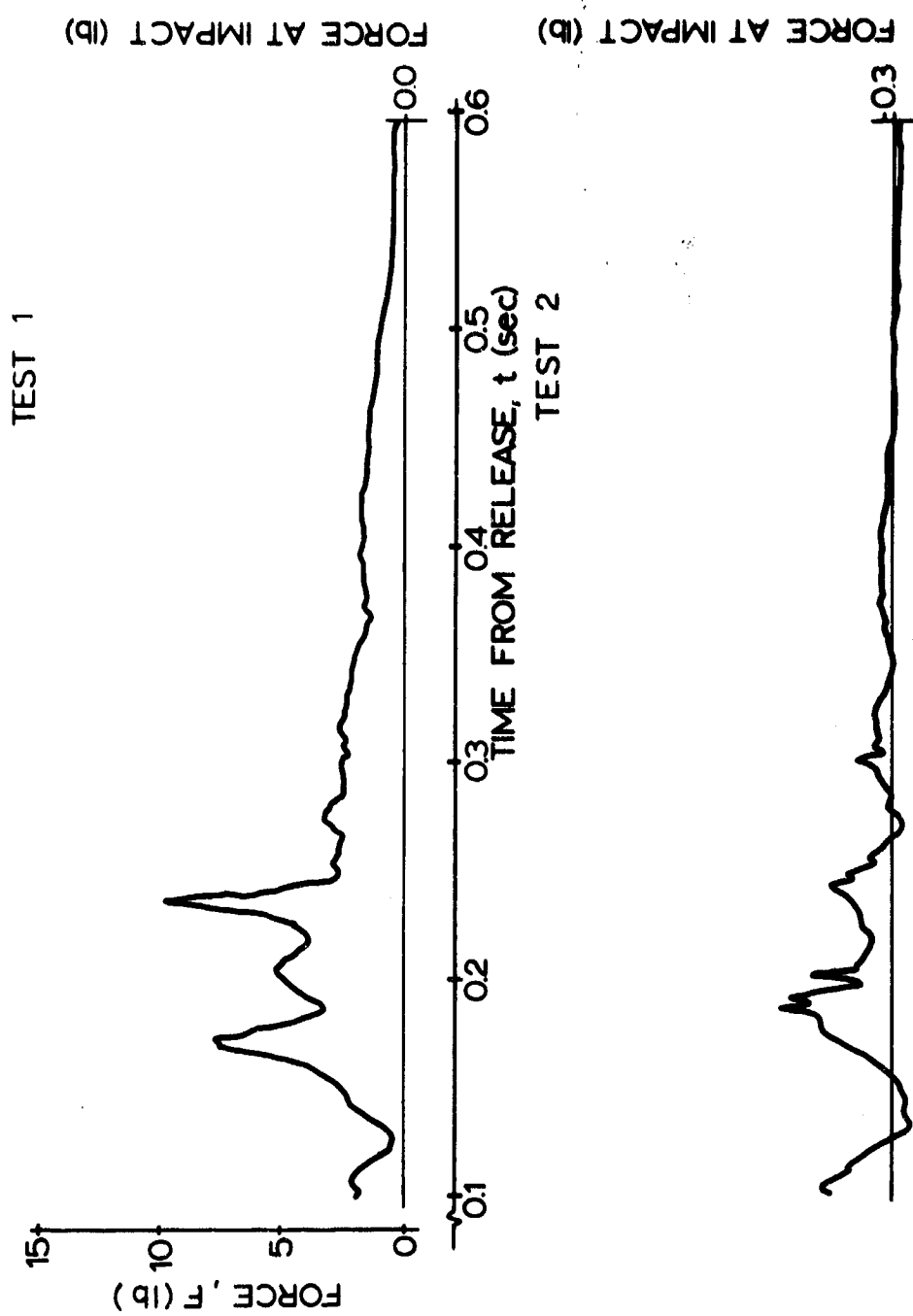
Fig 77 Single Parachute, No Modifications m* = 233

120
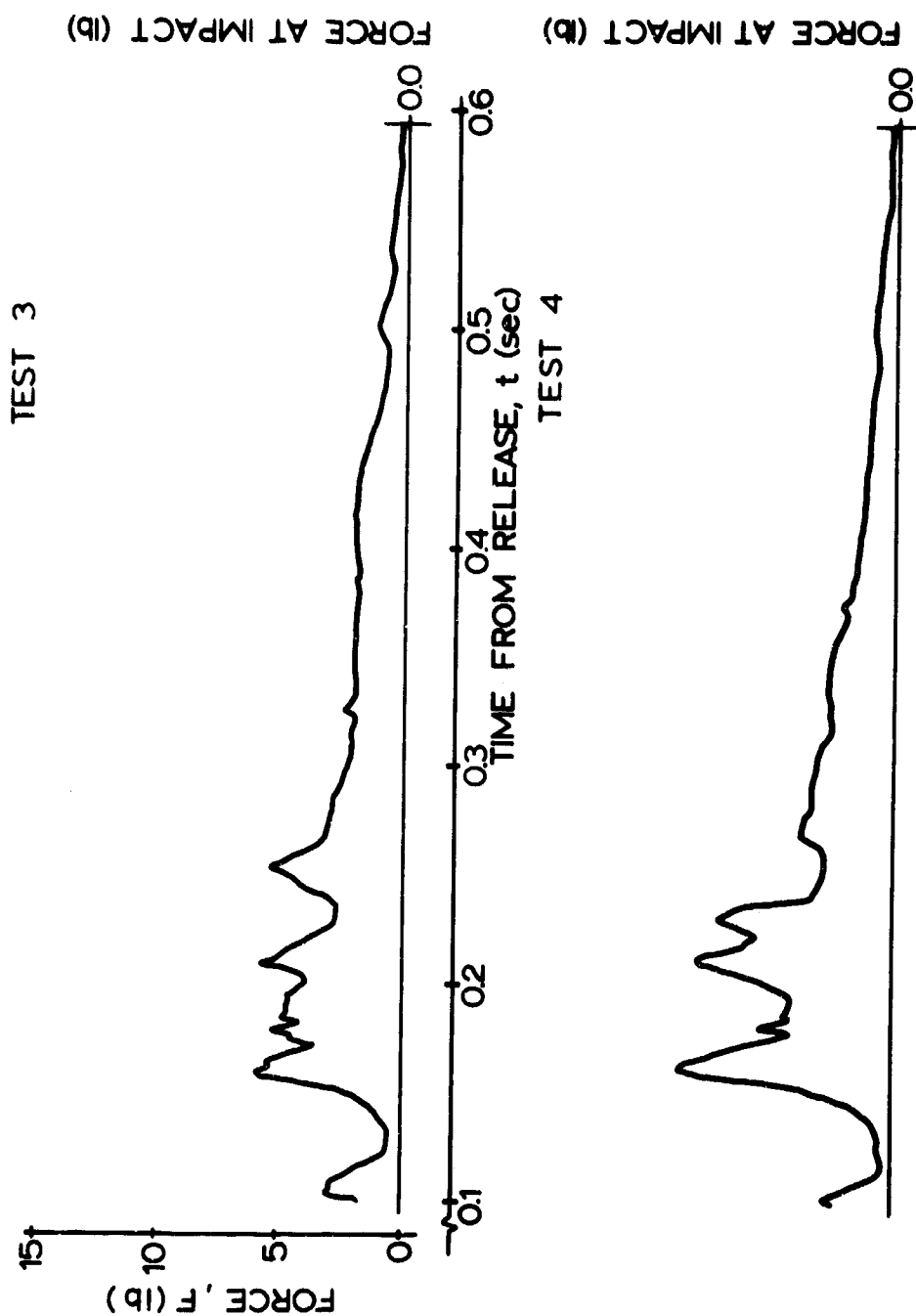
Fig 78   Single Parachute, No Modifications $m^* = 2.33$

121
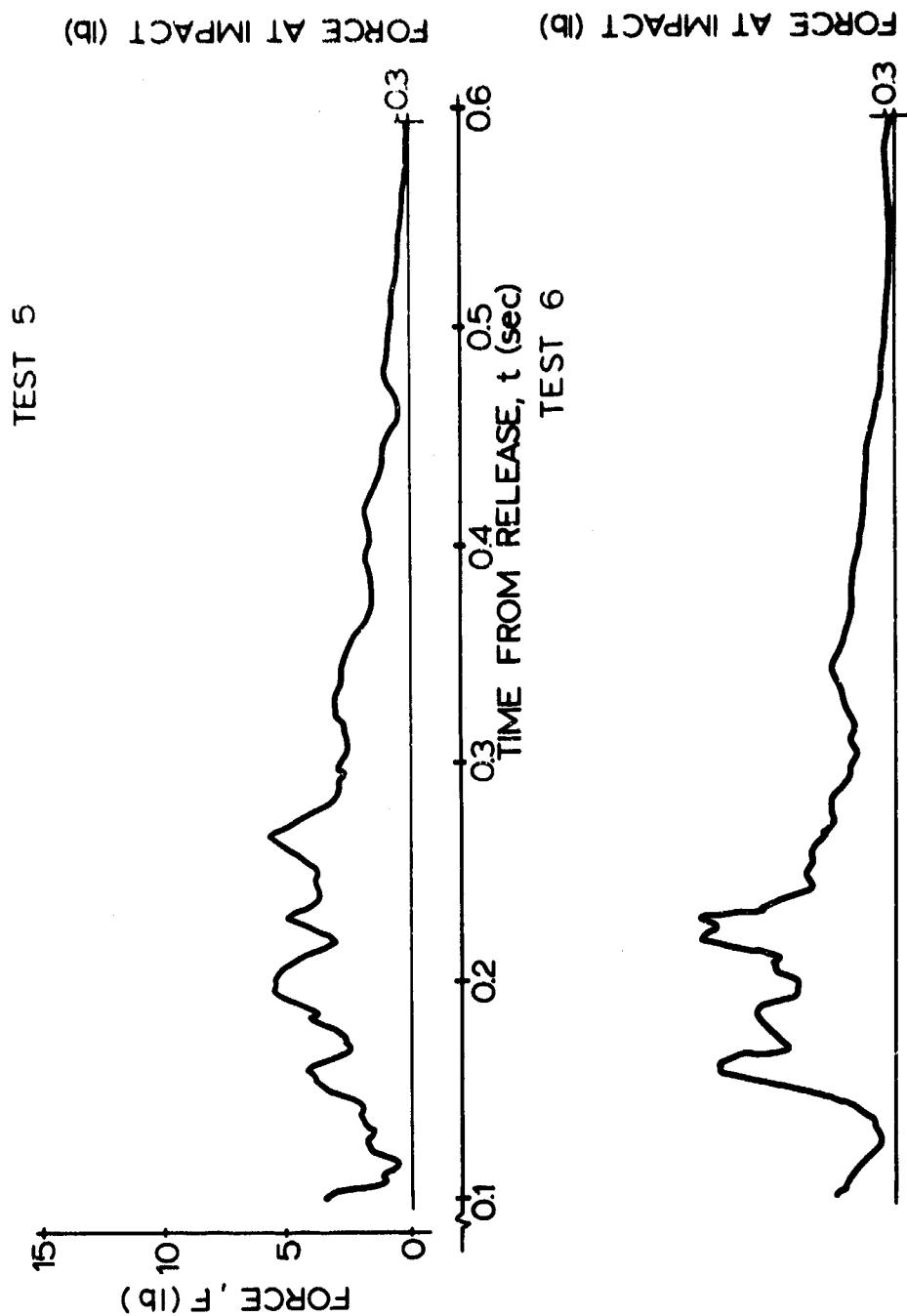
Fig 79   Single Parachute, No Modifications   m* = 2.33
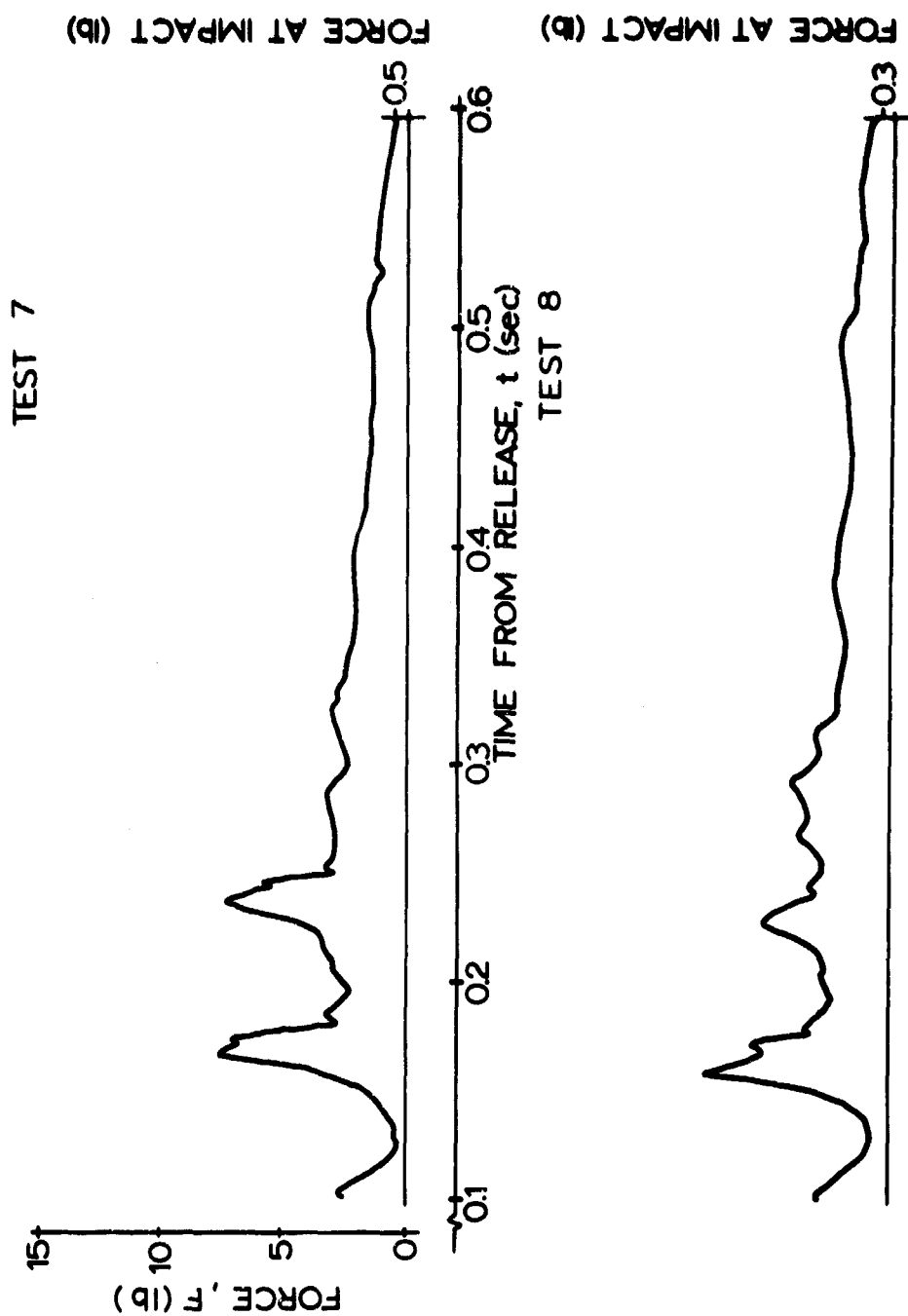
Fig 80 Single Parachute, No Modifications $m^* = 2.33$
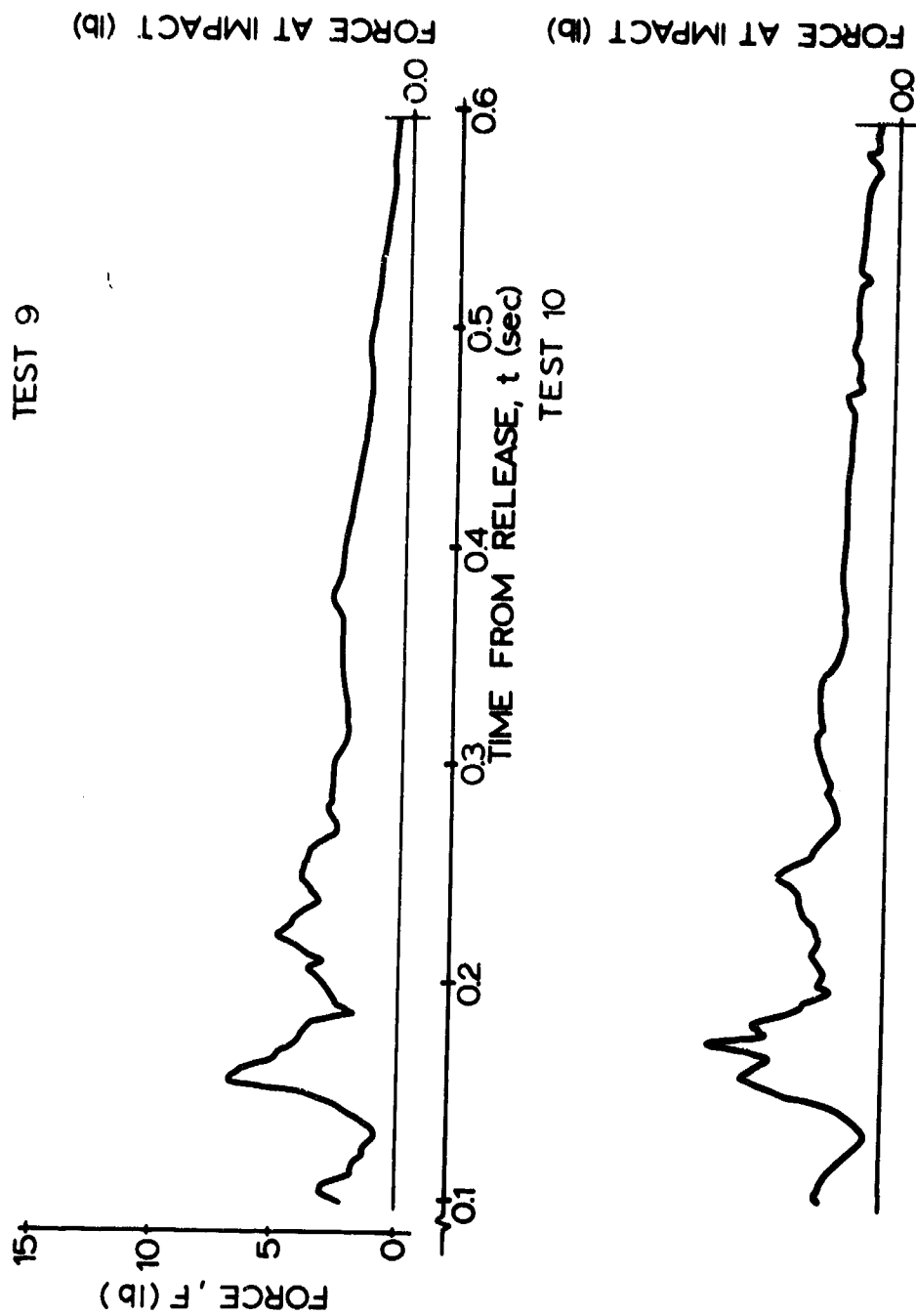
Fig 81   Single Parachute, No Modifications $m^* = 233$

124
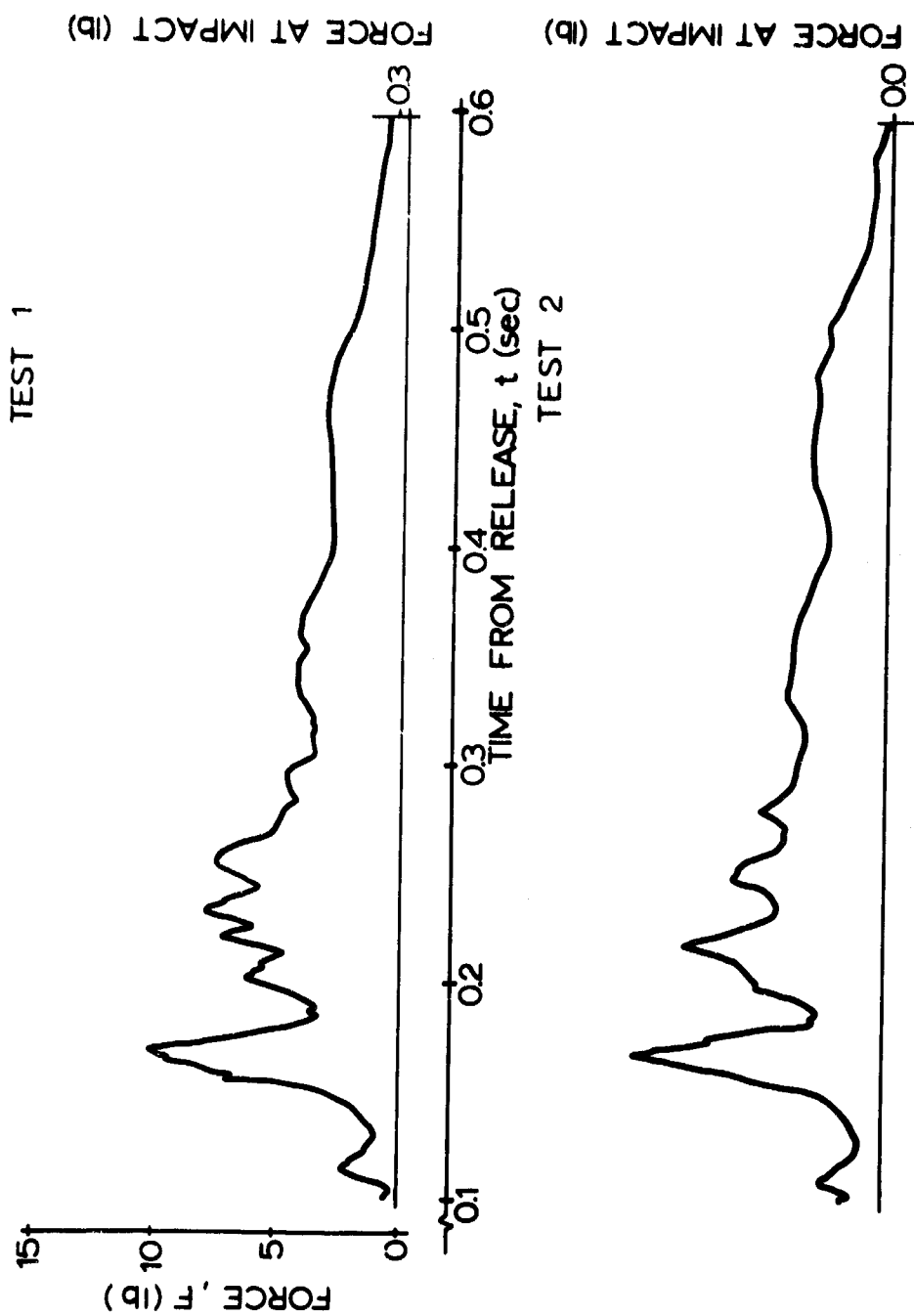
Fig 82 Single Parachute No Modifications m* = 1.57
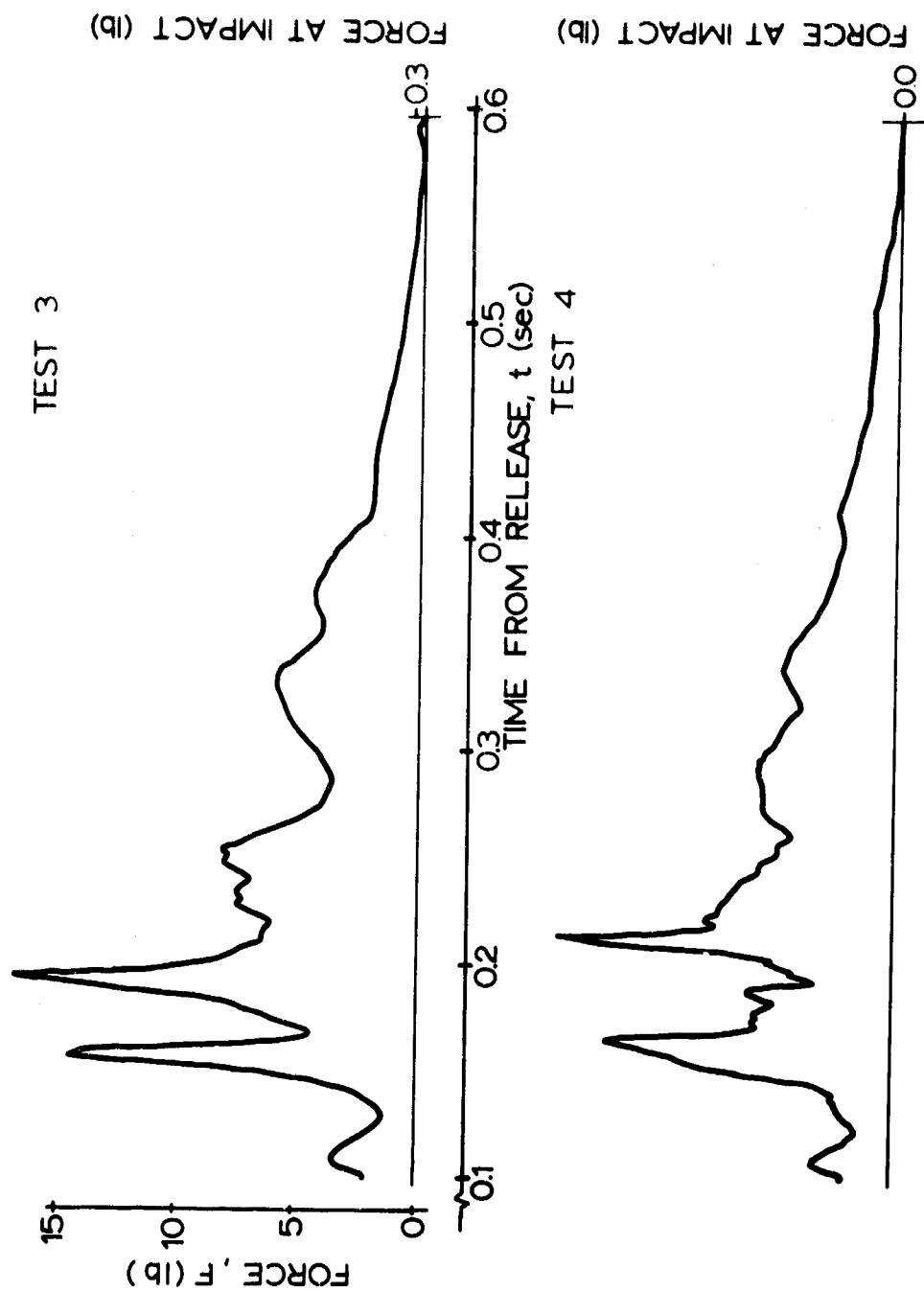
Fig 83   Single   Parachute   No   Modifications   m* = 1.57

126
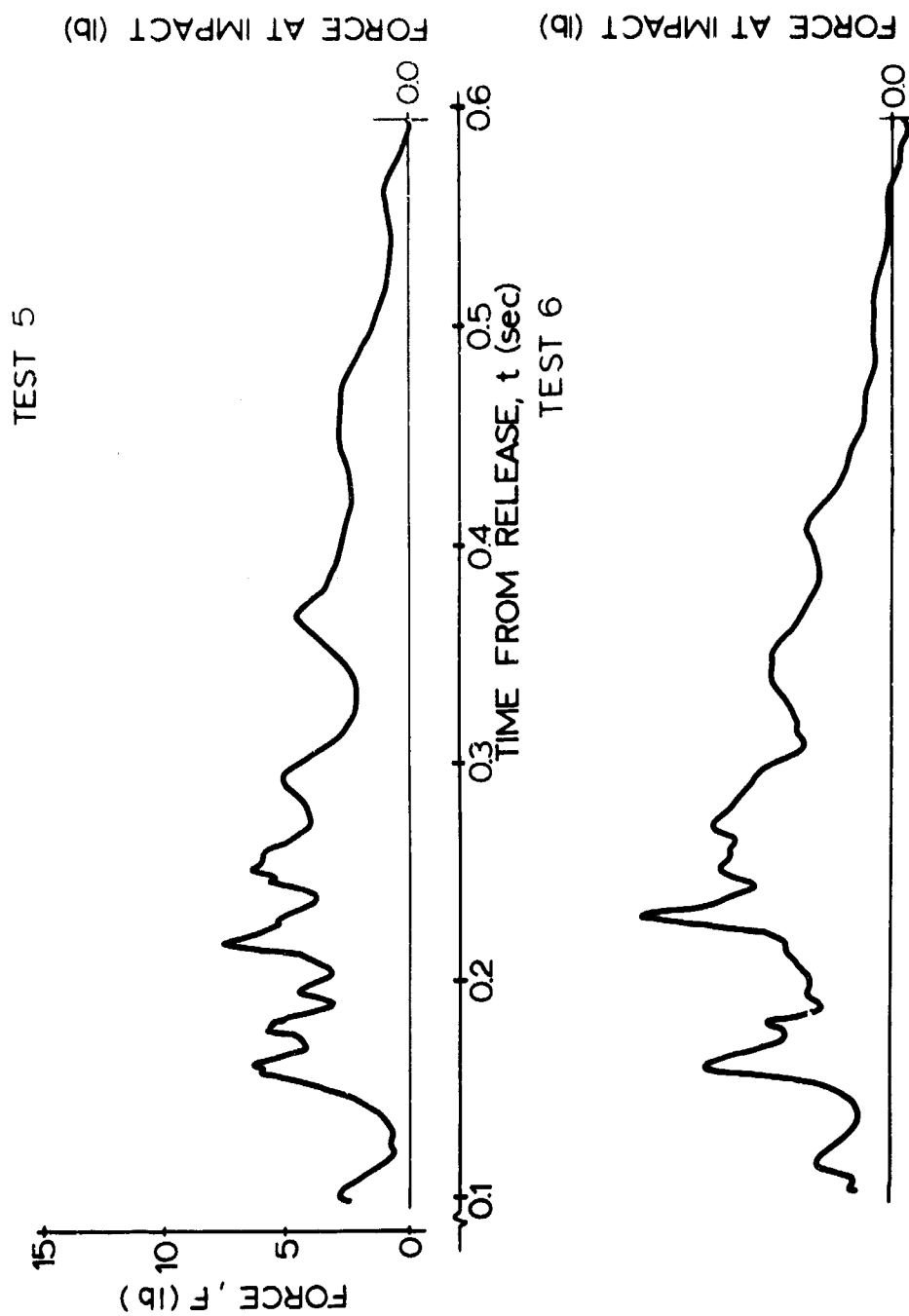
Fig 84 Single Parachute No Modifications m* = 1.57

127
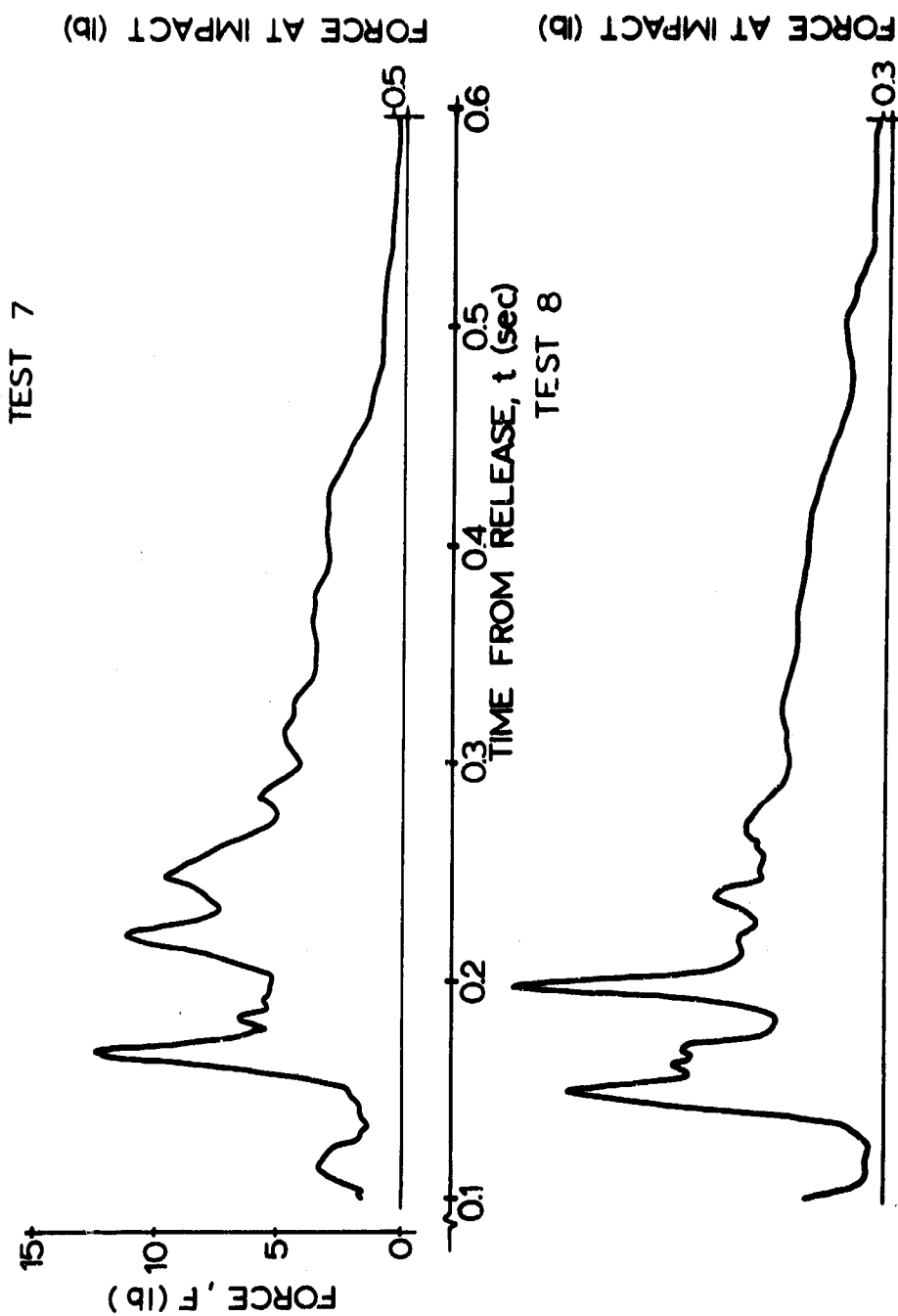
Fig 85 Single Parachute No Modifications $m^* = 1.57$

128
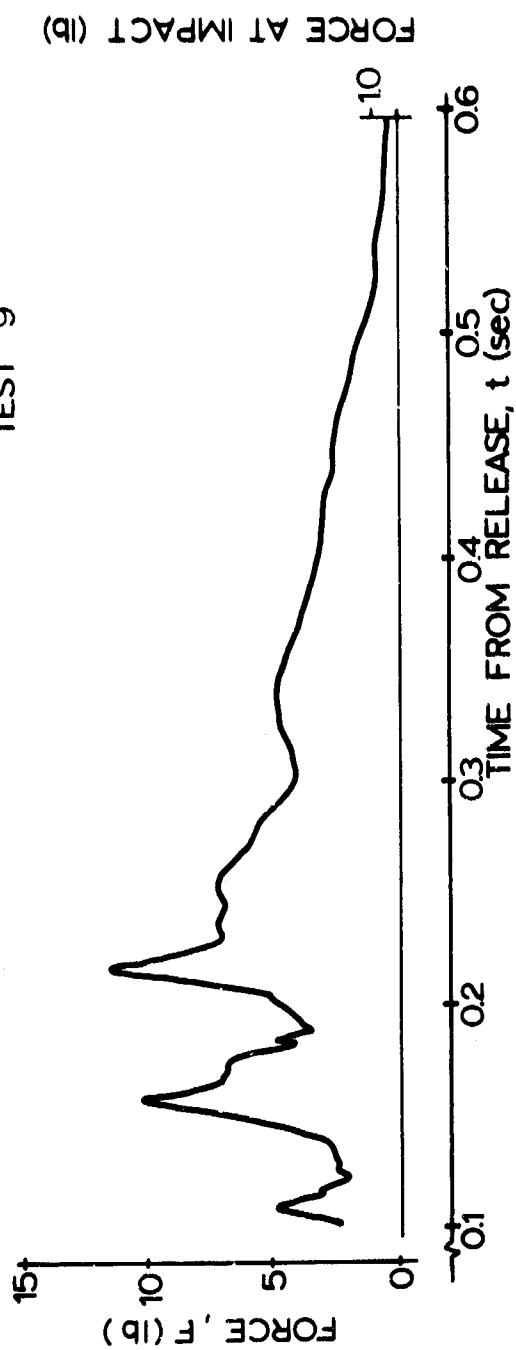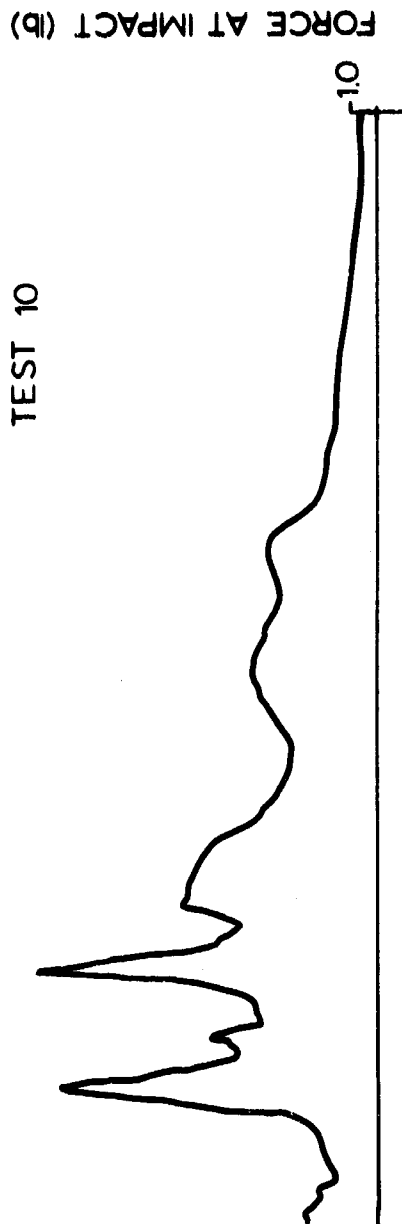
Fig 86 Single Parachute No Modifications m* = 1.57

129
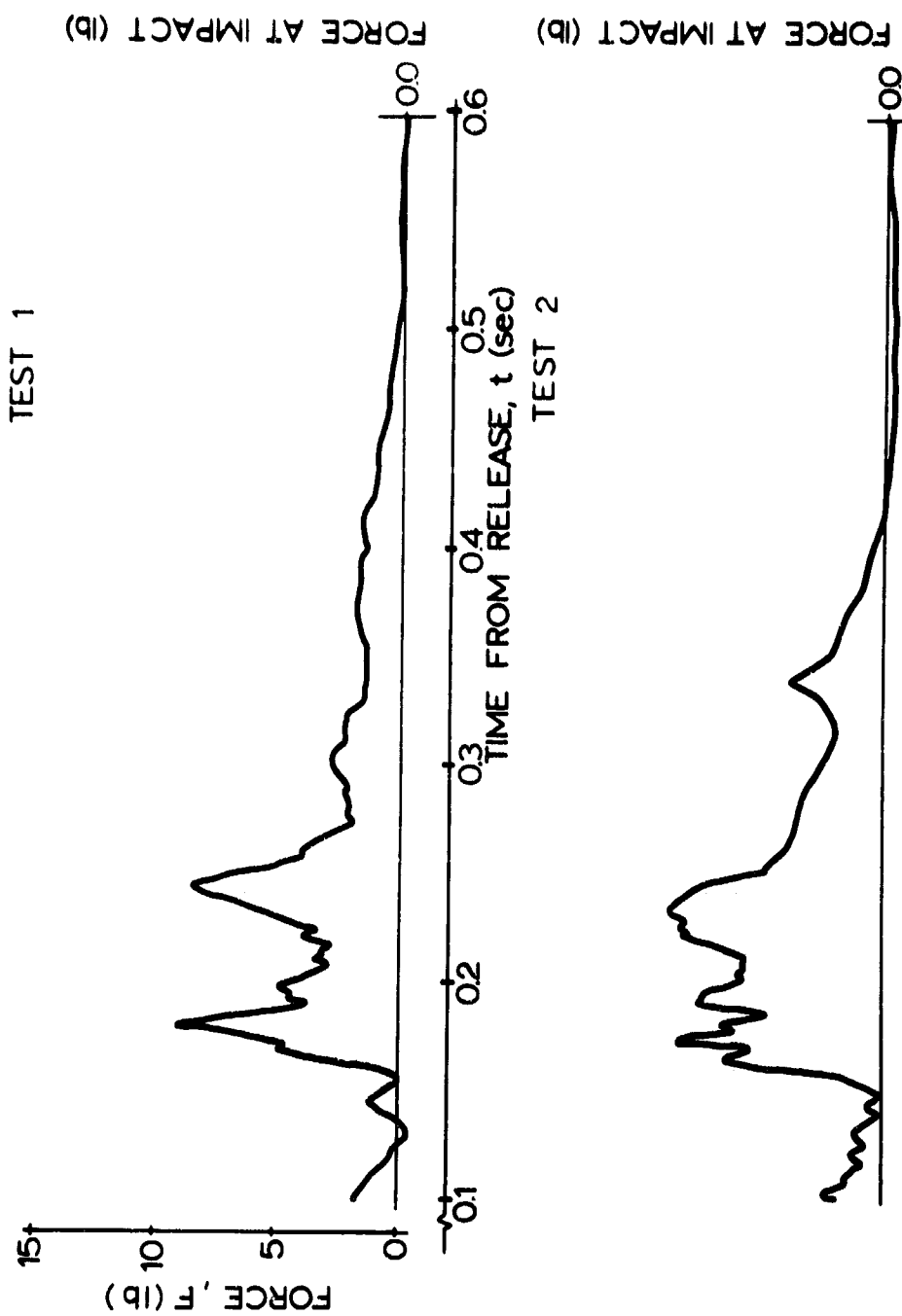
Fig 87   Single   Parachute, $L_c = 0.97\ D_o$

130

Fig 88 Single Parachute, $L_c = 0.97 \, D_o$

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FORCE AT IMPACT (lb)

TEST 5

FORCE, F (lb)

TIME FROM RELEASE, t (sec)
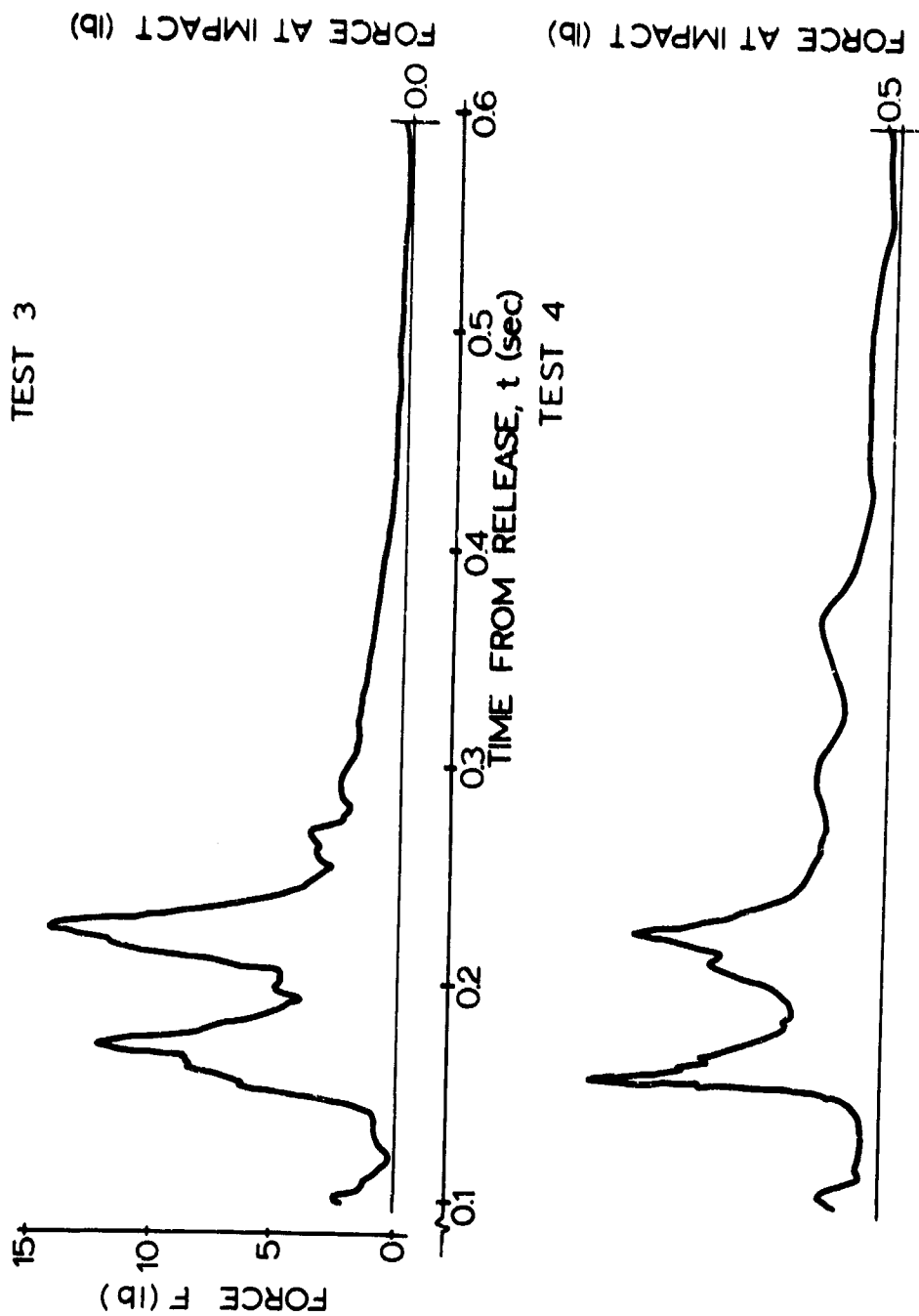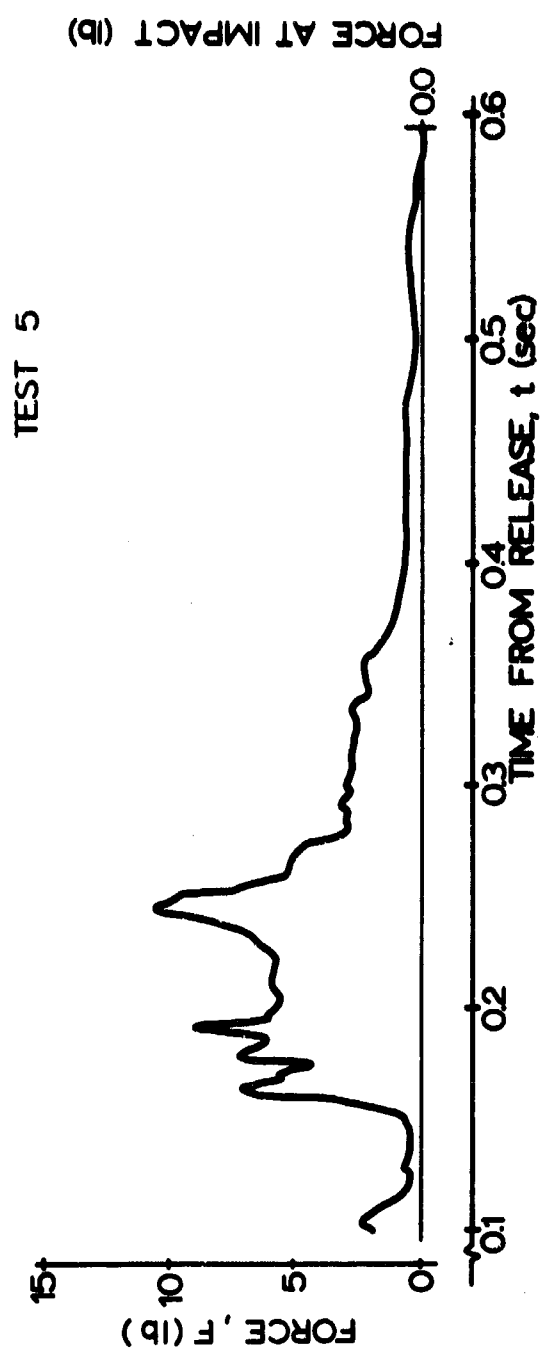
Fig 89   Single Parachute, $L_c = 0.97$ D_o

132
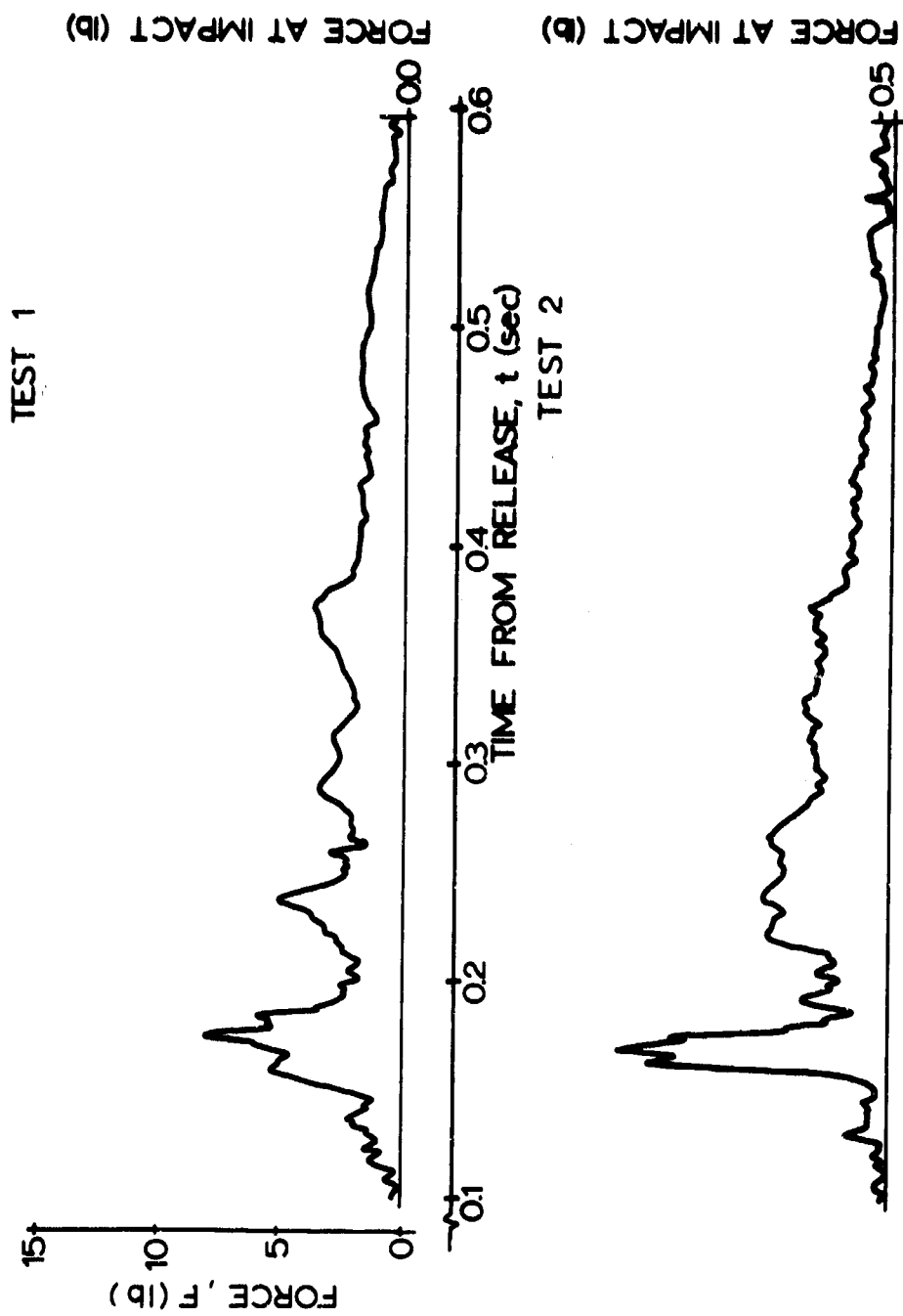
Fig 90 Single Parachute, $L_r = 0.4 D_o$

133

Fig 91   Single Parachute, $L_r = 0.4\ D_0$

134

TEST 5

FORCE AT IMPACT (lb)

FORCE , F (lb)

TIME FROM RELEASE, t (sec)
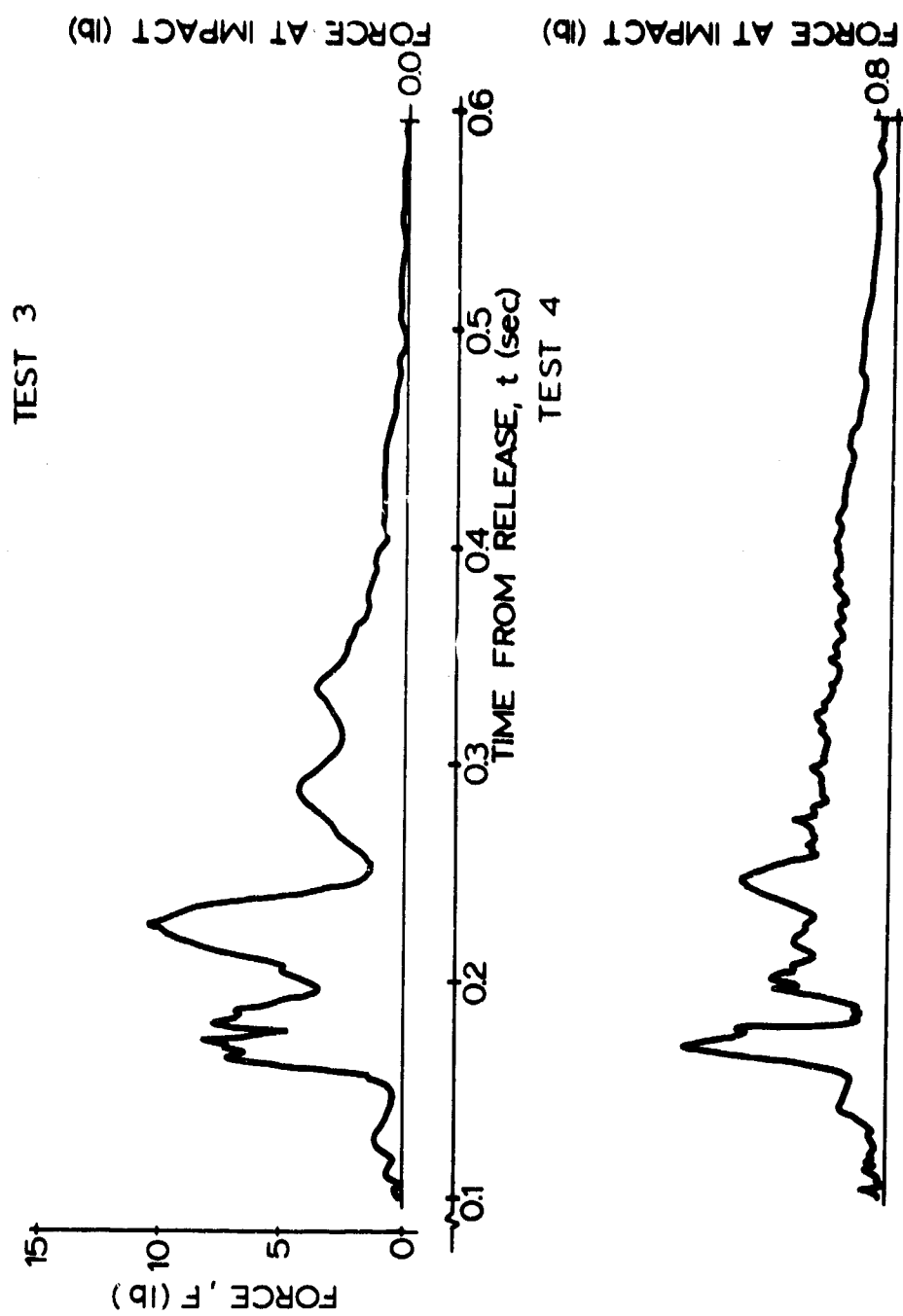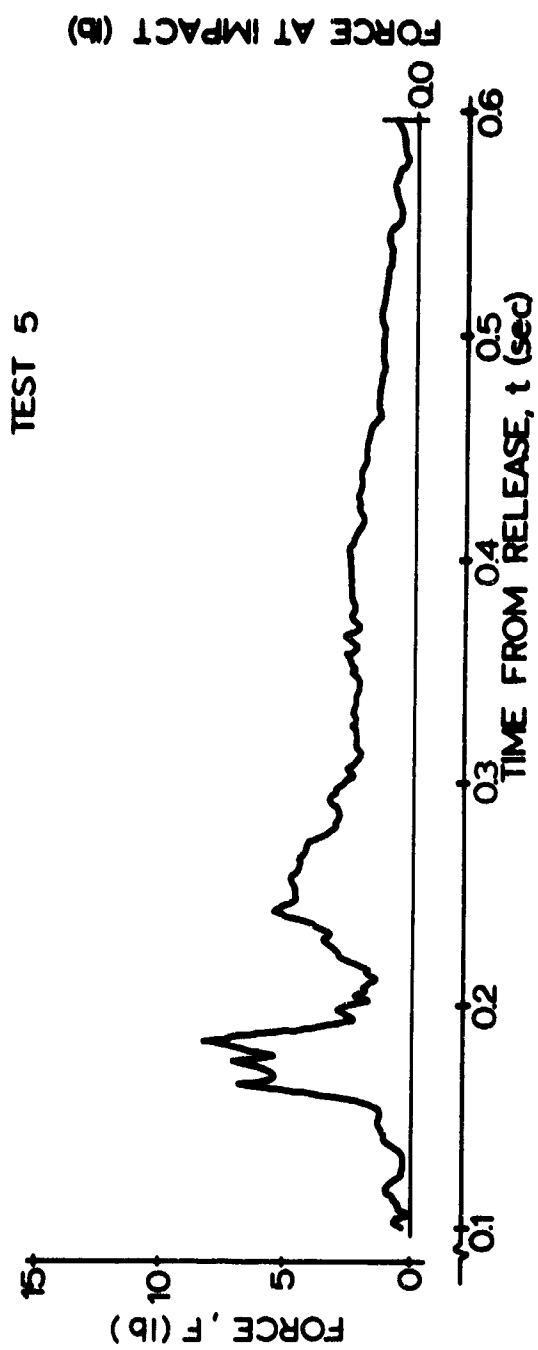
Fig 92   Single   Parachute, $L_r = 0.4\ D_0$

135
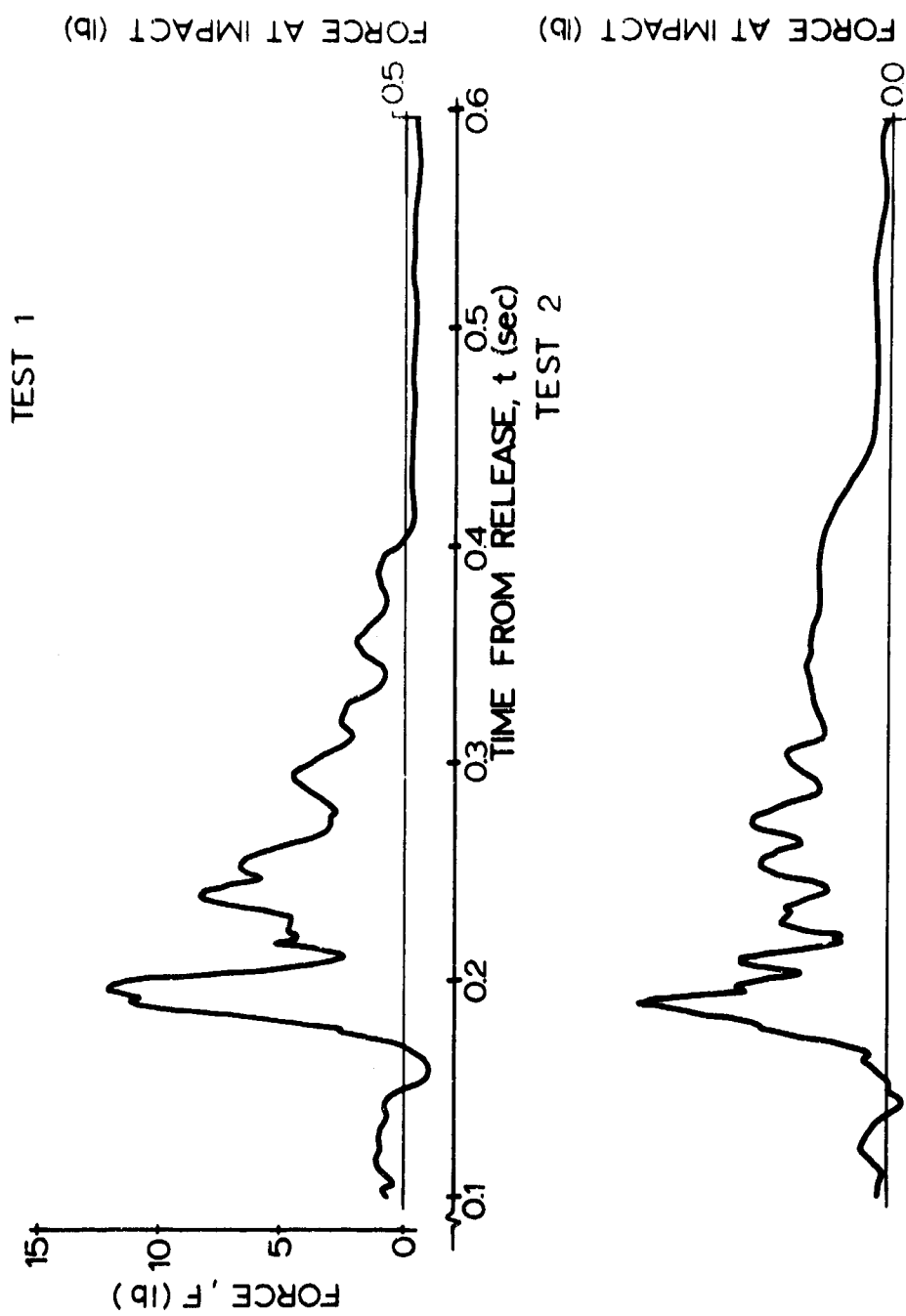
Fig 93   Single Parachute, $L_r = 0.4\ D_o + L_c = 0.97\ D_o$

136
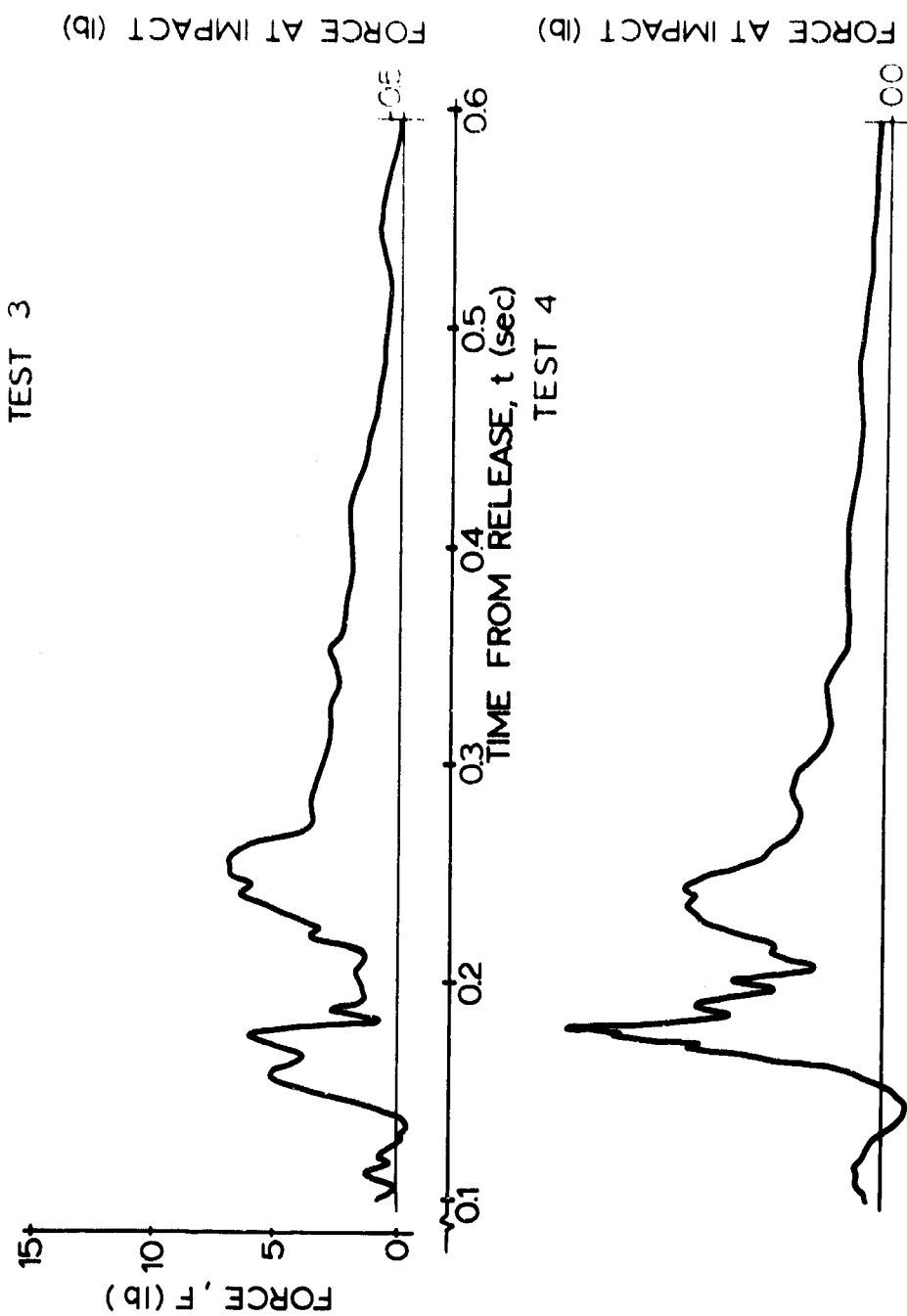
Fig 94 Single Parachute, $L_r = 0.4\ D_o + L_c = 0.97\ D_o$

137
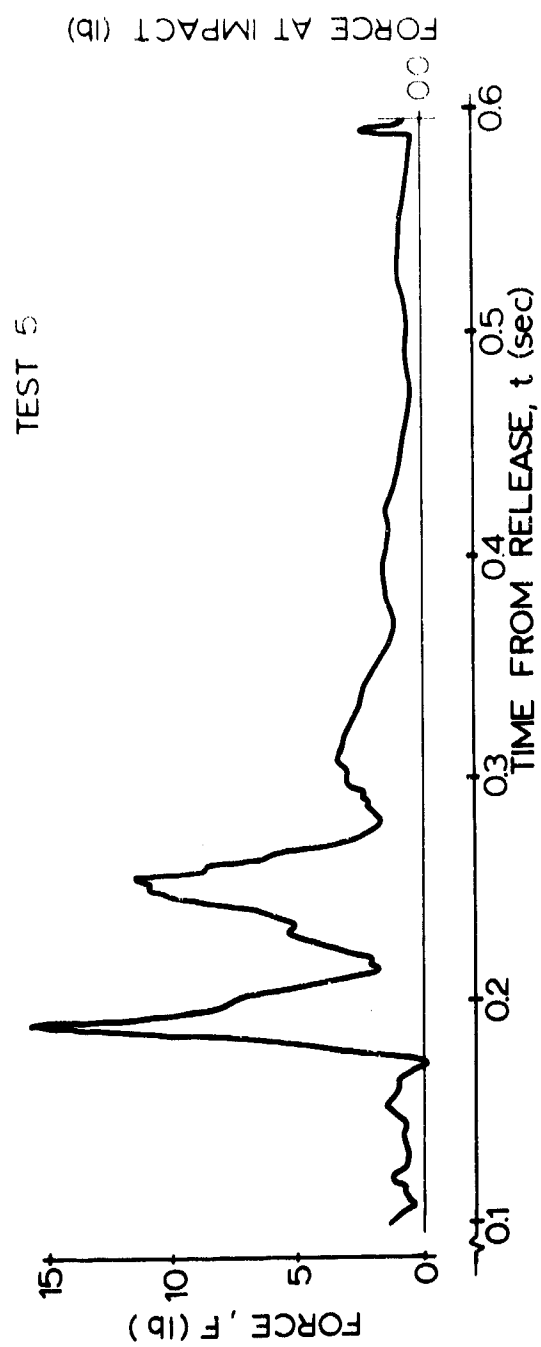
Fig 95 Single Parachute, $L_r = 0.4\ D_o + L_c = 0.97\ D_o$
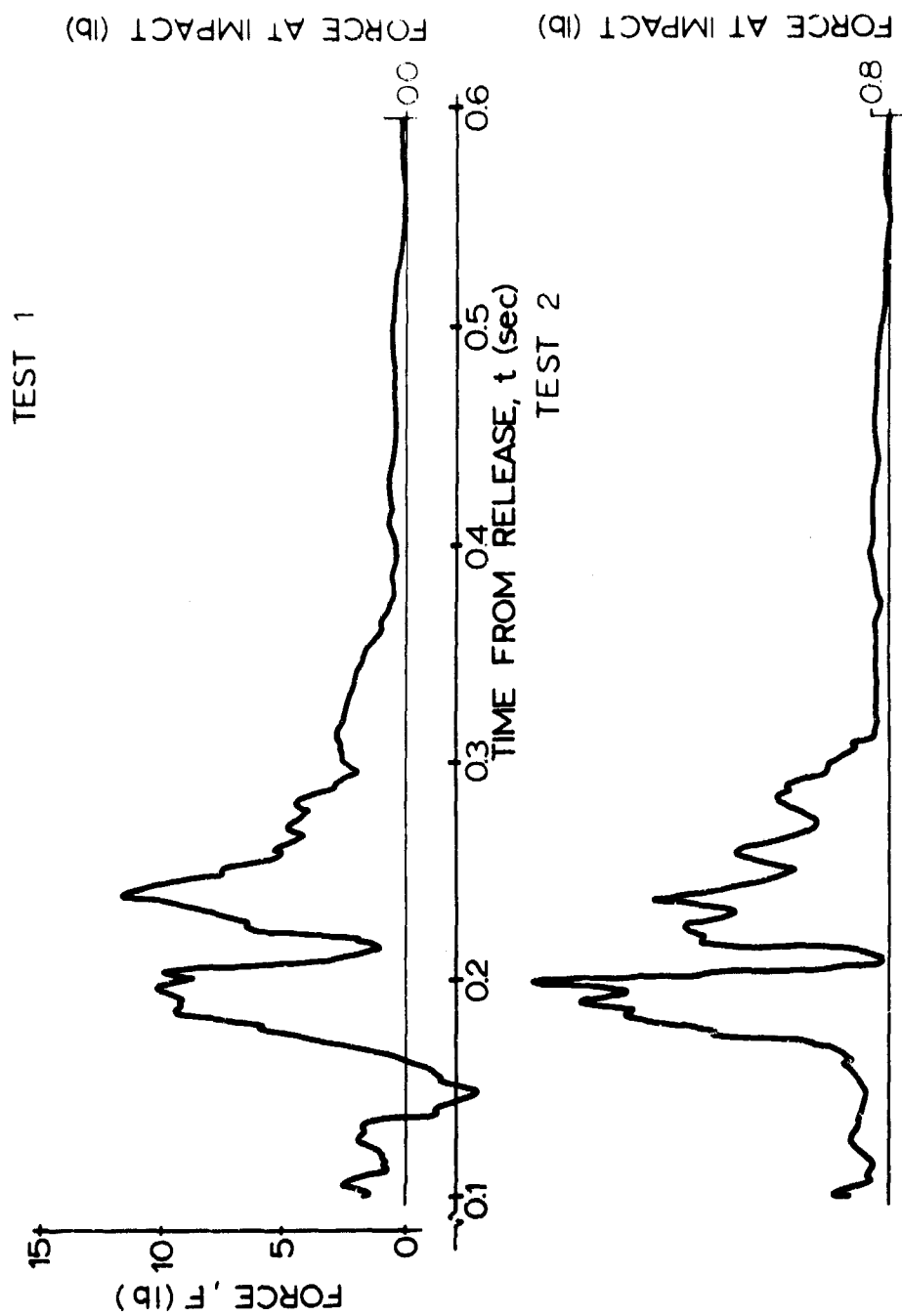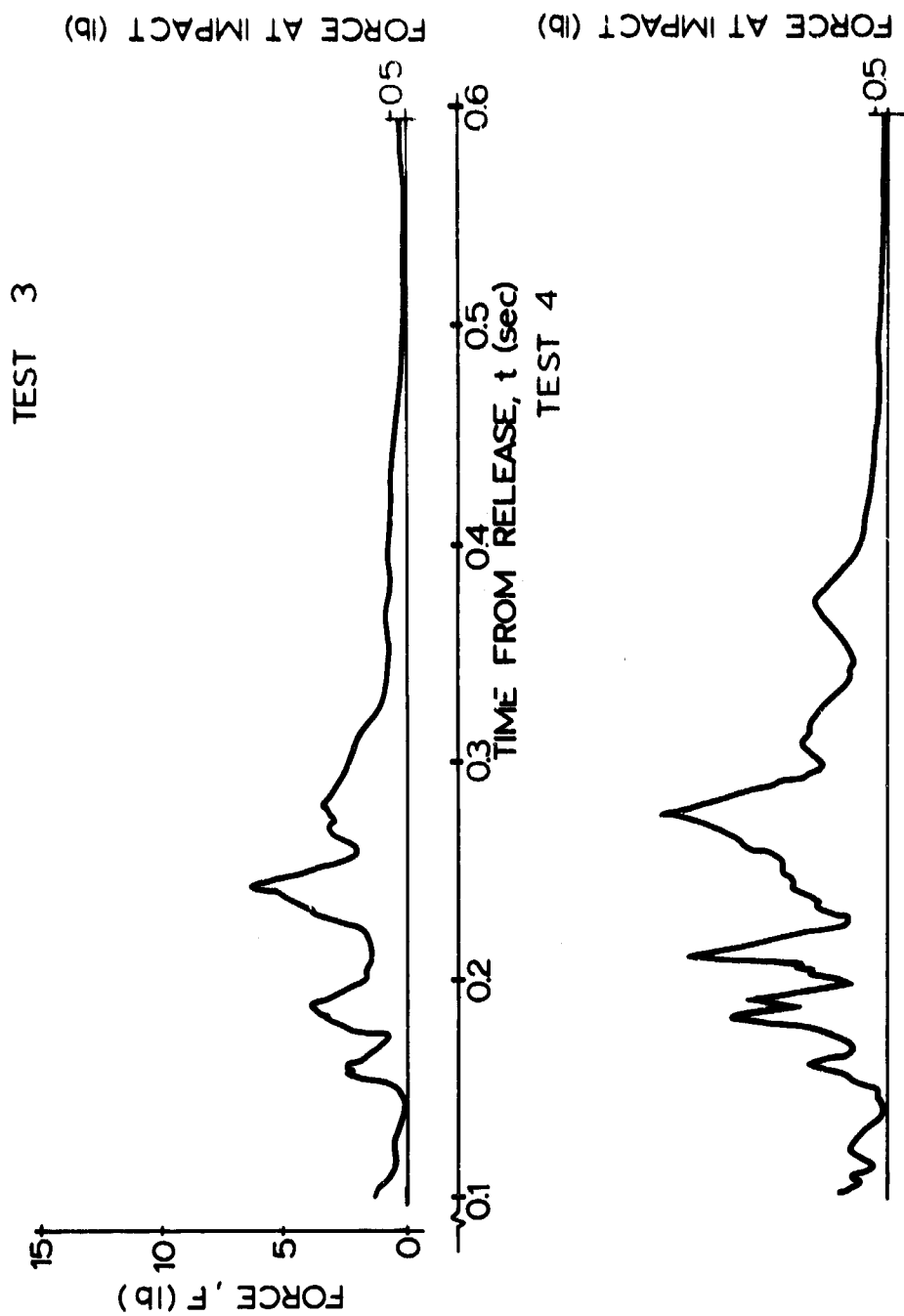
Fig 96 Single Parachute, $L_r = 0.4\ D_o + L_c = 0.88\ D_o$

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Fig 97 Single Parachute, $L_r = 0.4\ D_o + L_c = 0.88\ D_o$

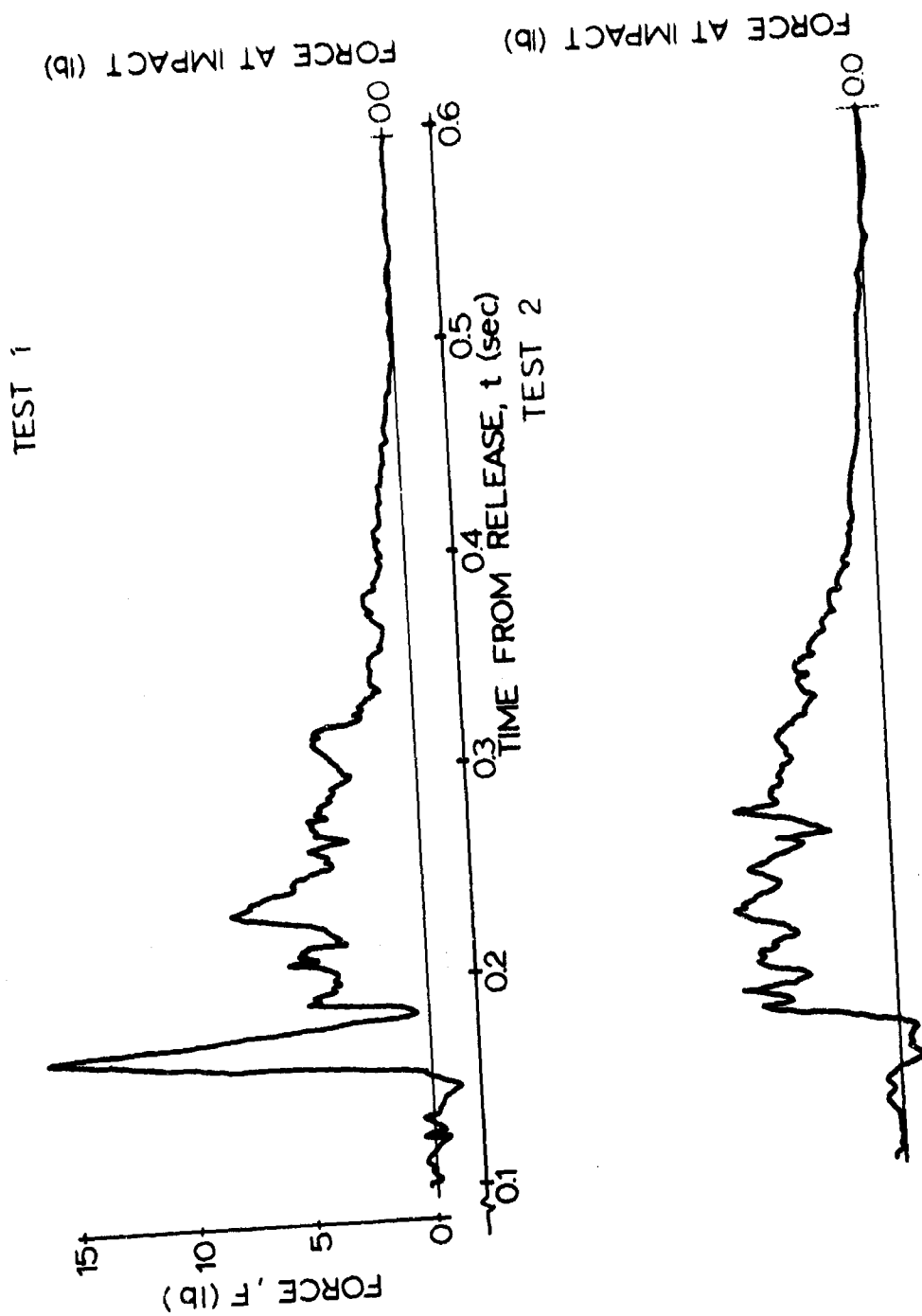Fig 98 Single Parachute, $L_r = 0.4 \, D_0 + L_c = 0.88 \, D_0$

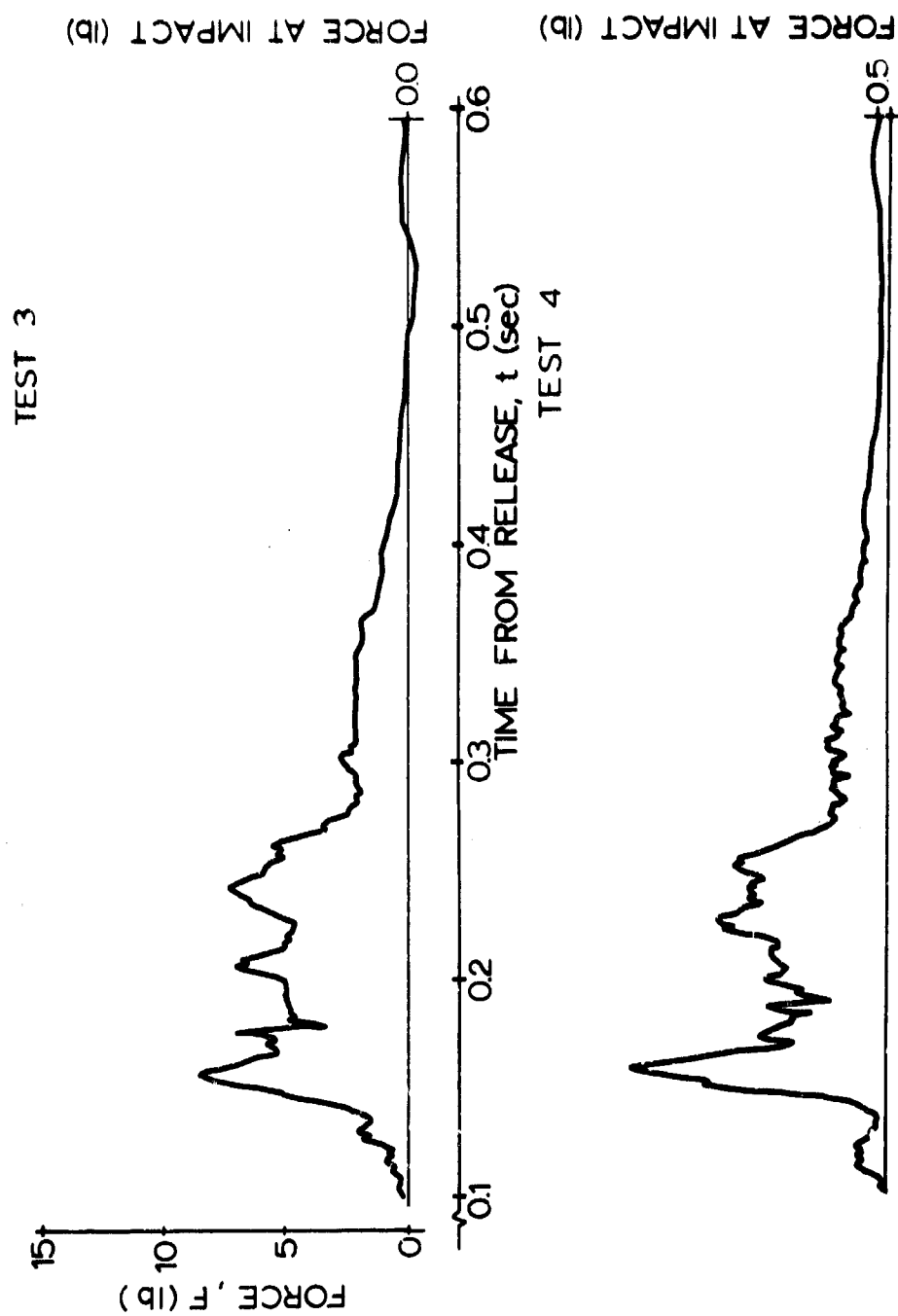Fig 99 Single Parachute, $L_r = 0.4 D_o$ + Internal Parachute, $0.2 D_o$

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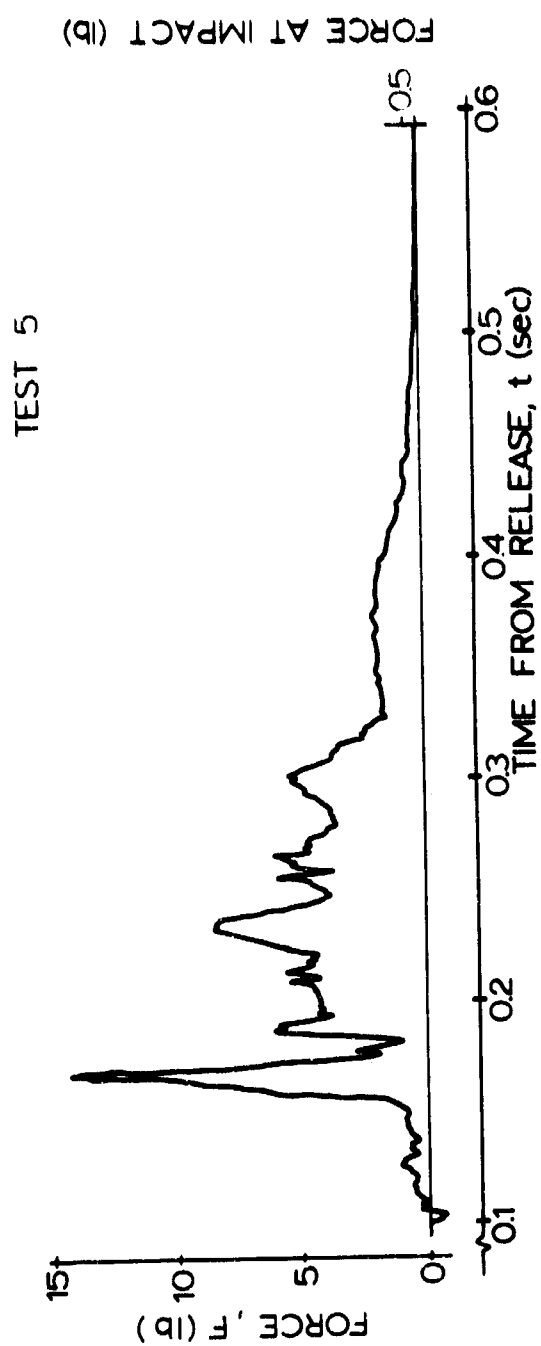Fig 100 Single Parachute, $L_r = 0.4\ D_o$ + Internal Parachute, $0.2\ D_o$

Fig 101 Single Parachute, $L_r = 0.4$ D$_o$ + Internal
Parachute, 0.2 D$_o$

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13. ABSTRACT

The uniformity of the opening characteristics of free flying model parachute clusters with and without inflation aids was investigated. Models of 5 ft. nominal diameter with low stiffness index were fired from a compressed air catapult and the parachute forces versus time were recorded. The ratio of included and suspended masses, the scaling parameter, was, with a few exceptions, identical to that for three 100 ft. solid flat parachutes with a suspended weight of 8,850 lb. The measurements were combined with qualitative observations of the load-parachute systems for the establishment of comparative qualifications. The model tests showed that in clusters of three parachutes the configurations of the standard parachute with riser extension of 0.2 D_O and the standard parachute with an internal canopy without riser extension had the best performance characteristics in view of the low averaged descent velocity and standard deviations. The times from the instant of snatch to the development of peak force of all configurations were about equal with the standard parachute having the largest deviations. Two configurations with combinations of riser extensions and centerlines as inflation aids failed to the extent that their testing was discontinued. The few values obtained for these configurations are not included in the numerical evaluation of the experiments described.

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