C.P. No. 751

C.P. No. 751

MINISTRY OF AVIATION

AERONAUTICAL RESEARCH COUNCIL

CURRENT PAPERS

A Theoretical Approach to Air Bag Shock Absorber Design

by

A. C. Browning, B.Sc.

LONDON: HER MAJESTY'S STATIONERY OFFICE

1964

PRICE 12s 6d NET

U.D.C. No. 621-798.1 : 621-567

C.P. No. 751

February, 1963

A THEORETICAL APPROACH TO AIR BAG SHOCK ABSORBER DESIGN

by

A.C. Browning, B.Sc.

SUMMARY

A simple theory of the compression of a cylindrical air bag shock absorber has been studied in detail by means of over 1000 step-by-step integrations. Many features of practical air bag performance have been reproduced and data charts are given which indicate the design parameters for useful bags. From these charts the effect of variation of bag loading, height, orifice area and the speed of the descent can be appreciated. The use of a strong patch covering the orifice, bursting at several pounds per square inch pressure, has been investigated but gives little change in performance. If an extensible fabric is employed an increase in both bag height and orifice area is necessary. Bags of very high or very low loading are found to be inefficient and it is concluded that air bags are most suitable at a loading of 150 to 200 lb per square foot. The theory does not take account of the wind speed which, if more than about 6 ft/sec, could cause the load to drift partly off the bags, reducing the retardation.

Replaces R.A.E. Tech Note No. Mech Eng 369 - A.R.C. 25,134.

LIST OF CONTENTS

LIST OF APPENDICES

LIST OF TABLES

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Cont'd)

1 INTRODUCTION

The present air bag consists of a cylinder made of imporous fabric, having one or more orifices in its top or sides, a typical installation is shown in Fig.1. The base of the bag is usually furnished with a valve through which the bag is inflated by ram air during the descent in much the same way as a parachute is inflated. A weak patch covers each orifice during this time. These bags are attached to the platform under the parachuted load, and on touchdown, the parachutes are disconnected from the load, the bag is compressed and the air pressure inside it rises causing the weak orifice patch to burst. During the subsequent compression the orifice flow controls the bag air pressure and this retards the load. The bag shown has around it wire grommets which improve the hoop strength. Photographs of the operation of air bags in descent with drift are shown in Fig.2.

The air bag has had extensive use in the past but still no sound method of design exists, and each new application, when this involves a change from a tried design, is tackled on its merits by ad hoc tests in a ground test rig or by field parachute trials. The testing is both expensive and time consuming, and could possibly be considerably reduced by a better "first guess" of bag height and orifice size.

A theoretical analysis was given by Powell[1], but the numerical computation was at that time tedious. However, electronic computers are now available and advantage has been taken of this to make a more comprehensive study. In addition loads more dense than those considered by Powell are now being parachuted, making it impossible to limit interest to bags with subsonic orifice airflow.

2 RANGE OF INVESTIGATION

The principal object of this Note is to present the results of a theoretical study, using numerical methods, of the equations of motion of an air bag system and to show the effects of systematic variation of the parameters occurring in these equations. The results are presented mainly in the form of data charts from which a bag designer can make a choice of the bag most suited to his purpose and at the same time be aware of the limits of performance of the bag.

Initially a study is made of a bag formed of inextensible material and with a very weak orifice patch. The effects of variation of orifice area, bag height, base area, descent speed and loading are considered in detail. This study is followed by two subsidiary studies in which the effect of a strong bursting patch covering the orifice is considered and bag fabric extensibility is taken into account; these enable the bag designer to ascertain for himself whether these factors are of significance in his particular application.

Problems associated with buckling bags and bouncing loads are investigated and guidance is given so that these can be avoided. Bag fabric flexibility is also considered and limits given for a reasonable combination of strength and flexibility in current materials. Two measurements of efficiency are defined and briefly discussed.

The Note concludes with a detailed plan for a design method and a complete example, together with a suggestion for producing a "standard" air bag of great versatility.

Appendices discuss the derivation of the theoretical air bag equations and the construction of the data charts from their solutions. A generalisation of the theory is given and a final Appendix deals with the effects of the residual gas energy in a fully compressed bag.

3 THE CYLINDRICAL AIR BAG MADE FROM AN INEXTENSIBLE FABRIC AND WITH A VERY WEAK ORIFICE PATCH

Theoretically, two equations suffice to describe the collapse of the air bag. They are:

(i) the equation relating the orifice flow to the loss of air from the bag, and

(ii) the equation of motion of the load.

The first of these equations is non-linear, and to obtain a solution recourse must be made to numerical methods. For this purpose a programme has been written for the DEUCE electronic computer to obtain step-by-step solutions rapidly.

3.1 The assumptions and the differential equations

Following Powell the assumptions listed below are made:

(a) The load lands vertically.

(b) The parachute lift is neglected.

(c) All air bags are geometrically similar and symmetrically placed beneath the load.

(d) There is no transfer of heat to or from the air in the bag during compression.

(e) The coefficient of discharge of the orifice obeys the law $C_D = 0{\cdot}9 - 0{\cdot}3/P$ (P = pressure ratio).

(f) The pressure in the bag is initially atmospheric.

(g) The bursting patch covering the orifice offers no resistance to bursting.

(h) The bag collapses such that at all times the cross sectional area cut by horizontal planes is constant along the bag.

(i) The change of shape of the bag due to extension of the fabric can be neglected.

Powell derived the two equations and applied them to study the barrel shaped bag. For the sake of completeness, equations equivalent to those found by Powell, but which apply to the cylindrical bag are derived in Appendix 1.

They are, in non-dimensional form, the orifice flow equation

$$\frac{dP}{dT} = -\frac{\left(\alpha\ Q + \beta\ \frac{dy}{dT}\right)}{\varepsilon\ y} \qquad (1)$$

and the equation of motion of the load

$$\frac{d^2y}{dT^2} = R\{S(P-1)-1\} \qquad (2)$$

In these equations

P = ratio of the bag air pressure to the atmospheric pressure

T = non-dimensional time $u_o\ t/h_o$

u_o = steady descent speed

h_o = initial bag height

y = ratio of the bag height to its initial height

and α, β, ε are functions of P (defined in Appendix 1).

The three non-dimensional parameters, Q, R and S are defined by

$Q = \frac{a}{Bu_o}\ \frac{c}{\sqrt{\gamma}}$ termed the orifice parameter

$R = \frac{h_o\ g}{u_o^2}$ termed the bag height parameter

$S = \frac{Bp_a}{Mg}$ termed the bag loading parameter

where

a = orifice area

B = bag base area

c = speed of sound at atmospheric temperature

γ = ratio of the principal specific heats of air

M = load mass

g = acceleration due to gravity

p_a = ambient atmospheric pressure

The orifice parameter (Q) is so called because it is directly proportional to the ratio of the orifice to base area when the descent speed is given.

For similar reasons R is termed the bag height parameter. It could be named the energy parameter, for

$$R = \frac{1}{2} \frac{Mg\, h_o}{\frac{1}{2} M u_o^2}$$

$$= \frac{1}{2} \frac{\text{Load potential energy at touchdown}}{\text{Steady descent kinetic energy}}$$

but in this Note its use is to determine the bag height and the former name is used.

The parameter S is inversely proportional to the bag loading and for this reason is termed the bag loading parameter. Thus heavily loaded bags have a small bag loading parameter S.

Using the standard values

$$C = 1116{\cdot}4 \quad \text{ft/sec}$$

$$\gamma = 1{\cdot}4$$

$$p_a = 14{\cdot}7 \quad \text{p.s.i. absolute}$$

the parameters are,

$$Q = 943{\cdot}6 \quad \frac{a}{Bu_o}$$

$$R = 32{\cdot}2 \quad \frac{h_o}{u_o^2}$$

$$S = 2116{\cdot}8 \quad \frac{B}{M} \qquad (M \text{ in lb}).$$

In the remainder of this Note these standard conditions are assumed whenever a conversion is made to or from the non-dimensional parameters.

To account for the choking of the orifice at sonic outflow speed, the function α must be changed (see Appendix 1) when the pressure ratio P exceeds the value 1·894.

When the bag begins to compress at T = 0 both the pressure ratio P and the bag height ratio y are equal to unity. The load velocity is equal to the steady descent speed, i.e.

$$\frac{dh}{dt} = -u_o$$

which leads to

$$\frac{dy}{dT} = -1$$

as $h = y\,h_o$ and $t = h_o T/u_o$.

The solution must be computed from $T = 0$ to $T = T_1$ when the load strikes the ground. To prevent the packed bag from projecting beneath the load platform it is usually mounted in a well (see Fig.1). Hence, on ground impact of the load the bag is not completely compressed and a stroke equivalent to the depth of the well is lost; this lost stroke has been arbitrarily taken as 15% of the initial bag height. The numerical integration is therefore stopped when y becomes equal to 0·15. As this does not normally occur at a step of the integration an interpolation process is used to calculate the velocity and time at $y = 0{\cdot}15$.

In this text, T_1 is referred to as the compression time but it must be remembered that it relates to the time to compress to the selected residual stroke and not to the first minimum height nor to the time to come finally to rest because, if the velocity is reduced to zero exactly when the residual stroke is reached, there is pressure left in the bag to cause a further bounce.

3.2 The main results and comparison with experiment

From the solution of the equations three particular results are extracted:

(i) The peak retardation d^2h/dt^2, denoted by Ng and which may occur at or before the ground impact of the load.

(ii) The ratio of the ground impact speed to the steady descent speed, denoted by σ.

(iii) The non-dimensional time at ground impact, denoted by T_1.

The peak retardation and the ground impact speed are both indicative of the susceptibility to damage of the load and both must therefore be below specified limits for a bag to be satisfactory. The compression time is a secondary factor but if it is unduly long then this (vertical impact) theory will be far from representative of the oblique impact of a load landing in a wind and drifting off the bags before the compression is complete (see Fig.2).

In order to confine the calculation to the more useful bags, interest is limited to the following:

(a) Bags with a peak retardation between 5g and 14g ($5 \leq N \leq 14$).

(b) Bags with a ground impact speed not more than half the steady descent speed ($\sigma \leq 0.5$).

(c) Bags with a non-dimensional compression time not more than 3 ($T_1 \leq 3$).

The first two of these are self explanatory. The limit on the non-dimensional compression time is roughly equivalent to twice the compression time of a bag which brings the load to rest at $y = 0{\cdot}15$ under uniform retardation. At this limit, $T_1 = 3$, the load will drift during the bag compression a distance equal to the bag height if the ratio of wind speed to descent speed is greater than 1/3. For descent speeds of up to 30 ft/sec this represents a wind speed of 10 ft/sec, and many practical landings will be in winds stronger than this (see Fig.2).

Only three papers[2,3,4] dealing with drop tests of cylindrical air bags are known to the author. Harwood and Stevens[2] tested a 38½" high bag, 34" in diameter with various orifices and in most cases obtained values for the peak retardation and the ground impact velocity. The comparison with the corresponding theoretical integrations is shown in Table 1. In the main the theoretical peak retardation and ground impact speed are a little higher than were found in practice.

Turnbow and Ogletree[3] tested both a British bag and an American bag using in their instrumentation a device for measuring the bag air pressure. The results for the British bag, 54" high and 37" diameter, are tabulated in Table 2 together with the corresponding theoretical integrations. All but two tests give a fair agreement with the theory. It is suspected that in these two the orifice patches did not burst, for the peak retardation in such a case would theoretically be about 11g and 13g. The American bag had a higher peak retardation than would be expected from the theory, and this was probably due to the effect of the variable area orifice impeding the air outflow at the early stages in the stroke. A comparison is, however, not easy because the theory in its present form must select a fixed orifice area.

Tomcsak[4] tested 35" diameter bags with heights varying from 35" to 45", also with a stretching orifice. The high peak retardation was again in evidence but many of the tests were unsatisfactory. These tests do however give some experimental confirmation of the effect of bursting patches, to be described in Section 5.

3.3 Construction and use of the data charts

The results of over five hundred integration runs have been condensed to six data charts, Figs.3 to 8. Each chart applies to a fixed bag loading parameter $S(=B\,p_a/Mg)$ and has on it contours of the three main results N, σ and T_1. The method by which the charts were constructed is given in Appendix 2.

The particular bag loading parameters for the six charts cover a wide range and were chosen so that two of them coincided, approximately, with the parameters of bags already in use. The parameters are:

$S = Bp_a/Mg$	Typical bag with this loading parameter
1·86	8,000 lb on a 36" diameter bag
3·75	4,000 lb " " " "
6·0	2,500 lb " " " "
10·0	1,500 lb " " " "
15·0	1,000 lb " " " "
30·0	500 lb " " " "

The bag corresponding to S = 10 is near to the present medium platform bag, and some tests have been done at R.A.E. on a bag where S = 3·75.

The use of the charts is illustrated by the following two examples:

Example 1

A load of 1,500 lb is to land on a 36" diameter bag, at a descent speed of 25 ft/sec, a peak retardation of 10g and a maximum ground impact speed of 5 ft/sec. What is the orifice area and the bag height?

The bag loading parameter is 10·0, and corresponds to Fig.6. From the speeds given

$$\sigma \leqslant 0{\cdot}2 \ .$$

Consider the point on Fig.6 where the N = 10 and σ = 0·2 contours intersect. At this point T_1 is well below 3 and so this point is considered suitable. The values are:

$$Q = 0{\cdot}93 = \frac{a}{Bu_o} \times 943{\cdot}6$$

giving an orifice area

$$a = 0{\cdot}93 \times \frac{25}{943{\cdot}6} \times B = 25 \text{ sq inches}$$

and

$$R = 0{\cdot}118 = 32{\cdot}2 \frac{h_o}{u_o^2}$$

giving a bag height

$$h_o = 0{\cdot}118 \times \frac{625}{32{\cdot}2} = 2{\cdot}29 \text{ ft} \ .$$

Example 2

A load of 914 lb is to land on a bag 24" diameter at a descent speed of 24 ft/sec, a peak retardation of 11g and a maximum ground impact speed of 5 ft/sec. What is the orifice area and the bag height?

The bag loading parameter is 7·26 which lies between the values of Figs.5 and 6, so that there is no chart from which a suitable point can be chosen. However, a point can be chosen to suit N $\simeq$ 11 and $\sigma \simeq$ 5/24 on all six charts, as shown below:

	Q	R
Fig.3, S = 1·86	0.31	0·283
Fig.4, S = 3·75	0·58	0·178
Fig.5, S = 6·0	0·74	0·137
Fig.6, S = 10·0	0·91	0·109
Fig.7, S = 15·0	1·04	0·104
Fig.8, S = 30·0	1·36	0·117

From these figures an interpolation can be made to obtain the values for $S = 7{\cdot}26$. The results are

$$Q = 0{\cdot}81 = \frac{a}{Bu_o} \times 943{\cdot}6$$

whence

$$a = 0{\cdot}81 \times \frac{24B}{943{\cdot}6} = 9{\cdot}3 \text{ sq inches}$$

and

$$R = 0{\cdot}124 = 32{\cdot}2 \frac{h_o}{u_o^2}$$

whence

$$h_o = 0{\cdot}124 \times \frac{576}{32{\cdot}2} = 2{\cdot}22 \text{ ft} .$$

The above Table does of course show how the bag height and the orifice size must be changed to compensate for various loads on a bag, the bag having a given performance. An increase in the load (decrease in S) requires a smaller orifice and a longer bag.

4 THE DATA CHARTS

Each data chart shows the effect of variation of the orifice and bag height parameters Q and R, on the bag performance. In every chart low values of Q lead to a long compression time T_1. High values of Q give a high ground impact speed if the R value is low and a low peak retardation if the R value is high. The regions of the chart where the limits

$$5 \leqslant N \leqslant 14$$

$$\sigma \leqslant 0{\cdot}5$$

$$T_1 \leqslant 3$$

are exceeded are easily seen, for example they are labelled on Fig.6.

To appreciate the effect of variation of the bag loading parameter S the charts must be compared. With an increase in S the pattern of the curves broaden, both the T_1 and the σ curves open out on the Q abscissa (see Fig.9). The centroid of the pattern also moves as S is increased towards higher values of Q and lower values of R. The T_1 and σ contours tend to run parallel but at the high values of S the contours for low values of σ curve more to the left and out the T_1 contours. It seems at first sight that for the $S = 1{\cdot}86$ chart the value of Q is very critical, due to the steepness of the contours. However, the range of Q is from 0·2 to 0·7, i.e. a ratio of $3\frac{1}{2}$ to 1 compared with 1·1 to 2·3 on the $S = 30$ chart, a ratio of 2 to 1. Thus considering percentage changes in Q it is the charts with the large S value which are the more sensitive.

In practice it is desirable to be able to estimate the effect of variation not of the non-dimensional parameters Q, R and S but of the orifice area, descent speed etc., and this aspect is studied in the following sections.

4.1 Variation of orifice area

A simple modification which can be made to a bag is a change in its orifice area. This implies a proportional change in the orifice parameter Q which is represented on the data charts by a horizontal displacement.

A glance at the charts will show that such a displacement will usually lead to marked changes in N, σ and possibly T_1. In every case a decrease in the orifice area will increase both N and T_1 and the load becomes more likely to bounce on the bag. The bouncing phenomenon is accompanied by the ground impact speed ratio σ not decreasing progressively at all values of the orifice parameter. As an example, in Fig.10 the way in which N, σ and T_1 change with a change in Q is shown for a typical bag. In this case a 10% decrease in orifice area leads to an increase of about 1g in the peak retardation.

4.2 Variation of bag height and base area

A change of bag height h_o changes R in proportion, and is represented by a vertical displacement on the data charts. Such a displacement will affect N and σ to a larger extent than it will affect T_1. A taller bag will have a lower peak retardation and will usually give a lower ground impact speed. The actual time of compression will increase both from the slight increase of T_1 and the presence of h_o in the formula

$$t = \frac{h_o}{u_o} T .$$

The data chart method of presenting the numerical solutions is not suited to the assessment of a change of bag base area, as this involves a change in S and several charts must be consulted. Quite often however, the bag base area is decided by other considerations, e.g. load base size or the size to give a particular bag loading (see Section 9). A change δB in the base area gives a change in the orifice parameter Q inversely proportional to δB and a change in the bag loading parameter S proportional to δB. These are represented on the data charts by a horizontal displacement together with a change of chart. A horizontal displacement has been discussed in the previous section and a change of chart is equivalent to a change of load only and is discussed fully in the following section.

4.3 Variation of descent speed and load

Once a bag is in service use it can be used with various loads and parachute systems. The good air bag must be versatile enough to cope with a certain amount of variation of this nature, i.e. small changes in descent speed and/or load should not cause large variations in peak retardation or ground impact speed.

A rough idea of the effect of variation of descent speed can be obtained by constructing parabolae

$$R = \text{constant} \times Q^2$$

on the data charts, for R is proportional to $1/u_o^2$ and Q to $1/u_o$. On Fig.7 a typical parabola has been drawn and it is seen that it is roughly parallel to the σ and T_1 contours but cuts many N contours. Thus, the general effect of an increase of descent speed is to increase the peak retardation markedly with but little effect on the ground impact speed ratio or the non-dimensional compression time. The ground impact speed is proportional to the descent speed and the actual compression time is inversely proportional to it.

To obtain an idea of the effect of changes in bag loading corresponding points on the six data charts must be compared. If the diamond shaped areas of the data charts are drawn on one chart (see Fig.9) then variation of bag loading is manifested by displacement of these areas roughly in the direction of the N contours, together with a change in width of the diamond. Thus a change of load has a small effect on the peak retardation but can give a long compression time for light loads and a high ground impact speed for heavy loads.

These points are illustrated in the following studies of two typical bags.

Example 1

A good bag has been chosen to the requirements:

Load 1,500 lb on a 36" diameter bag
Maximum retardation 10g
Descent speed 24 ft/sec

which has parameters

$$Q = 0{\cdot}887$$
$$R = 0{\cdot}1288$$
$$S = 10\ .$$

Changes of up to ±20% in load and descent speed have been considered applied simultaneously to this bag and the results are presented in Fig.11. The peak retardation is almost independent of the load, very dependent on the descent speed and these effects act independently (see the approximately parallel contours of Fig.11a). It is interesting to note that the loss of three parachutes out of a cluster of eight would give a 20% increase in descent speed, which would cause a rise in peak retardation from 10g to above the arbitrary limit of 14g.

The effects of variation of load and descent speed do not act independently on the ground impact speed, for the combination of an excess load of 10% to 20% with an excess descent speed of 10% to 20% gives a higher ground impact speed than would be expected (see Fig.11b, lowest curve).

Example 2

A similar investigation has been made for a bag retarding a much heavier load

$$Q = 0{\cdot}604$$
$$R = 0{\cdot}1880$$
$$S = 3{\cdot}75$$

(an example of this loading is a 4,000 lb load on a 36" diameter bag). This bag also has a peak retardation of 10g together with low ground impact speed and short time of compression.

Variation of load and descent speed are again independent in their effect on the peak retardation (Fig.12a). This is far from true of the effect on the ground impact speed, which can be seen from the non-parallel contours of Fig.12b. The ground impact speed increases markedly for low descent speeds unless the load is light. For high descent speeds and light loads the compression time is greater than the arbitrary limit of $T_1 = 3$ (i.e. the load tends to bounce). Quite small changes of load and descent speed can lead to a bag performance approaching the arbitrary limits of 14g, $\sigma = 0{\cdot}5$ and $T_1 = 3$, showing that heavily loaded bags are not very versatile.

5 THE EFFECT OF A STRONG BURSTING PATCH COVERING THE ORIFICE

It is but a small modification to the computor programme to set Q to be zero until a certain bag pressure has been reached and by this means the effect of a strong orifice bursting patch can be studied. It is impractical to construct six more data charts for each of several bursting pressure ratios, but in order to show the main points one new chart has been prepared (Fig.13).

It was thought that the addition of a strong bursting patch to a bag would lead to an increase of the peak retardation. However, for bursting pressures of up to about half an atmosphere this was not the case, the peak retardation decreased a little and there was an increase in the compression time. This is attributed to the fact that the air pressure builds up earlier in the stroke, and when the patch bursts the air escapes at a higher pressure, and therefore faster than it would at a comparable stage of the compression of the unpatched bag. The early occurrence of the peak retardation slows the load at an early part of the stroke, causing the long compression time. In his experiments Tomosak[4] found a decrease in peak retardation as the bursting pressure was raised.

With very strong patches (bursting pressure above 8 p.s.i.) the peak retardation is somewhat greater than that for zero bursting pressure, but the rise is not large compared with that obtained by small changes in orifice area or descent speed.

In the manner of Appendix 2 a data chart has been prepared for a bag loading of S = 10, and a patch bursting pressure of 5 p.s.i. (Fig.13). The bag loading corresponds to the medium platform bag currently in service and comparison with the data chart for the unpatched bag of the same loading (Fig.6) shows that:

(a) The N contours are consistently slightly lower (except for N = 5 where they are almost coincident), implying a small decrease of peak retardation.

(b) The $T_1 = 2$ and $T_1 = 3$ contours are both further to the right, implying a longer compression time, and

(c) All the σ contours except $\sigma = 0{\cdot}2$ are more to the right, implying a lower ground impact speed in most cases. Even with bags near the $\sigma = 0{\cdot}2$ contour the increase in ground impact speed is small only occurring for longer bags. The decrease in σ with short bags near the 0·3, 0·4 and 0·5 contours is of the order of 0·1.

In general, although the use of a 5 p.s.i. patch appears to be advantageous, the same performance can be achieved with an unpatched bag by a small decrease in orifice area and a small increase in bag height. For example, the unpatched bag

$$Q = 0{\cdot}102 \quad R = 0{\cdot}1024 \quad S = 10$$

has N = 10, $\sigma = 0{\cdot}4$ (see Fig.6). With a 5 p.s.i. patch the performance is N = 9·5, $\sigma = 0{\cdot}3$ (Fig.13) but the unpatched bag

$$Q = 0{\cdot}098 \quad R = 0{\cdot}1098 \quad S = 10$$

(about a 10% increase in length) has the performance N = 10, $\sigma = 0{\cdot}3$ and the compression time is only slightly longer.

Thus although bursting patches do have a predictable effect, in many cases this can be achieved without recourse to a strong patch.

This short study indicates the features of patch strength as applied to a limited selection of bags. Discretion must be used in applying the results to bags which have not been studied.

6 THE EFFECT OF BAG FABRIC EXTENSIBILITY

In Appendix 3 the modifications to the two differential equations for a simple theory of a bag made from extensible fabric are given. A fabric of realistic extensibility has been chosen for study, and a further six data charts prepared. These are presented in Figs.14 to 19 to the same scales as the inextensible bag charts, so that a comparison of inextensible and extensible bags for the same loading is easily made by reference to the corresponding charts. The fabric extensibility chosen is such that for a pressure difference of one atmosphere across the fabric the bag base area is increased by 25%, the increase in base area being assumed to be proportional to the pressure difference. This represents a fabric strain of about 12%, roughly half of the breaking strain of many fabrics.

The new charts for the more lightly loaded bags, i.e. those with a low peak pressure and therefore small fabric extension, are very little different from the inextensible bag charts. This is not true with the heavy loadings, and for S = 3·75 an extensible 10g bag of good ground impact speed and compression time must be about 35% longer than the corresponding inextensible bag (an R value of about 0·242 compared with 0·177). For the heaviest bag loading considered, S = 1·86, it is possible to find an extensible bag with no orifice at all which will compress to 15% of its original height before bouncing. Such bags would of course bounce the load very violently in practice, the ground impact adding to the upward force.

Except with the extremely heavily loaded bags the effect of extensibility is to increase the peak retardation by up to 30%, the highest increase occurring with the combination of a heavy load and a long bag (small S, large R) or a light load and a short bag (large S, small R). The lowest increase is at the other extremes, heavy load and short bag or light load and long bag. At the heaviest load considered ($S = 1{\cdot}86$) the peak retardation does actually decrease for smaller values of R (short bags).

The effect of extensibility on ground impact speed and compression time is not so clear for in some cases an extensible bag bounces whereas the corresponding inextensible bag does not, but there is little effect on ground impact speed, except for short bags (R small) when heavy loads cause a heavy landing and light loads a light landing. The effect on compression time is not very marked and will normally be of less importance than the peak retardation or the ground impact speed. In the cases where extensibility causes bouncing the compression time is important, but such cases can be seen by inspection of the data charts.

7 OTHER SIGNIFICANT FACTORS

7.1 Bouncing loads

As remarked in Section 4.1, and illustrated in Fig.10, air bags with small orifices are liable to bounce the load. This is found to be true in practice. However, when bags become more highly loaded than the case illustrated in Fig.10 a rather different effect upon the ground impact velocity and compression time arises from a variation of the orifice parameter, Q. For each value of R, bag height parameter, there exists a value of Q which gives a zero ground impact speed and at yet smaller values of Q both bouncing and a heavy landing will occur (see Fig.20). The data charts can, therefore, be divided sharply into two regions corresponding to bouncing and non-bouncing loads. The locus of transition, termed the 'bounce line' is labelled 'L' on Figs.3,4,14 and 15.

It must be remembered that the 'bounce line' has been determined for a bag which has not been fully compressed ($y = 0{\cdot}15$) and, at touchdown, the bag pressure is still high. Although the load has been brought to rest in contact with the ground the load would in practice be lifted again unless the bags burst at this point. If the load does bounce the second impact is likely to be heavy and it is important to estimate the energy associated with this impact.

At the first impact a ground shock is applied to the load which brings it to rest, approximately with no change in bag height or air pressure. The two differential equations of motion still apply after the impact and in particular the acceleration due to the bag air pressure is unchanged. If this acceleration is upward then the load will rise again, and the condition for this is, from equation (2),

$$P_1 \geq 1 + \frac{1}{S} \qquad (3)$$

where P_1 is the bag air pressure ratio at the first ground impact.

An air bag which allows its load to be accelerating downward as it strikes the ground would possibly be wasting some of its stroke, and thus the best air bags are likely to give a small 'ground bounce', the second impact being acceptable as well as the first. More than two impacts are not likely to be acceptable owing to the increase of the total time of retardation.

A rough idea of the magnitude of the second ground impact can be obtained by calculating the potential energy of the compressed air in the bag at the end of the first impact. If this is only a small fraction of the initial kinetic energy of steady descent then the second impact cannot be severe. This calculation is presented in Appendix 4 and curves representing a bag air potential energy of 30% of the descent energy are drawn in Fig.21. Clearly the most heavily loaded bags (S = 1·86) within the data chart limits are well above this 30% limit. The S = 3·75 bags are near to the limit, those having a low peak retardation being just below it.

It may be argued that at the second fall the load is still protected by the bag, and that this may absorb the second shock. However, for bags above the 30% limit there is sufficient energy in the bag air at the first impact to throw the load up a considerable distance to give a long time of retardation, by which time the load may have drifted off the bag (Fig.2).

With the very heavy bag loadings then, it is seen that bags near the 'bounce line' are not attractive, and should be avoided.

7.2 Buckling bags

To avoid the possibility of bags buckling rather than collapsing from the ends, there should be a limit to the bag height/diameter ratio. In past practice this ratio has seldom exceeded 1·5.

The bag diameter is usually decided by the size, shape and density of the load and to indicate the height/diameter ratio a rapid estimate of the bag height can be obtained by reference to the definition of R

$$h_o = \frac{Ru_o^2}{g} .$$

This formula is graphed in Fig.22 for the range of values of R occurring in the data charts. Once a point on a data chart has been chosen a glance at this figure will give the bag height. It should be noted that bags of peak retardation less than 5g and descent speed greater than 25 ft/sec must be at least 4 ft high (see data charts 1 to 6), and so an upper limit to the bag height represents a lower limit to the peak retardation.

7.3 Bag fabric flexibility

If heavy loads are used on air bags then the fabric must be very strong. This imposes a limit on the bag loading, for above a certain strength fabrics are likely to be inflexible due to their thickness and proofing. This would make the bags impossible to pack into a small space for carriage in the aircraft. The limit depends on the fabrics currently available, but to give an indication of it the peak fabric tension is calculated.

If the bag collapses as a cylinder without bulging the hoop tension is

$$H = \frac{(P-1)p_a D}{24} \quad \text{lb/inch}$$

where D is the bag diameter in feet.

The peak pressure from the dimensional form of equation (2) in Appendix 1, is given by

$$P-1 = \frac{N+1}{S}$$

and thus the peak hoop tension is

$$H = \frac{(N+1)p_a D}{24\ S}$$

or

$$H = 88\,\frac{(N+1)D}{S} \quad \text{lb/inch} .$$

The most heavily loaded bags, $S \leqslant 3{\cdot}75$, if only 2 ft in diameter and giving a 6g peak must have a fabric strength in excess of 300 lb/inch. A larger bag diameter or peak retardation would increase this value. Considering this together with the results of Section 7.1 on "bouncing loads", practical bags cannot be expected to be successful for loadings higher than that equivalent to $S = 6$, i.e. about 350 lb/sq ft. Fig.23 shows this bag loading in terms of the bag diameter.

8 AIR BAG EFFICIENCY

Even though an air bag may be acceptable for the job that it performs it is not necessarily perfect and an indication of the possible scope for improvement can be found by calculating efficiency values.

There are two important efficiency values which can be discussed theoretically, arising from the requirements that

(i) a large amount of kinetic energy must be destroyed,

(ii) an upper limit to the retardation is usually specified and if excessively high bags are to be avoided the mean retardation should be close to this limit.

8.1 Energy efficiency

The energy efficiency of a shock absorbing device can be defined as the ratio of the energy it destroys to the original kinetic and potential energy, i.e. for an air bag this efficiency is

$$E_1 = \frac{\frac{1}{2} M u_o^2 - \frac{1}{2} M\sigma^2 u_o^2 + 0 \cdot 85 \, Mg \, h_o}{\frac{1}{2} M u_o^2 + 0 \cdot 85 \, Mg \, h_o}$$

$$= \frac{1-\sigma^2 + 1 \cdot 7R}{1 + 1 \cdot 7R} > 1 - \sigma^2 .$$

Thus a good air bag with $\sigma = 0 \cdot 3$, has an energy efficiency of over 91%.

8.2 Retardation efficiency

The ideal shock absorber may be regarded as one which produces a uniform retardation throughout the whole of its compression time. Practically this ideal can be approached in an air bag by pre-pressurising the bag and then adjusting the orifice area to maintain the pressure. A measure of the efficiency of the system with respect to retardation can be defined by considering the ratio of the peak retardation produced by the actual system to the retardation provided by an ideal shock absorber. Denoting this ratio, called the retardation efficiency, by E_2

$$E_2 = Ng \Bigg/ \frac{(1-\sigma^2) \, u_o^2}{2(h_o - 0 \cdot 15 \, h_o)}$$

or

$$E_2 = 1 \cdot 7 \, NR/(1-\sigma^2)$$

assuming 15% of the stroke is lost.

The closer E_2 approaches unity the more efficient the system. It is found with heavily loaded bags that their retardation efficiency is poor; this is not surprising for to produce even a moderate retardation on a heavy load (with an unpressurised bag system) the bag air must reach a pressure of several atmospheres and much of the available stroke is lost in producing this compression. The situation is improved if the bag is pre-pressurised. The bags with the best retardation efficiency are found to be those lightly loaded and operating at a high peak retardation.

8.3 Mixed bags

To increase the efficiency of a set of air bags under a load it may be possible to use, symmetrically, bags of differing heights. For lightly loaded bags the main retardation occurs early in the stroke, the latter part being practically wasted. If the shorter bags were designed to strike the ground just as the longer ones become ineffective then it could be possible to improve the retardation efficiency, and probably also the energy efficiency of the combined system. A simple device which suddenly blocks up part of the orifice after part of the stroke has been completed would have this effect without the use of two separate sets of bags. Such a device is sketched in Fig.24.

9 DESIGN METHOD AND A COMPLETE EXAMPLE

Before designing an air bag the following information is likely to be known:

(i) load mass,

(ii) maximum base area,

(iii) descent speed,

(iv) maximum retardation allowable during stroke,

(v) maximum ground impact speed allowable.

Looking at this information critically:

(1) The lowest possible bag loading (even with square bags) is easily calculated from the load mass and the maximum base area and this must be below 350 lb/sq ft for it to be possible to design satisfactory air bags. If not an alternative method of shock absorption should be considered.

(2) The energy efficiency (represented by $1-\sigma^2$) should not exceed about 90%. For example if the descent speed is 24 ft/sec it is unreasonable to expect an air bag to give a ground impact speed less than about 8 ft/sec.

(3) At a ground impact speed of 8 ft/sec the load will receive a shock and must be robust enough to withstand this. The air bag system need not be designed to impart substantially less shock than associated with this final impact.

(4) If the descent speed is less than 20 ft/sec the parachute is probably large, and if possible its weight should be estimated. On the other hand it is unreasonable to expect to be able to design an air bag for use at speeds higher than 30 ft/sec, unless correspondingly high ground impact speeds can be tolerated (see (2) above).

Passing on to the air bag design:

(5) Many possible air bag systems (n bags, D ft in diameter) should be considered, and for each system the load per bag calculated. In this design method it is assumed that all the bags under the load are identical and take an equal share of the load.

(6) Inspection of Figs.22 and 23 can eliminate those bags which are very long or have too heavy a loading. This ensures that the bags will not buckle or give a severe ground bounce.

(7) If there is still the choice of few or many bags, many should be chosen because the fabric stress is lower. Systems using a very great number of bags will have been eliminated by (6) because the bags would be too narrow.

(8) The peak fabric tension can be calculated for each system from the formula

$$H = \frac{(N+1)\ DM}{24B} \quad \text{lb/inch} \quad (M \text{ in lb})$$

and a fabric should exist which can withstand this. The bags, if made of this fabric, must be flexible enough to pack.

(9) The bag parameters Q and R are chosen from suitable points on the data charts and these give the bag orifice area and height. The height parameter R gives the bag height as

$$h_o = \frac{Ru_o^2}{g} \quad \text{ft} .$$

No extra height should be added for packing space, for 15% of h_o is already taken to be "lost stroke". If it is expected that the fabric will stretch somewhat, then the "extensible bag" data charts 1E to 6E will give better values of Q and R.

At this point the bag height should be checked to see that it is less than about 1·5D.

(10) The point chosen from the data charts gives the orifice parameter Q, the orifice area being calculated from

$$a = \frac{BQu_o}{943 \cdot 6} \quad \text{sq ft} .$$

Again, if the bag fabric is expected to stretch, the data charts 1E to 6E should be used instead of charts 1 to 6.

(11) It is important to check that the descent speed is not likely to be, in practice, very different from the specified value, for the bag height is proportional to the square of the descent speed.

(12) The bag should be furnished with between five and ten wire grommets and a weak orifice bursting patch (e.g. a single sheet of thin rubber).

<u>A complete design example</u>

A loaded container weighing 2500 lb has a base 4 ft by 3 ft 6 in. and is to be dropped using a parachute to give it a descent speed of about 28 ft/sec. The container will withstand a free fall of one foot (8 ft/sec) on to the type of terrain on which it will be used operationally, and during the air bag stroke a peak retardation of 13g is not to be exceeded.

Following the design method:

(1) The lowest possible bag loading is 2500/14, i.e. 179 lb/sq ft which is well below the 350 lb/sq ft limit.

(2) The value of σ is 8/28, i.e. 0·285, giving an energy efficiency of 91·9%. This is a little high and in practice the ground impact velocity of 8 ft/sec may not be achieved.

(3) The peak retardation of 13g is covered by the data charts, and if on a ground impact at 8 ft/sec a uniform retardation of 13g was sustained then there would be an impression depth of about 1 inch. The estimate of 13g is therefore not unreasonably low.

(4) The descent speed of 28 ft/sec is high but within the range expected.

(5) Possible bag systems using from 1 to 12 bags are now considered, and many of these are rejected by consultation of Figs.22 and 23. The details are given in the following table:

Number of bags	Bag diameter inches	feet	Base size covered	Load per bag	Remarks
1	42	3·5	42" × 42"	2500 lb	Acceptable
2	24	2·0	24' × 48"	1250 lb	Loading too high
3	21	1·75	42" × 42"	833 lb	Loading too high
4	21	1·75	42" × 42"	625 lb	Acceptable
6	16	1·33	32" × 48"	416 lb	Loading too high
8	12	1·0	24" × 48"	312 lb	Loading too high
9	14	1·16	42" × 42"	277 lb	Bags too long
12	12	1·0	36" × 48"	206 lb	Bags too long

(6) Only the systems comprising one 42" diameter bag or four 21" diameter bags remain.

(7) The four bag system is preferred to the one bag system to give less fabric stress.

(8) The peak fabric tension is

$$H = \frac{14 \times 1{\cdot}75 \times 625}{24 \times 2{\cdot}40} = 268 \text{ lb/inch} .$$

This is quite a high tension and a strong fabric with many grommets will probably be necessary.

(9) The bag loading is 260 lb/sq ft, i.e. S = 8·13, and the data charts show that the height parameter for a peak retardation of 13g should be about

$$R = 0{\cdot}100$$

giving a bag height of

$$h_o = \frac{0{\cdot}100}{g} \times 784 = 2{\cdot}43 \text{ ft} = 29{\cdot}2 \text{ inches} .$$

This is the height of a bag made of stron fabric. If a weaker fabric were used, the fabric stretching somewhat during the stroke, then R should be 0·123. This would give a bag height of 35·9 inches, over 1·7 times the bag diameter. Thus to save height a strong fabric should be used to lessen the fabric extension.

(10) From the point chosen from the data charts the orifice parameter for the inextensible 13g bag of loading parameter S = 8·13 is

$$Q = 0 \cdot 82$$

giving an orifice area

$$a = 2 \cdot 4 \times 28 \times \frac{0 \cdot 82}{943 \cdot 6} = 0 \cdot 0584 \text{ sq ft },$$

i.e. an orifice of 3·38 inches diameter. If a weaker fabric is used, Q should be 0·83 enlarging the orifice to 3·40 inches in diameter.

(11) Descent speeds higher than 28 ft/sec will produce retardation peaks considerably greater than 13g. If this is not acceptable then a lower peak retardation must be designed for.

(12) In this case a large number of grommets, say 8 or 10, should be used to reduce the fabric extension, which in turn keeps the bag height down to about 1·5 times the diameter.

The nine bag system, eliminated by consideration of the bag length/diameter ratio (Fig.22) is the most promising of the rejected systems. However, the bag loading is 260 lb/sq ft and the bag height is the same as calculated above, i.e. 29 to 36 inches, certainly too long for a 14 inch diameter bag.

The other acceptable bag, a single bag 42 inches in diameter, has a fabric hoop tension of 536 lb/inch at the peak. A fabric of this strength is unlikely to be very flexible. It was for this reason that the four bag system was preferred.

A sketch of the four bag system is given in Fig.25. A glance at Fig.21 shows that the energy in the bag air at ground impact is well below 30% of the descent energy.

In the event of the bag being used on very hard terrain, so that an impression depth of one inch is not likely to be obtained, then the effect of soft ground could be simulated by affixing crushable material to the base of the load, between the bags, to crush at about 13g.

10 AN ATTEMPT TO FIND A "STANDARD" AIR BAG

A standard air bag, of fixed dimensions and orifice which can be affixed under any load landing at any speed to give an acceptable peak retardation and ground impact speed does not exist. However, a bag with an adjustable orifice area (set by a sliding shutter) could well be "standard" in that before the drop it need only be necessary to adjust the orifice area. There may be many such "standard bags", and one example is given below.

A descent speed of 25 ft/sec is taken as standard because this is representative of many present day parachute applications. It represents an upper limit in that even good bags have an energy efficiency little more than 90%, and the resultant 8 ft/sec ground impact is likely to give a hard shock to most loads. Thus

$$R = \frac{h_o S}{625} .$$

It happens that the inextensible bags of $\sigma = 0{\cdot}3$ and $R = 0{\cdot}138$ have roughly constant peak retardation in the loading range $6 \leq S \leq 30$. The details are:

Q	R	S	N	σ
0·802	0·138	6	10·0	0·3
1·095	"	10	7·6	"
1·302	"	15	7·7	"
1·727	"	30	7·7	"

The R value of 0·138 gives immediately from the formula above a bag height of 32" which is reasonable for a "standard" bag. If a bag diameter of 24" is chosen then the S range corresponds to a load mass range

$$222 \text{ lb} \leq M \leq 1120 \text{ lb} .$$

This bag then, of 32" height and 24" diameter, given a suitable orifice, will retard any load mass between 250 lb and 900 lb from 25 ft/sec to about 7 or 8 ft/sec at a peak retardation of about 8g. The orifice area required depends on the load, as can be seen from the table, and is given, approximately, by the formula

$$a = 1{\cdot}61 M^{-0{\cdot}38} \text{ sq in.}$$

(where M is measured in lb).

Large loads will of course require more than one bag and the potentialities of the scheme can be assessed from the following table

Number of bags	Load (lb) Min.	Load (lb) Max.	Base shapes
1	250	900	Circular 2 ft diameter
2	500	1,800	Rectangular 2 ft by 4 ft
3	750	2,700	Triangular, about 5 ft side
4	1,000	3,600	Square, 4 ft side
6	1,500	5,400	Rectangular, 4 ft by 6 ft
7	1,750	6,300	Circular, 6 ft diameter
8	2,000	7,200	Rectangular, 4 ft by 8 ft
9	2,250	8,100	Square, 6 ft side
10	2,500	9,000	Rectangular, 4 ft by 10 ft
12	3,000	10,800	Rectangular, 6 ft by 8 ft

This data is presented in Fig.26 together with contours showing the orifice areas required per bag. Bags would of course have to be made with sufficient strength to sustain the heaviest load, i.e. a fabric strength of about 220 lb/in.

The provision of an adjustable orifice area to an existing bag could well widen the range of loads it could carry and this could be assessed in much the same way by inspection of the data charts.

11 CONCLUSIONS

The theory given in this paper is idealised and because of this there may be discrepancies between it and the results of experimental trials. However, it is likely to be useful in showing the most important points and indicating the effect of changes in design. The only empirical part of the theory is the discharge coefficient C_D ($C_D = 0.9 - 0.3/P$), otherwise well known principles are used. There is reasonably good agreement with some earlier drop tests, but no experiments have yet been devised to check points arising from the theory. In parachute dropping there is rarely zero wind speed, and the sideways moving descent could modify the motion considerably (see Fig.2). For this reason a more elaborate theory may be of little extra value.

In choosing a good air bag, the peak retardation, ground impact speed and compression time should all be satisfactory. The bag height must not be too great compared with its width or the bag may collapse by buckling, and the fabric from which the bag is made must not be so thick that it cannot be folded. Variation of the descent speed for a given bag affects the peak retardation very markedly. Change of load is not very important but a heavy load receives a slightly heavier landing and a light load has a longer compression time. The use of a strong patch covering the orifice which bursts at up to 10 p.s.i. is found to cause little change in performance, even in peak retardation. At most about 10% of the height is saved. If a bag is made from an extensible fabric (i.e. the fabric is used near to its breaking strength) then both the orifice area and the bag height must be increased somewhat.

<u>The range of usefulness of air bags</u>

(1) <u>Descent speed</u>: The descent speed of the load is not likely to be less than about 15 ft/sec due to the weight of parachutes. It should also not be greater than 30 ft/sec because the ratio of ground impact speed to descent speed cannot always be made less than 0.3.

(2) <u>Bag loading</u>: Above about 350 lb/sq ft even the best bags are not very efficient as much of the energy is not dissipated but is transformed into potential energy of the bag air to cause violent bouncing. Also, unless a large number of grommets are used, the fabric strength must be so high that the bag will be too stiff to pack easily, although the use of unproofed fabric could ease this situation. At the light loadings, below 100 lb/sq ft, bags behave as if the air in them was incompressible and bags with a low peak retardation have a very low efficiency.

(3) <u>Peak retardation</u>: A range from 5g to 14g has been considered in this paper. Bags larger than 1.5 times their diameter are liable to buckle in use, and this sets a lower limit of about 5g on all but the widest bags (see Section 7.2). The upper limit of 14g is arbitrary, and values of this order are recommended for practical use, for a ground impact shock at about 8 ft/sec is likely to produce quite a high retardation peak on most soils, and the air bag peak retardation should be of the same order as this. Bags giving a high retardation must be very strong, and there is an

upper limit to the peak retardation, above which the fabric must be so strong that it is too stiff to pack. This limit depends on many factors but is likely to be less than 50g.

(4) Ground impact speed: This is unlikely to be much less then 30% of the descent speed and therefore unless special protection is provided, in the form of crushable material for example, an upper limit of about 10 ft/sec is expected.

(5) Wind drift: For the theory to be valid in wind drift conditions the wind speed should not be more than 6 ft/sec.

Within these limitations, and assuming no fabric extension data charts 1 to 6 give the parameters Q and R from which the orifice area and bag height may be found.

It may be possible to increase the efficiency of air bags by causing a sudden decrease in the orifice area part way through the stroke. Bags with a strong orifice patch and a variable orifice which prevents the pressure drop in the latter part of the stroke may also be practicable, and would further increase the efficiency.

ACKNOWLEDGEMENT

This research was initiated before the author was able to compile programmes for the DEUCE computer and he is indebted to Miss K. Mills of R.A.E. for the original integration part of the air bag programme.

LIST OF SYMBOLS

Symbol	Description	Units
a	orifice area	ft^2
B	bag base area	ft^2
c	ambient speed of sound	ft/sec
C_D	orifice discharge coefficient	-
d	orifice diameter	in.
D	bag diameter	ft
E_1	energy efficiency defined in 8.1	-

<u>LIST OF SYMBOLS</u> (Cont'd)

Symbol	Description	Units
E_2	energy efficiency defined in 8.2	-
F(H)	stress strain relation, $B/B_o = 1 + 2\ F(H)$	-
g	acceleration	ft sec^{-2}
h	bag height at any time	ft
H	hoop tension	lb $in.^{-1}$
k	extensibility constant	-
K	if Hookean fabric $F(H) = KH$	in. lb^{-1}
M	load mass	slug
N	peak retardation, number of g units	-
p	bag air pressure	lb ft^{-2}
P	bag air pressure ratio p/p_a	-
q	velocity of flow through the orifice	ft sec^{-1}
Q	orifice parameter $ac/Bu_o \sqrt{\gamma}$	-
r_o	unstrained bag radius	in.
R	bag height parameter $h_o\ g/u_o^2$	-
S	bag loading parameter $B\ p_a/Mg$	-
t	time from start of bag compression	sec
T	non-dimensional time $T = u_o\ t/h_o$	-
T_1	value of T at ground impact	-
u_o	steady descent speed	ft sec^{-1}
v	volume of air in bag	ft^3
W	work done by air in expansion (Appendix 4)	ft lb
y	bag height ratio h/h_o	-

LIST OF SYMBOLS (Cont'd)

Symbol	Description	Units
α	$\sqrt{\frac{2\gamma}{\gamma-1}\left(P^{1-\frac{1}{\gamma}}-1\right) C_D}$	-
$\bar{\alpha}$	$\alpha(1.894)\left(\frac{P}{1.894}\right)^{\frac{\gamma+1}{2\gamma}}$	-
β	$P^{\frac{1}{\gamma}}$	-
γ	ratio of the principal specific heats of air	-
ε	$\frac{1}{\gamma} P^{\frac{1}{\gamma}-1}$	-
μ	$2\, y_1(1+2.5\, P_1-3.5\, P_1{}^{5/7})$	-
ρ	bag air density	slug ft^{-3}
σ	ground impact velocity ratio u_1/u_o	-

Suffices

o	value at the commencement of bag compression
or	value at the bag orifice
1	value at ground impact
I	relates to "ideal" air bag
a	relates to ambient atmospheric conditions

LIST OF REFERENCES

No.	Author	Title, etc.
1	Powell, M.A.	Design of air bags for reducing landing shock of parachuted loads. Unpublished M.O.A. Report.
2	Harwood, K. Stevens, G.W.H.	Further developments of air bags as landing shock absorbers. Unpublished.M.O.A. Report.
3	Turnbow, J.W. Ogletree, W.B.	The energy dissipating characteristics of air bags. University of Texas, Structural Mechanics Research Laboratory. Contract DA 19-129-QM-1383 O.I. No.9118 (Aug. 1959).
4	Tomcsak. L.	Decelerator bag study. WADC TR 59-775 (P 96677) (June 1960).
5	Ower, E.	Measurement of air flow (1st edition) Chapman & Hall (1927).
6	Browning, A.C.	A comparison between an exact theory of an air bag shock absorber and some approximate design methods. Unpublished M.O.A. Report.

APPENDIX 1

DERIVATION OF THE AIR BAG EQUATIONS

The air bag is assumed at all times to be cylindrical, have a height h, cross-sectional area B, an orifice area a, and the air inside it to be of pressure p, and density ρ. The areas a and B are constant.

THE ORIFICE FLOW EQUATION

Taking the discharge coefficient for the orifice to be C_D and equating the loss of air from the bag with the orifice flow

$$\rho_{or}\, a\, q\, C_D = -\frac{d}{dt}(\rho\, h\, B) \qquad (4)$$

where ρ_{or} is the air density at the orifice and q is the speed of flow there.

The bag compression usually takes about 1/5 sec to occur and this is sufficiently rapid for negligible heat transfer from the air. The adiabatic relation then holds:

$$\rho = \rho_a \left(\frac{p}{p_a}\right)^{\frac{1}{\gamma}} = \rho_a \; P^{\frac{1}{\gamma}} \qquad (5)$$

where p_a is the initial (atmospheric) pressure and $P = p/p_a$.

The orifice flow equation can now be written

$$\frac{dP}{dt} = -\frac{\left(\frac{\rho_{or}}{\rho_a}\frac{a}{B}\, q\, C_D + P^{\frac{1}{\gamma}}\frac{dh}{dt}\right)}{\frac{h}{\gamma}\, P^{\frac{1}{\gamma}-1}} \; . \qquad (6)$$

At the orifice the airspeed q may be subsonic or sonic, but because there is no diverging nozzle it cannot be supersonic. The orifice flow is thus divided into one of two possible regimes, and as choking occurs with sonic flow the regimes must be considered separately.

Bernoulli's equation for steady streamline airflow is

$$\frac{\gamma}{\gamma - 1}\, p + \tfrac{1}{2}\rho\, q^2 = \text{constant}$$

and if the air in the bag is considered to be at rest except for the air actually passing through the orifice, and the flow quasi steady, then

$$\frac{\gamma}{\gamma - 1}\,\frac{p}{\rho} = \frac{\gamma}{\gamma - 1}\,\frac{p_{or}}{\rho_{or}} + \tfrac{1}{2}\,q^2 \quad .$$

With an unchoked orifice the pressure at the orifice can be taken to be equal to the atmospheric pressure p_a, therefore

$$q^2 = \frac{2\gamma}{\gamma - 1}\left(\frac{p}{\rho} - \frac{p_a}{\rho_{or}}\right) \quad .$$

Also the adiabatic relation (5), with $p_{or} = p_a$ gives

$$\rho_{or} = \rho_a$$

and therefore

$$q^2 = \frac{2\gamma}{\gamma - 1}\,\frac{p_a}{\rho_a}\left(P^{1 - \frac{1}{\gamma}} - 1\right)$$

$$= \frac{2\gamma}{\gamma - 1}\,\frac{c^2}{\gamma}\left(P^{1 - \frac{1}{\gamma}} - 1\right) \quad . \qquad (7)$$

The orifice flow equation now becomes,

$$\frac{dP}{dt} = -\,\frac{\dfrac{a\,C_D}{B}\sqrt{\dfrac{2\gamma}{\gamma - 1}\,\dfrac{c^2}{\gamma}\left(P^{1 - \frac{1}{\gamma}} - 1\right)} + P^{\frac{1}{\gamma}}\,\dfrac{dh}{dt}}{\dfrac{h}{\gamma}\,P^{\frac{1}{\gamma} - 1}}$$

or following Powell and introducing three non-dimensional functions of P

$$\left.\begin{aligned} \alpha &= \sqrt{\frac{2\gamma}{\gamma - 1}\left(P^{1 - \frac{1}{\gamma}} - 1\right)}\;C_D \\ \beta &= P^{\frac{1}{\gamma}} \\ \varepsilon &= \frac{1}{\gamma}\,P^{\frac{1}{\gamma} - 1} \quad . \end{aligned}\right\} \qquad (8)$$

(It is assumed that C_D is a known function of P, in this paper taken to be equal to 0.9 - 0.3/P (Ref.5).)

The equation of orifice flow is then

$$\frac{dP}{dt} = -\frac{\left(\frac{a}{B}\frac{c}{\sqrt{\gamma}}\,\alpha + \beta\,\frac{dh}{dt}\right)}{h\,\varepsilon} \quad . \tag{9}$$

With a choked orifice q is always equal to c and the pressure at the orifice is greater than atmospheric, the ratio of bag pressure to orifice pressure being fixed at 1.894 (see equation (7), $\gamma = 1.4$). The flow expands to supersonic speed outside the bag but soon breaks down to subsonic speed by shock waves.

The adiabatic flow equation (5) now gives

$$\rho_{or} = \rho_a \left(\frac{p_{or}}{p_a}\right)^{\frac{1}{\gamma}} = \rho_a \left(\frac{P}{1.894}\right)^{\frac{1}{\gamma}}$$

and the expression for the orifice speed q is

$$q^2 = \frac{2\gamma}{\gamma - 1}\,\frac{p_a}{\rho_a}\left(P^{1-\frac{1}{\gamma}} - \left(\frac{P}{1.894}\right)^{1-\frac{1}{\gamma}}\right)$$

or

$$q^2 = \frac{2\gamma}{\gamma - 1}\,\frac{p_a}{\rho_a}\left(1.894^{1-\frac{1}{\gamma}} - 1\right)\left(\frac{P}{1.894}\right)^{1-\frac{1}{\gamma}} \quad .$$

The orifice flow equation in this case is

$$\frac{dP}{dt} = -\frac{\left(\frac{a\,c}{B\sqrt{\gamma}}\,\bar{\alpha} + \beta\,\frac{dh}{dt}\right)}{h\,\varepsilon}$$

which is the same as the unchoked equation except that α is replaced by $\bar{\alpha}$ where

$$\bar{\alpha}(P) = \alpha(1.894) \times \left(\frac{P}{1.894}\right)^{\frac{\gamma+1}{2\gamma}} \quad . \tag{10}$$

The equation is rendered non-dimensional by the substitutions

$$\begin{cases} \dfrac{h}{h_o} = y & \text{non-dimensional bag height} \\[2ex] \dfrac{u_o\,t}{h_o} = T & \text{non-dimensional time} \end{cases}$$

yielding

$$\frac{dP}{dT} = -\frac{\left(\alpha\, Q + \beta\, \frac{dy}{dT}\right)}{\varepsilon\, y} \qquad (1)$$

where Q is a non-dimensional number termed the orifice parameter, defined by

$$Q = \frac{a\, c}{Bu_o \sqrt{\gamma}}$$

which, for standard atmosphere conditions becomes, when u_o is measured in ft per sec and a and B in the same units

$$Q = 943.6 \frac{a}{Bu_o} \quad .$$

THE EQUATION OF MOTION OF THE LOAD

The air bag orifice is usually in the top of the bag and if the escaping air is deflected horizontally it gains no vertical momentum. The total upward force on the bag top and deflector, is therefore equal to the force on the base, $(P-1)p_a$ B. The equation of motion of the load is thus, neglecting parachute lift, (which would give at most an error of 1g in the retardation)

$$M \frac{d^2h}{dt^2} = -Mg + (P-1)p_a B \quad .$$

This equation, when rendered non-dimensional by the substitutions given above, is

$$\frac{d^2y}{dT^2} = R(-1 + S(P-1)) \qquad (2)$$

where R and S are two non-dimensional numbers,

$$R = \frac{h_o\, g}{u_o^2}$$ termed the bag height parameter

$$S = \frac{B\, p_a}{Mg}$$ termed the bag loading parameter.

Standard values for g and p_a of 32.2 and 2116.8 have been used in all the numerical examples.

The two differential equations (1) and (2) above define the motion and from them the pressure ratio P and the bag height ratio y can be found in terms of the non-dimensional time T. When the pressure ratio P reaches the value 1.894 the function α must be replaced by $\bar{\alpha}$ to give the effect of orifice choking.

It should be noted that at any time the load velocity is

$$-\frac{dh}{dt} = -\frac{d(h_o y)}{\frac{h_o}{u_o} dT} = -u_o \frac{dy}{dT}$$

and the retardation is

$$\frac{d^2h}{dt^2} = \frac{u_o^2}{h_o} \times \frac{d^2y}{dT^2} .$$

APPENDIX 2

CONSTRUCTION OF THE DATA CHARTS

Each data chart incorporates the results of about one hundred integration runs, with the same bag loading parameter S.

About 15 integrations were made for one value of R and various values of the orifice parameter Q, the three main results N, T_1 and σ being noted. An example of such a set of results is given in Fig.10 (for S = 10 and R = 0.1288). The arbitrary "limits of interest" of N = 14, T_1 = 3 on one side and N = 5, σ = 0.5 on the other are included in the graph and the range of useful bags is clearly shown. For small orifice parameters the load bounces one or more times on the bag and for large orifice parameters the bag has almost no retarding effect. From this graph the values of Q where N = 5, 6, 8, 10, 12, 14; T_1 = 2 and 3, σ = 0.2, 0.3, 0.4 and 0.5 were read off. This was done for several (about 6) values of the bag height parameter R and all these points were marked on the data chart to give contours of N, T_1 and σ. The points read off Fig.10 appear on the data chart of Fig.6 and are marked with crosses.

Useful bags lie in a region of the chart, roughly diamond shaped, bounded by the limits N = 14 and 5, T_1 = 3 and σ = 0.5.

APPENDIX 3

MORE GENERAL THEORY

Two modifications have been made to the simple mathematical model of Part I of this paper. They are

(1) the inclusion of a strong bursting patch covering the orifice to conserve air at the start of the compression

(2) the use of extensible fabric in the construction of the bag.

STRONG ORIFICE PATCHES

A strong bursting patch covering the orifice is simulated by setting the orifice area at zero ($Q = 0$) until a certain pressure is reached, and then giving it the desired value. The differential equations are unchanged and it is only in the step-by-step solution that any change arises. The DEUCE programme is easily modified to do this, but there is a small error because the orifice must be opened at one of the steps of integration and the bag pressure at that step may be slightly above the desired bursting pressure. This error could have been avoided by an interpolation but it was not large enough to warrant this.

EXTENSIBLE FABRIC

With the heavy loads now being parachuted the bag fabric stresses must be near to the breaking point because bag failures are frequent. The effect of fabric extension should not therefore be neglected.

If the bag fabric stretches it will do so in the direction of the tension in it. For a bag supported by several wire grommets (see Fig.1) the fabric tension, and hence the extension, is in the hoopwise direction, and will be zero at the grommets and a maximum between them. To study the effect of fabric extension the assumption is made that the bag extends its diameter by an average amount, still retaining its cylindrical shape. Thus if the hoop tension is H lb/in and the bag radius r_o in. the hoop tension is given by

$$14.7\,(P-1) = \frac{H}{r_o} .$$

If the bag radius is increased by a small amount δr and the stress/strain relation is

$$\frac{\delta r}{r_o} = F(H)$$

then the change in base area is given by

$$\frac{B}{B_o} = \frac{(r_o + \delta r)^2}{r_o^2} = 1 + \frac{2\delta r}{r_o} \text{ to the first order}$$

i.e.

$$\frac{B}{B_o} = 1 + 2F(H) \quad .$$

If the fabric obeys Hooke's law,

$$F(H) = KH$$

where K is a small constant. Thus

$$\frac{B}{B_o} = 1 + 29.4\ K(r_o + \delta r)(P - 1) \quad .$$

Expanding this, the term involving the product of K and δr is second order, leading to the approximate formula

$$\frac{B}{B_o} = 1 + k(P - 1) \qquad (11)$$

where k is a constant (equal to $29.4\ r_o\ K$).

In order to choose a realistic value for k we note that if P = 2 (two atmospheres inside the bag and one outside) the base area is increased to $B_o(1 + k)$. The value of k taken in the numerical calculations is 0.25, representing about 12% fabric strain at this pressure difference.

Inserting the variable base area into the orifice flow equation, (equation (4)),

$$\rho_{or}\ a\,q\,C_D = - B_o(1 + k(P - 1))\ \frac{d}{dt}\ (\rho h) - \rho h\ \frac{d}{dt}\ (B_o(1 + k(P - 1)))$$

which leads to

$$\frac{dP}{dT} = - \frac{\left(\alpha\ Q + (1 + k(P - 1))\ \beta\ \frac{dy}{dT}\right)}{[(1 + k(P - 1))\ \varepsilon + \beta k]y} \quad . \qquad (1e)$$

The equation of load motion must also use the variable base area, and this leads to

$$\frac{d^2y}{dT^2} = R[-1 + (1 + k(P - 1))(P - 1)S] \quad . \qquad (2e)$$

More generally, if the stress/strain relation is not Hookean, then the base area can be written

$$B = g(P)\, B_o$$

and the pair of equations is

$$\frac{dP}{dT} = - \frac{\left(\alpha\ Q + g(P)\ \beta \frac{dy}{dT}\right)}{[g(P)\ \varepsilon + \beta\ g'(P)]y} \qquad (1g)$$

$$\frac{d^2y}{dT^2} = R[-1 + g(P)\ (P-1)S] \quad . \qquad (2g)$$

APPENDIX 4

THE RESIDUAL GAS ENERGY IN THE FULLY COMPRESSED BAG

At worst, all the excess internal energy in the air left in the bag when fully compressed (i.e. as fully as the bag can be compressed) is available to cause a heavy second impact, by throwing the load up. This energy is estimated below.

If the volume of air is v_1 and the pressure p_1, then during the adiabatic expansion when the load is being thrown upward

$$Pv^{\gamma} = P_1 v_1^{\gamma}$$

or

$$v = P_1^{\frac{1}{\gamma}} v_1 P^{-\frac{1}{\gamma}}$$

and

$$dv = -\frac{P_1^{\frac{1}{\gamma}} v_1 P^{-1-\frac{1}{\gamma}}}{\gamma} dP \quad .$$

The work done in expansion to atmospheric pressure P = 1 is

$$W = p_a \int_{v_1}^{v} (P-1)\, dv$$

$$= p_a \frac{P_1^{\frac{1}{\gamma}} v_1}{\gamma} \int_{1}^{P_1} \left(P^{-\frac{1}{\gamma}} - P^{-1-\frac{1}{\gamma}}\right) dP$$

which, for $\gamma = 1.4$ becomes

$$W = p_a v_1 [1 + 2.5 P_1 - 3.5 P_1^{5/7}] \quad .$$

The volume v_1 is equal to B h_o y_1, thus

$$\frac{\text{Gas energy}}{\text{Descent energy}} = \frac{B\, h_o\, y_1\, p_a}{\frac{1}{2} M u_o^2} \left[1 + 2.5\, P_1 - 3.5\, P_1^{5/7} \right]$$

or

$$\frac{\text{Gas energy}}{\text{Descent energy}} = R\, S\, \mu \tag{12}$$

where

$$\mu = 2 y_1 \left[1 + 2.5\, P_1 - 3.5\, P_1^{5/7} \right] .$$

If $R\,S\,\mu$ is less than σ^2 then the second ground impact is certain to be less violent than the first. Unfortunately this aspect was not appreciated until the majority of the DEUCE integrations had been done, and it could not be included in the programme. However, if the peak pressure is high then it must occur late in the stroke and inspection of some of the solutions in detail shows that it occurs actually at the ground impact. Thus

$$P_1 = 1 + \frac{N + 1}{S}$$

and in all cases P_1 cannot exceed this value.

Using this value for the air pressure at ground impact, then for the gas energy to be less than 30% of the initial descent energy we must have

$$R\, S\, \mu(P) < 0.3$$

or

$$R\, S\, \mu(S,N) < 0.3 \quad . \tag{13}$$

This last formula is graphed in Fig.21. Given the bag loading and peak retardation, a glance will show whether a bag of any height parameter has at the first impact more than 30% of the descent energy remaining as potential energy of the residual air.

TABLE 1

Tests at R.A.E. (Ref.2)

Bag height $38\frac{1}{2}$ in. diameter 34 in. two circular orifices												
				Experimental results						Theoretical results		
Drop	Load (lb)	Orifice dia	u_o	N	σ	Bounce?	Q	R	S	N	σ	T_1
1	600	$4\frac{1}{2}$ in.	24 ft/sec	-	-	Yes	1.38	0.179	22.2	7.53	0.233	2.10
2	750	"	24	-	-	Yes	1.38	0.179	17.8	6.61	0.261	1.67
3	900	"	23.4	5.21	0.23	-	1.41	0.189	14.8	5.64	0.308	1.40
4	900	"	23.4	4.8	0.21	-	1.41	0.189	14.8	5.64	0.308	1.40
5	900	"	23.5	5.86	0.21	-	1.41	0.187	14.8	5.71	0.305	1.42
6	1000	"	26	6	-	Yes	1.27	0.153	13.3	5.66	0.303	1.30
≠ 7	1000	"	23	-	-	Yes	1.43	0.195	13.3	5.14	0.341	1.30
* 8	1000	$5\frac{1}{2}$ in.	24	-	-	Yes	2.06	0.179	13.3	2.94	0.663	0.97
* 9	1000	6 in.	24	-	-	Yes	2.45	0.179	13.3	1.99	0.778	0.92
10	1000	$4\frac{1}{4}$ in.	21	3.6	0.21	No	1.41	0.234	13.3	4.88	0.302	1.50
11	1000	"	24	5.1	-	No	1.23	0.179	13.3	6.46	0.252	1.55
12	1000	"	25	6.25	0.16	No	1.18	0.165	13.3	7.02	0.238	1.55
13	900	$4\frac{1}{2}$ in.	24	5.9	-	-	1.38	0.179	14.8	5.96	0.298	1.42
14	1000	"	24	5.8	-	-	1.38	0.179	13.3	5.61	0.328	1.30
15	1000	"	24	5.0	0.24	-	1.38	0.179	13.3	5.61	0.328	1.30
16	1200	"	24	4.2	0.33	-	1.38	0.179	11.1	5.07	0.395	1.15
17	1500	"	22	3.14	0.39	-	1.50	0.213	8.9	3.65	0.521	1.03
Fig.4	900	"	23	5.21	0.23	No	1.43	0.195	14.8	5.47	0.311	1.42

≠ see also Fig.7 of Ref.2

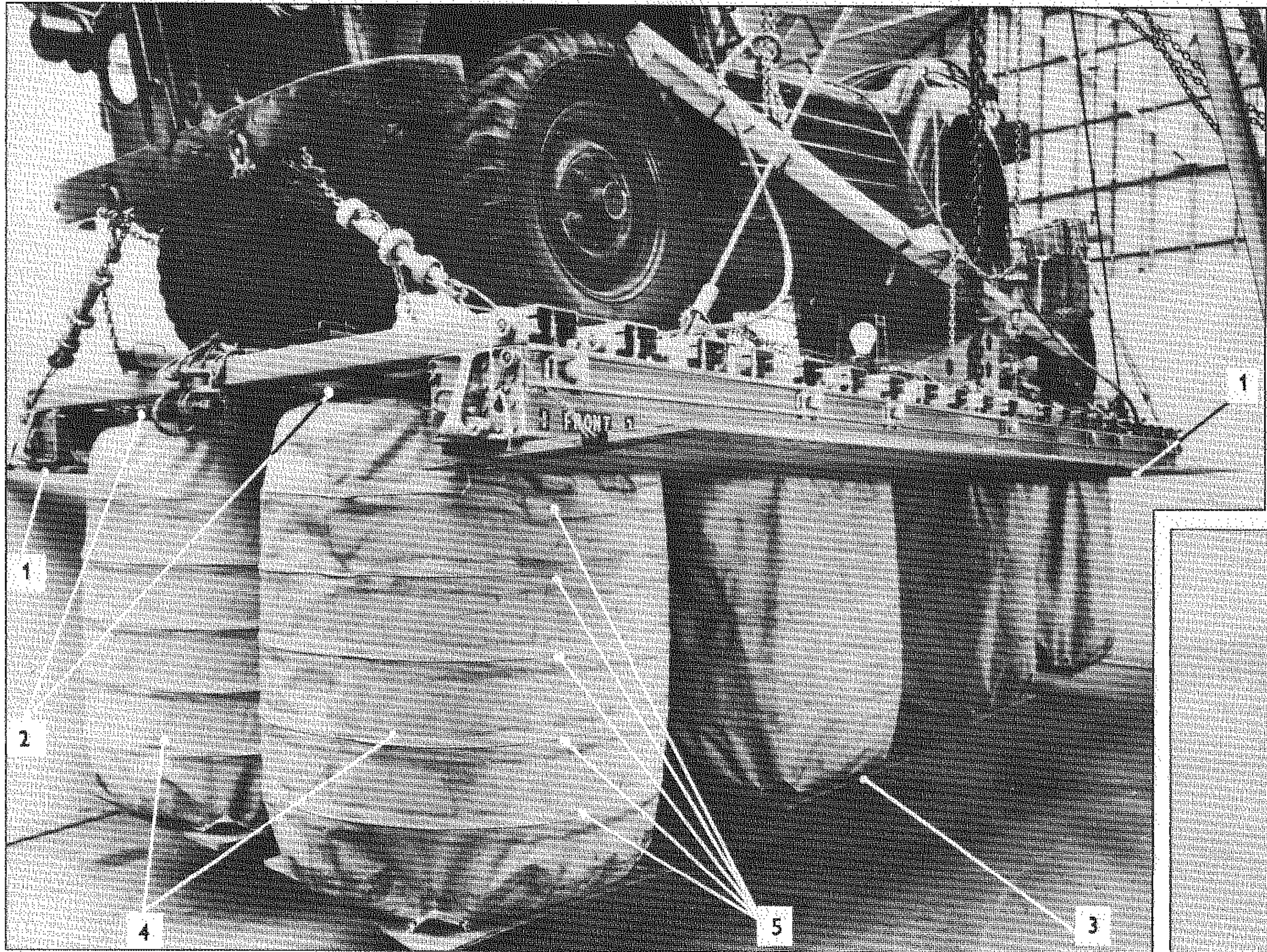
* orifice obscured

TABLE 2

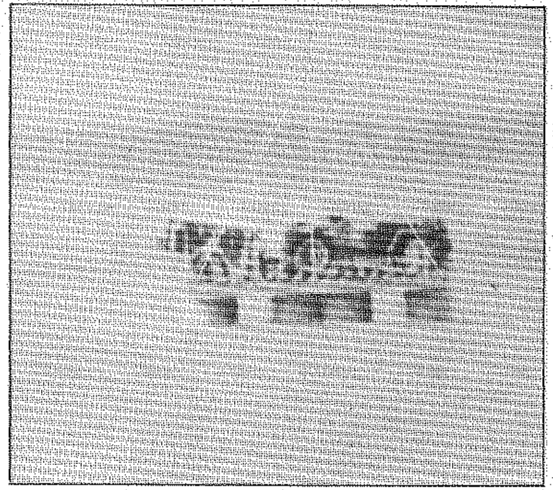
Tests in U.S.A. (Ref.3)

British bag, height 54 in. diameter 37 in. four orifices each $3\frac{1}{4}$ in. diameter											
Drop	Load (lb)	u_o	Experimental results			Q	R	S	Theoretical results		
			N	σ	T_1				N	σ	T_1
1	658	21 ft/sec	5.6	0.17	1.05	1.40	0.329	24.0	6.02	0.238	2.84
2	1087	21	5.3	0.47	0.8	1.40	0.329	14.5	4.48	0.291	1.96
3	1087	24	5.8	0.34	1.2	1.22	0.251	14.5	5.80	0.241	2.16
4	1364	21	3.0	0.45	1.25	1.40	0.329	11.6	3.93	0.312	1.63
5	1364	24	4.1	0.35	1.2	1.22	0.251	11.6	5.17	0.260	1.75
6	1527	21	3.1	0.44	1.2	1.40	0.329	10.4	3.69	0.325	1.48
7	1527	24	10.8	0.45	1.0	1.22	0.251	10.4	4.90	0.268	1.57
8	1652	21	12.3	0.37	0.95	1.40	0.329	9.6	3.54	0.337	1.39

Printed in England for Her Majesty's Stationery Office by the Royal Aircraft Establishment, Farnborough. W.T.60.K.4.



¾ SIDE VIEW OF PLATFORM SHOWING BAGS AND SKID DOORS EXTENDED



GENERAL VIEW OF PLATFORM AND STORE JUST AFTER TOUCHDOWN WITH AIR BAGS PARTIALLY COMPRESSED

KEY:-

1. SKID DOORS IN EXTENDED POSITION AS FOR LANDING
2. UPPER MATTRESS BOARDS
3. BOTTOM MATTRESS BOARDS SHOWING TIES SECURING AIR BAGS
4. CYLINDRICAL AIR BAGS IN EXTENDED POSITION BUT ONLY PARTIALLY INFLATED
5. WIRE GROMMETS

FIG.1. PRACTICAL AIR BAG SHOCK ABSORBER

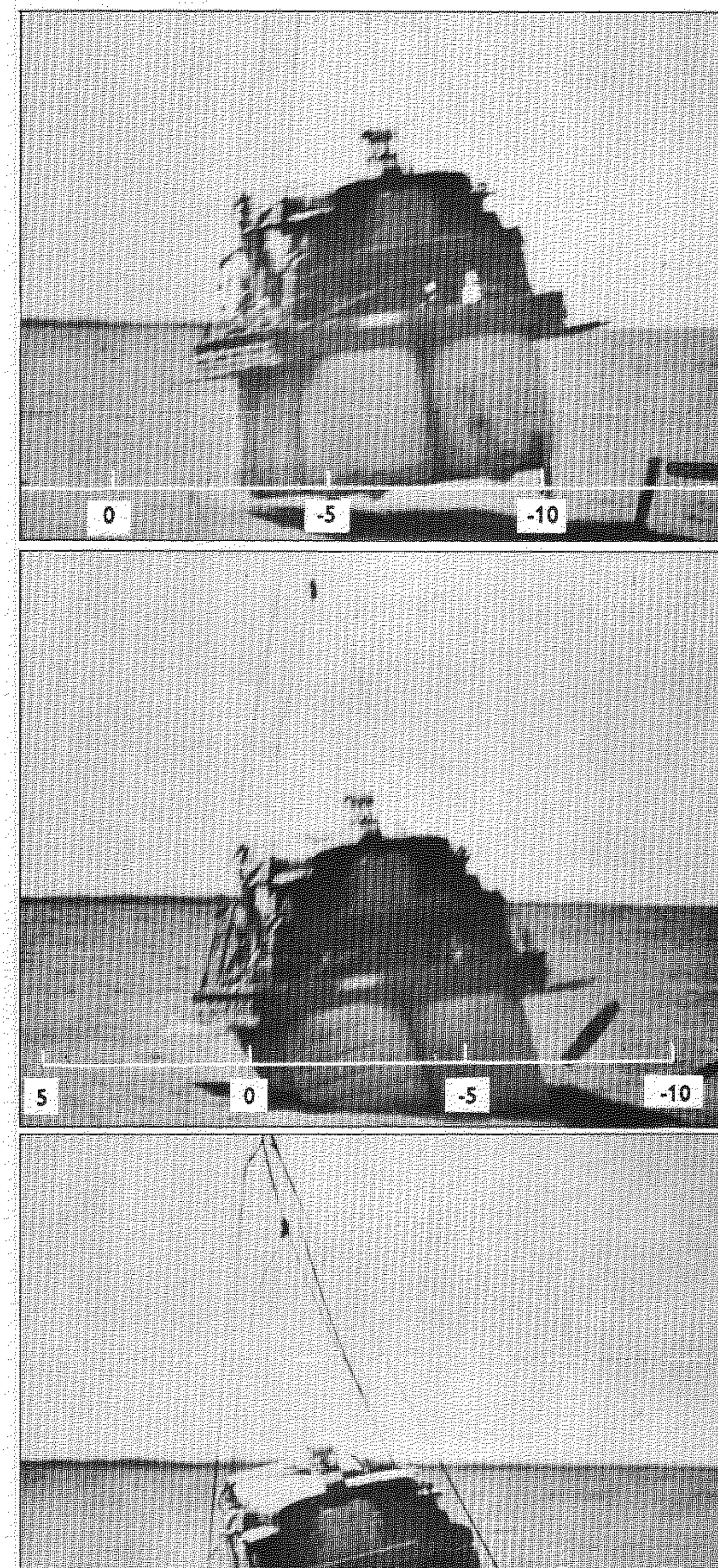


FIG.2. AIR BAG OPERATION IN CONSIDERABLE WIND DRIFT

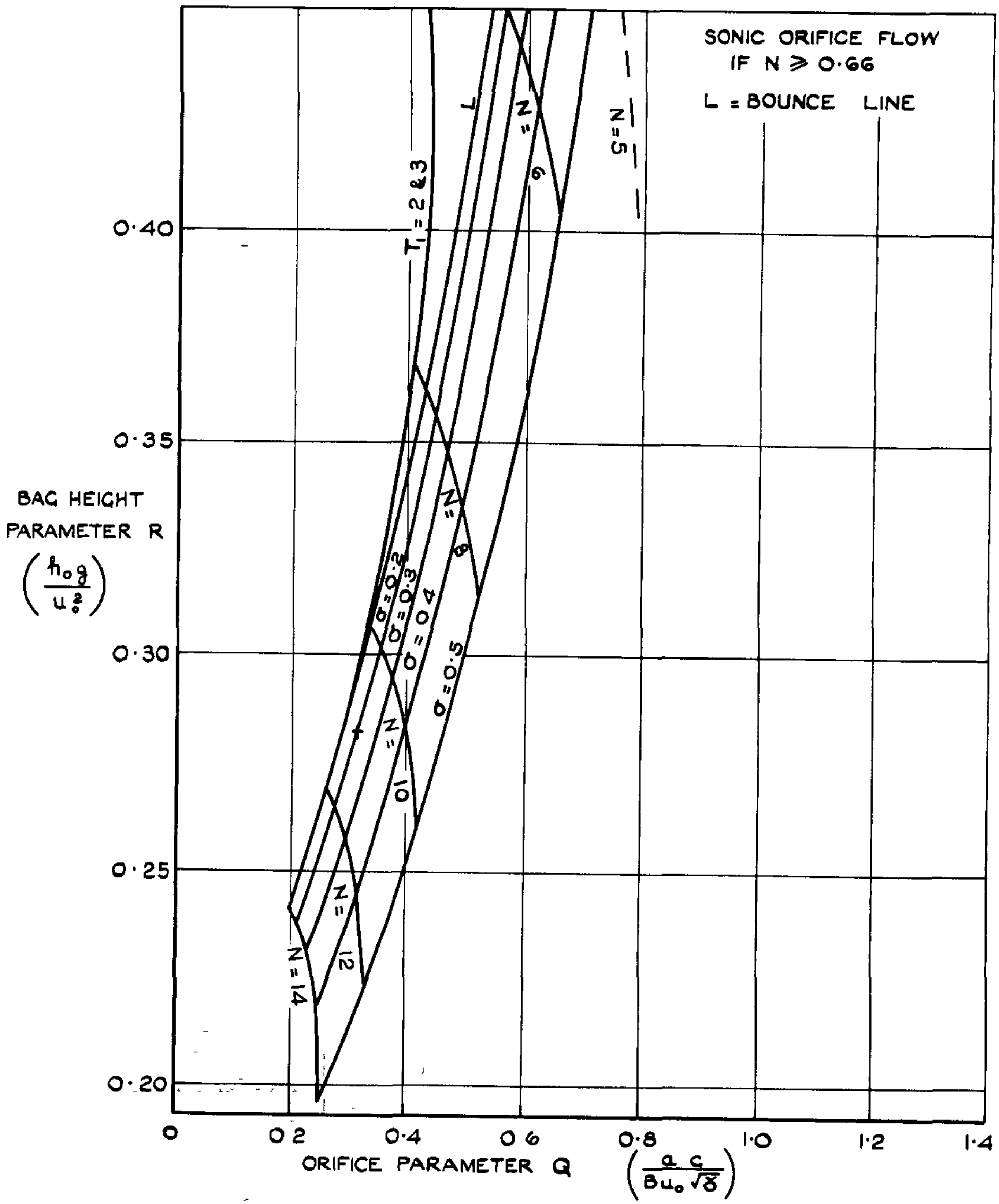


FIG. 3. DATA CHART No. 1.
INEXTENSIBLE BAG S = 1·86

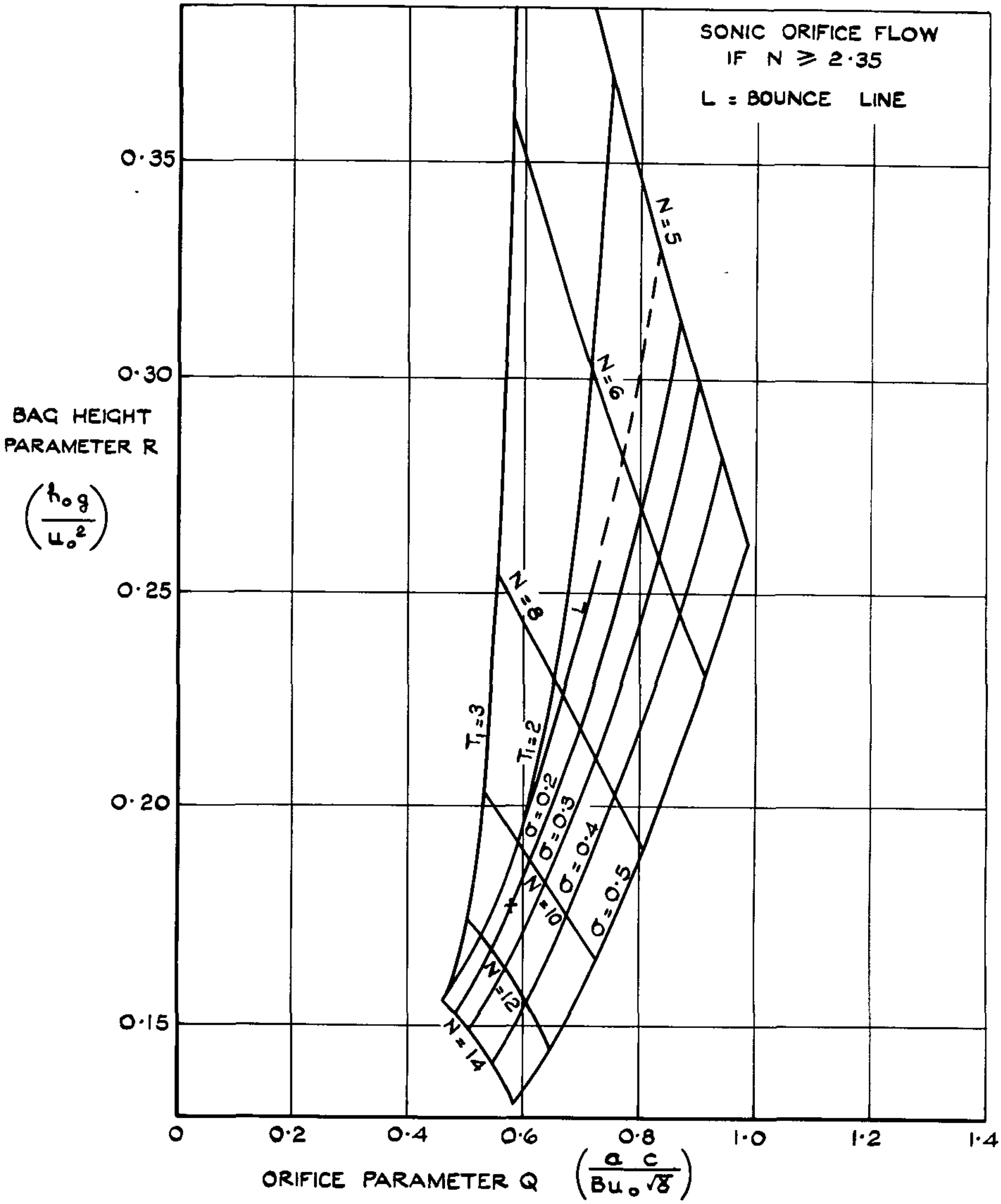


FIG. 4. DATA CHART No. 2
INEXTENSIBLE BAG S = 3·75

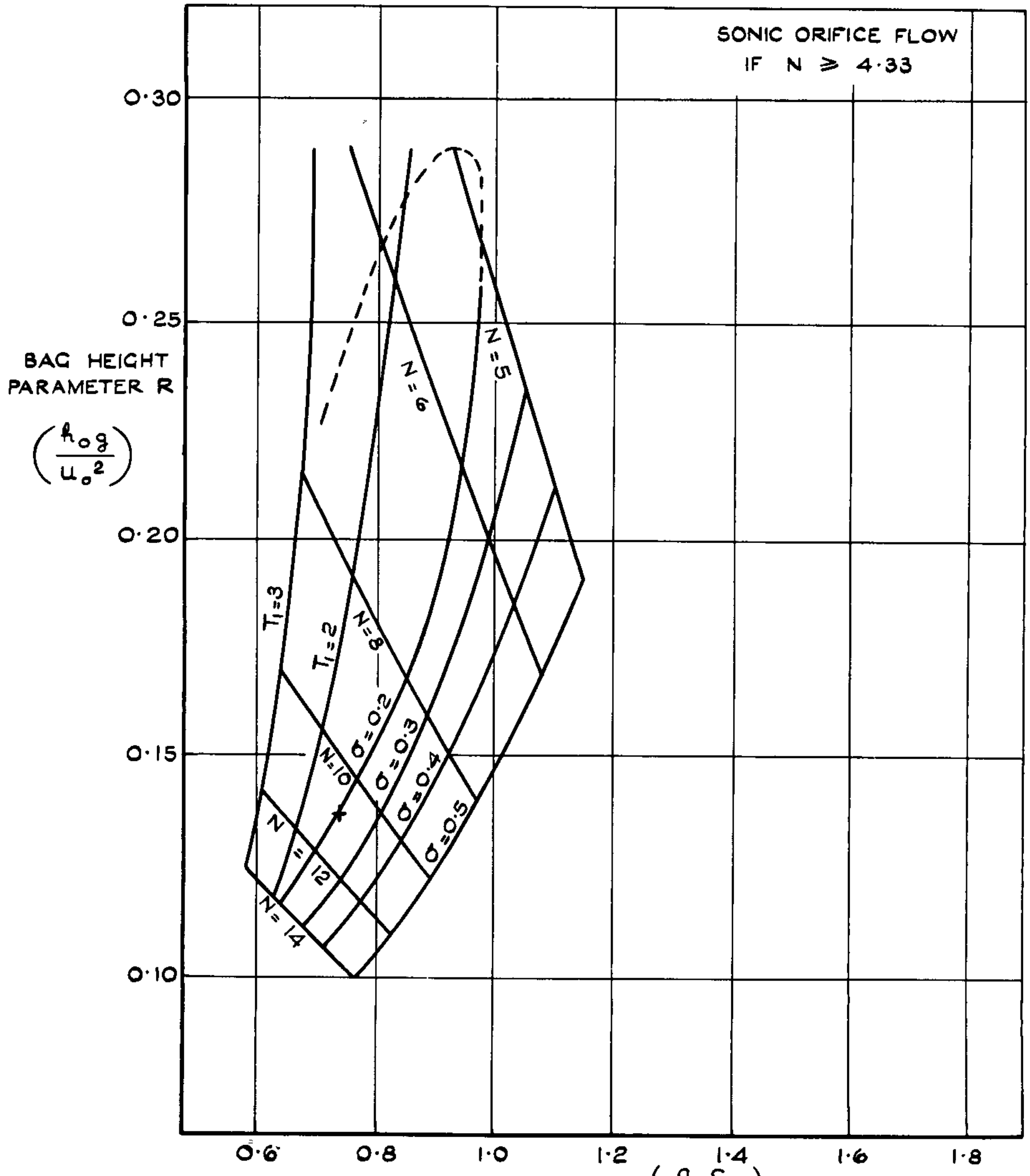


FIG. 5. DATA CHART No. 3
INEXTENSIBLE BAG S = 6

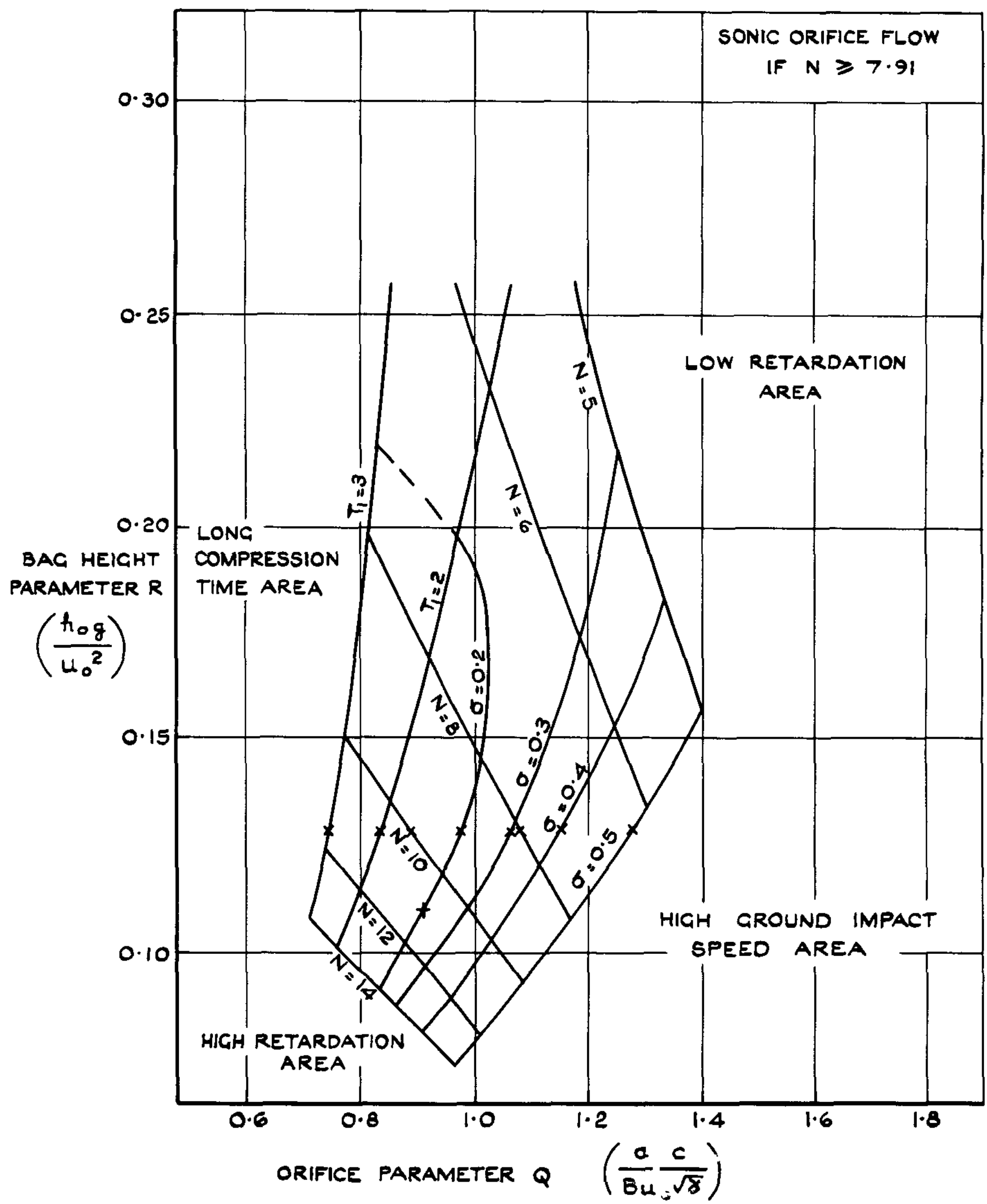


FIG. 6. DATA CHART No. 4
INEXTENSIBLE BAG S = 10

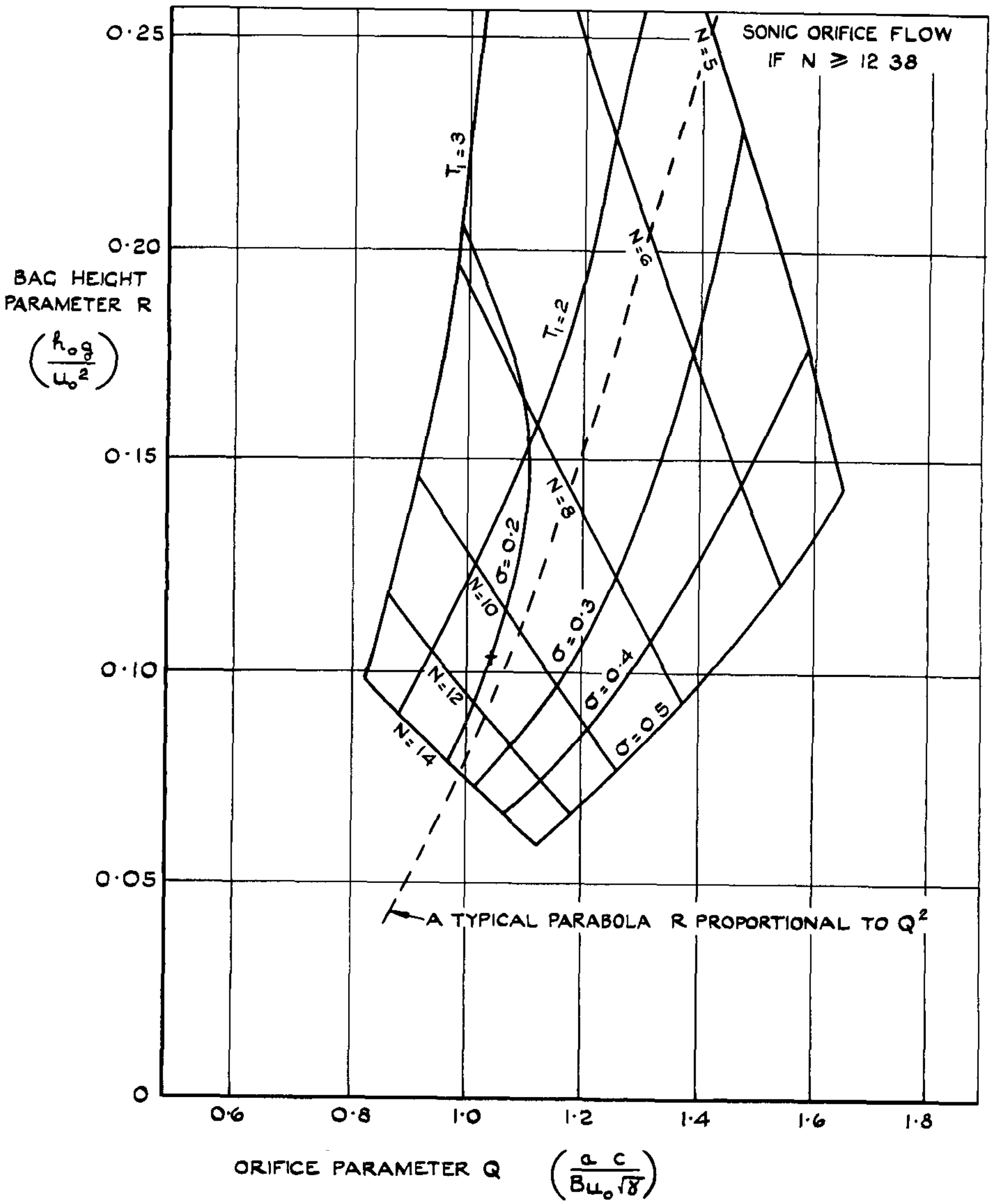


FIG. 7. DATA CHART No. 5.
INEXTENSIBLE BAG S = 15

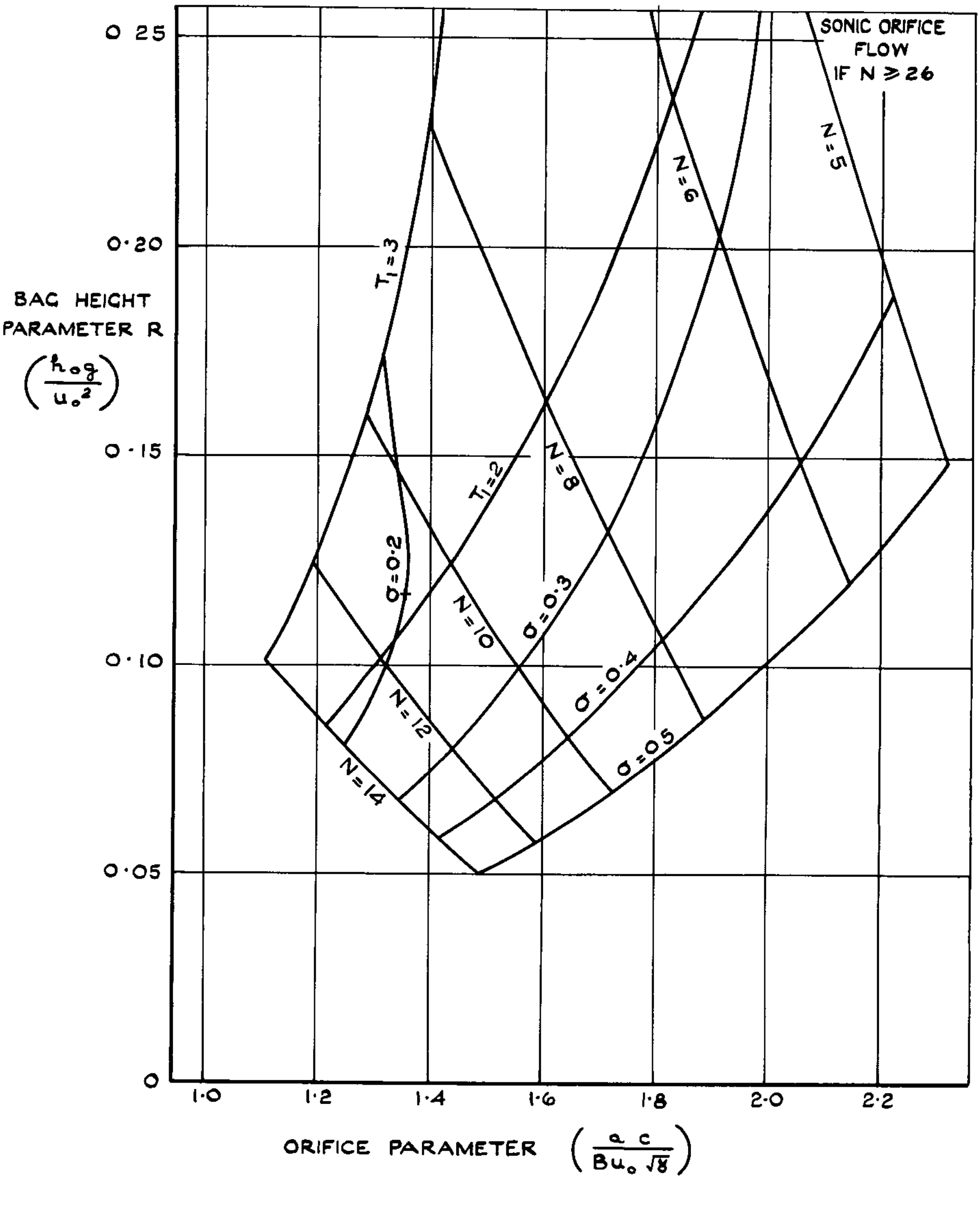


FIG. 8. DATA CHART No. 6.
INEXTENSIBLE BAG S = 30

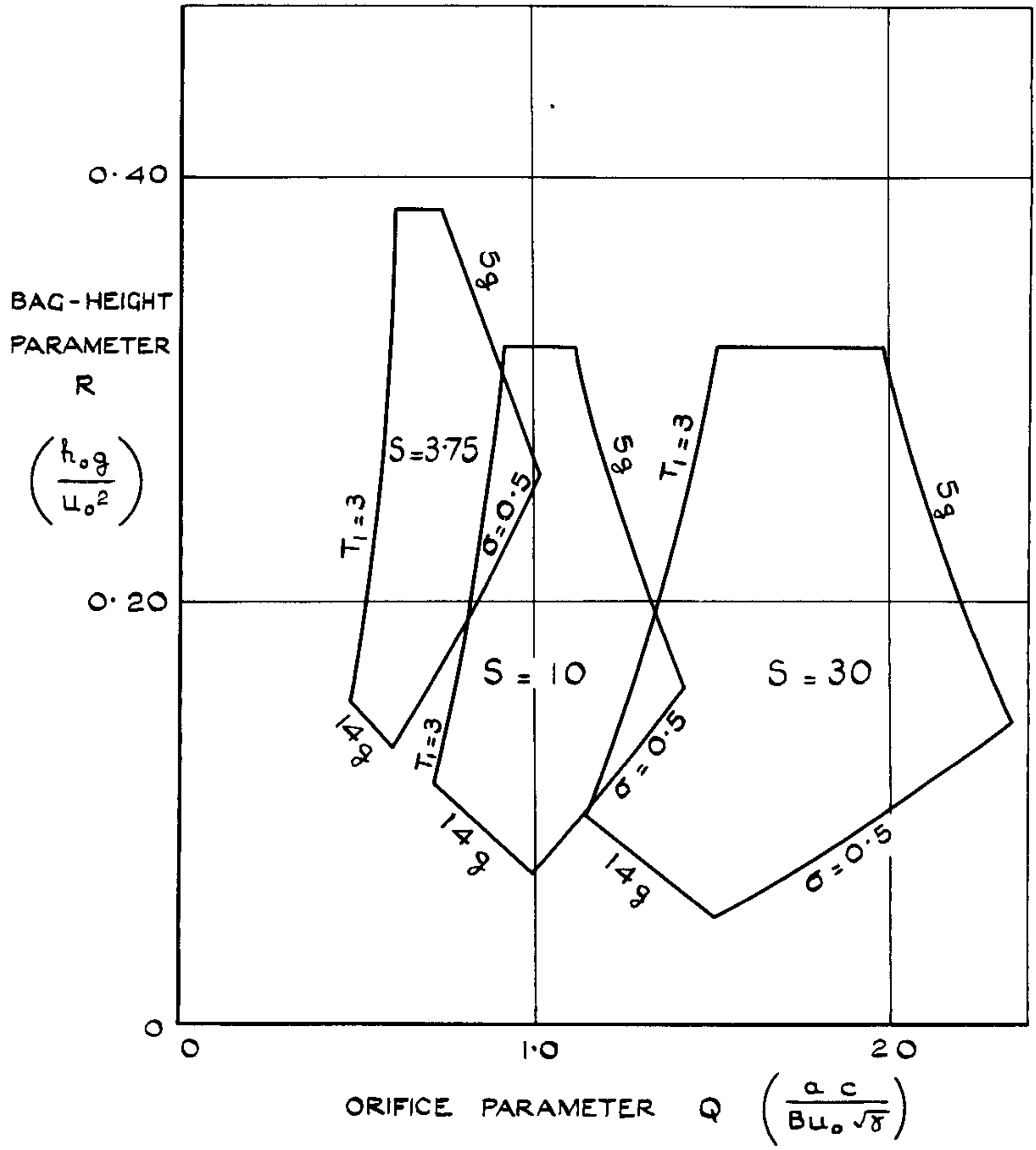


FIG. 9. VARIATION OF LOADING ON AN INEXTENSIBLE BAG

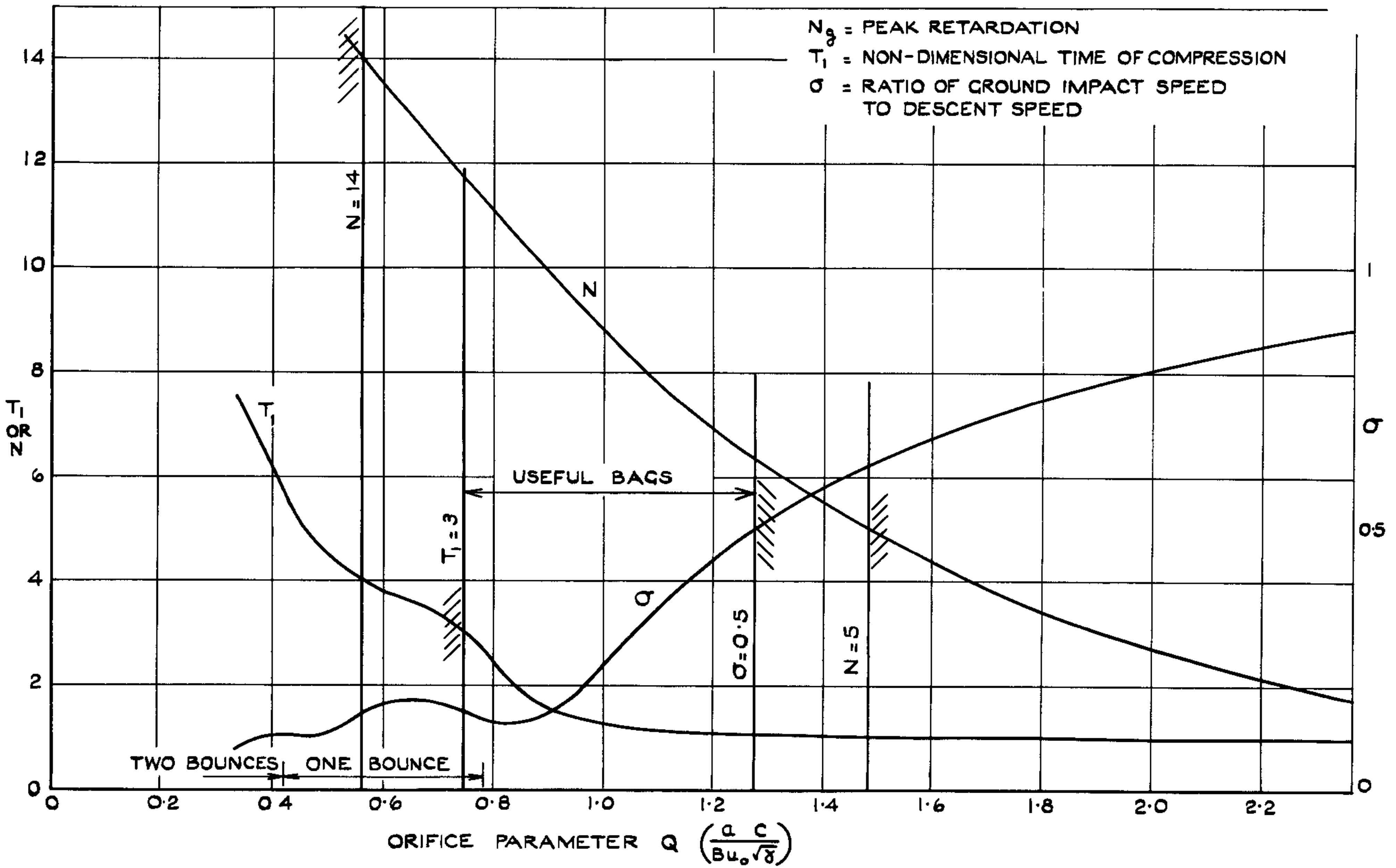
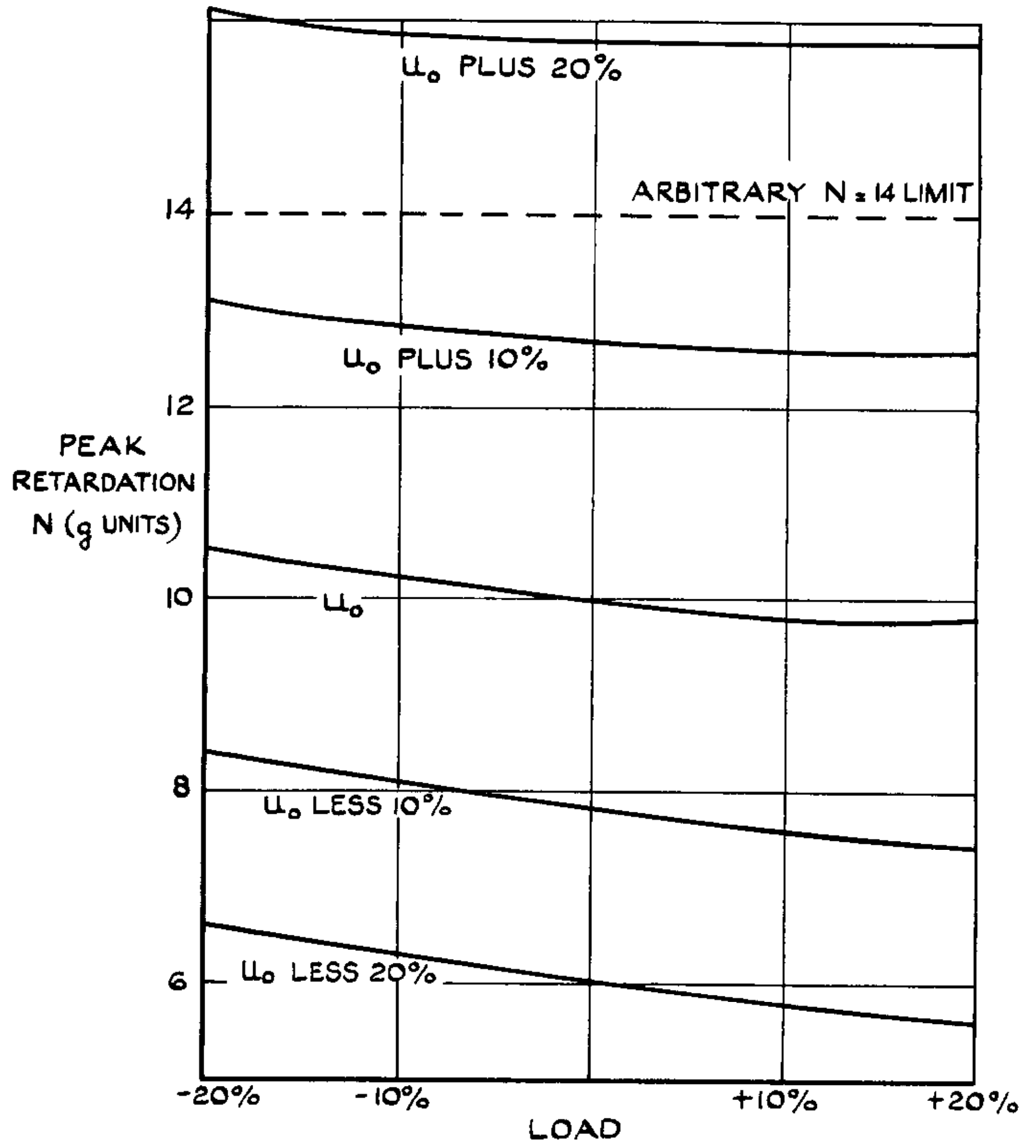
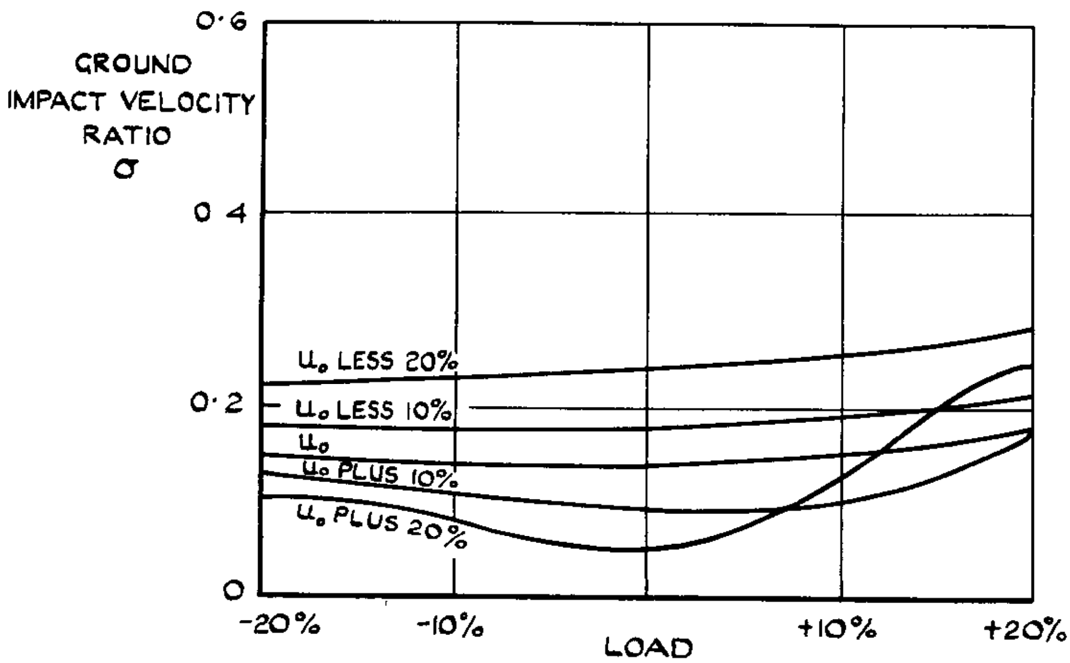


FIG. 10. VARIATION OF THE ORIFICE PARAMETER ONLY. R = 0·1288 S = 10
(MEDIUM PLATFORM BAG)

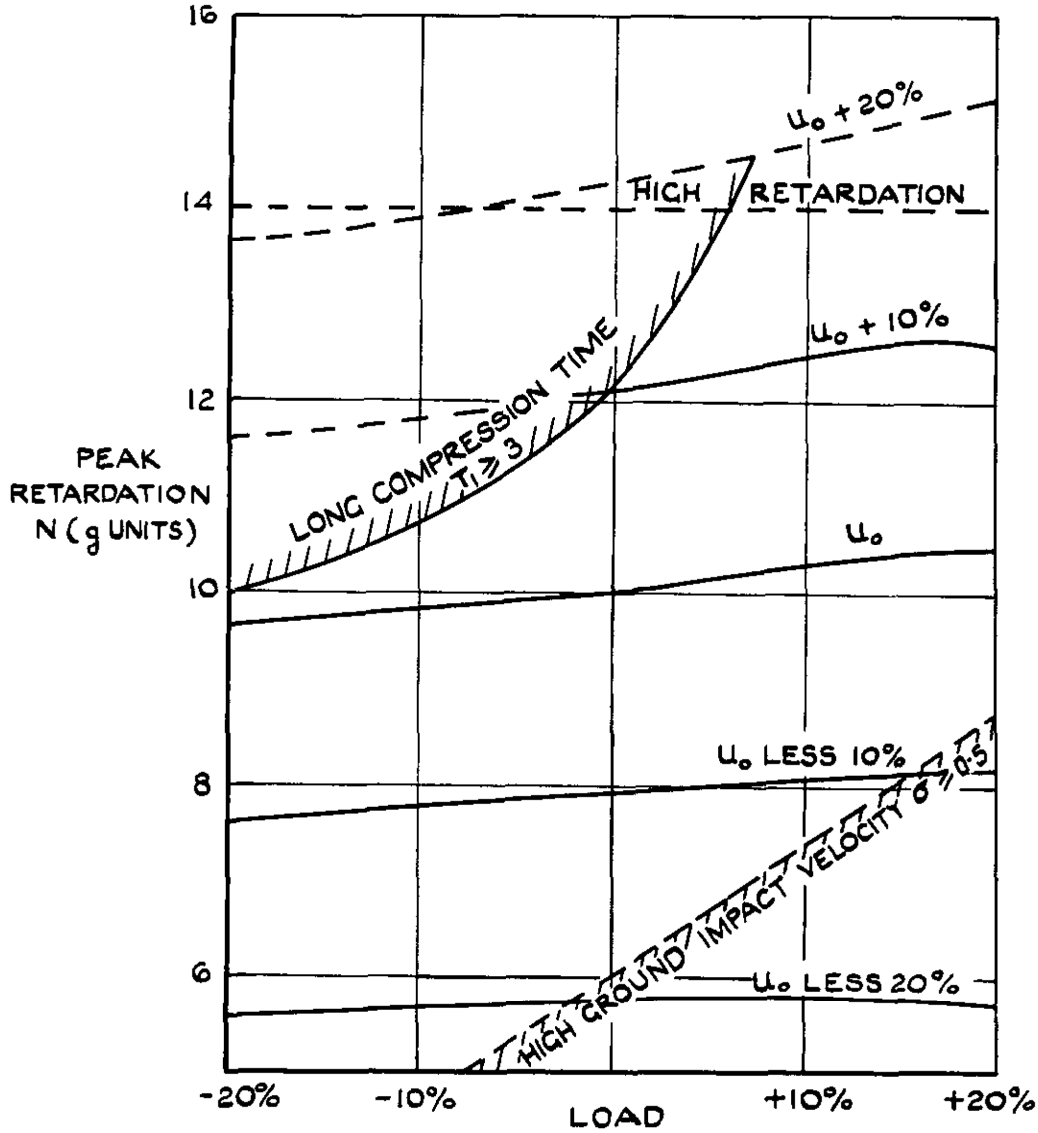


(a) THE PEAK RETARDATION

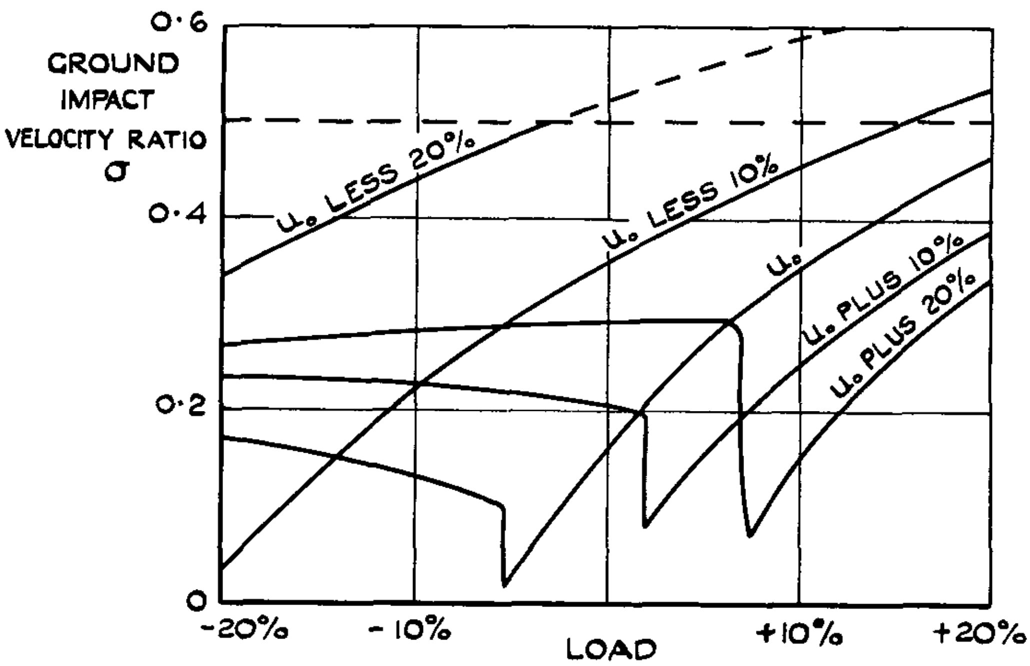


(b) THE GROUND IMPACT VELOCITY RATIO.

FIG.11.(a & b) VARIATION OF DESCENT SPEED AND LOAD TOGETHER ON A GOOD BAG. (Q = 0·887; R=0·1288; S = 10)



(a) THE PEAK RETARDATION.



(b) THE GROUND IMPACT VELOCITY RATIO.

FIG.12 (a&b) VARIATION OF DESCENT SPEED AND LOAD ON A HEAVILY LOADED BAG. (Q=0·604; R = 0·1880; S=3·75

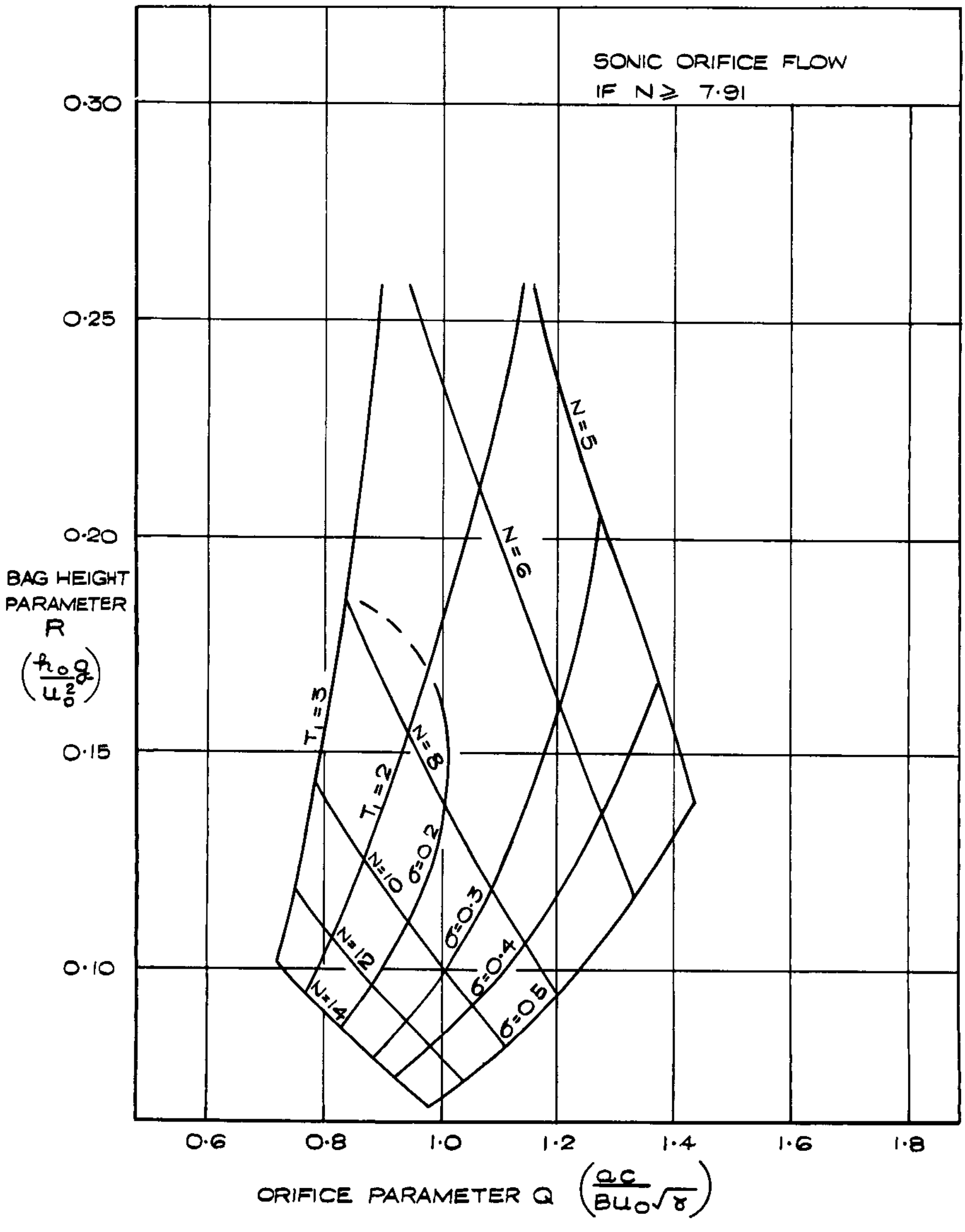


FIG. 13. DATA CHART No.4 P
INEXTENSIBLE BAG WITH A 5 P.S.I. PATCH
S = 10

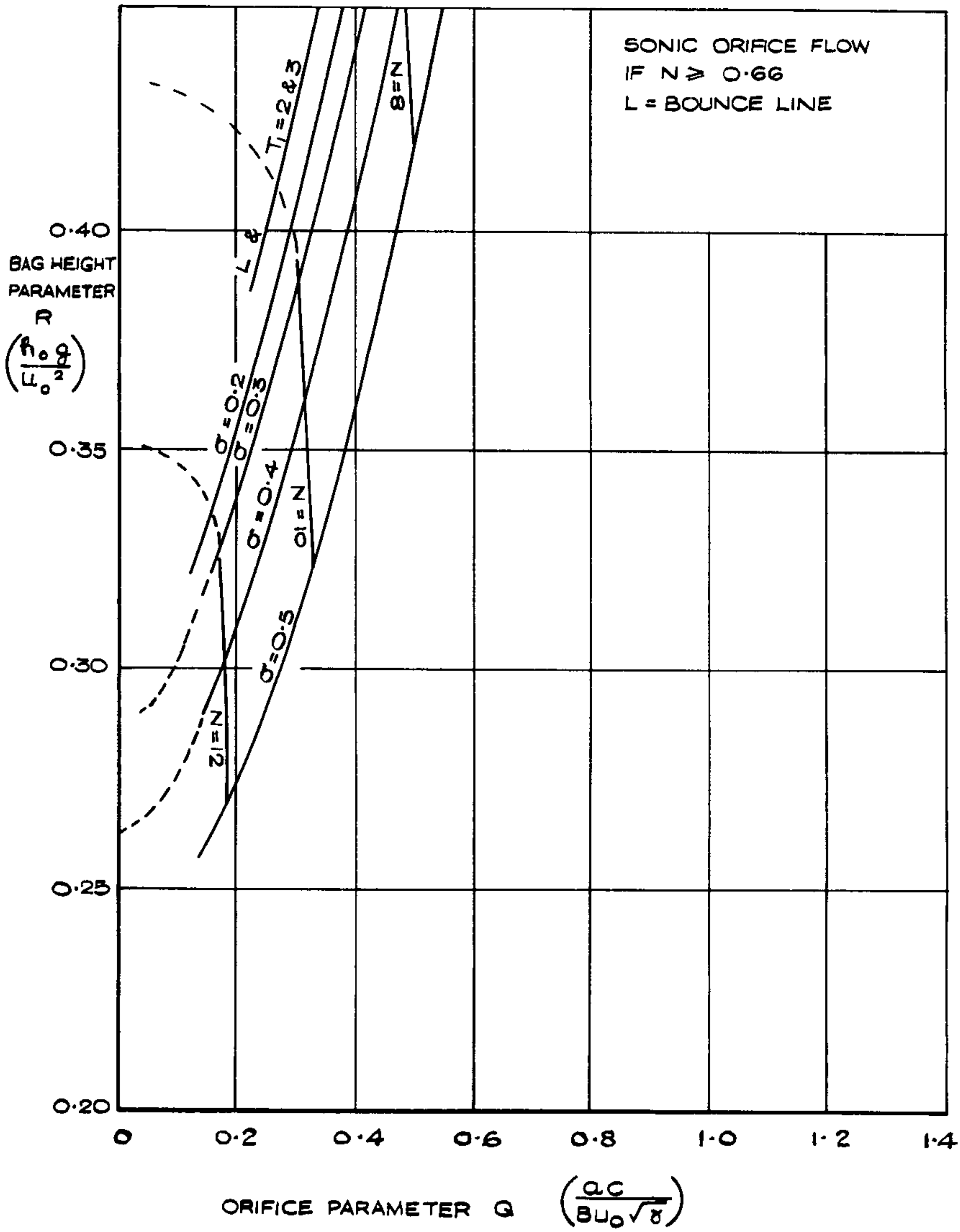


FIG. 14. DATA CHART No.1E
EXTENSIBLE BAG, k = 0·25, S = 1·86

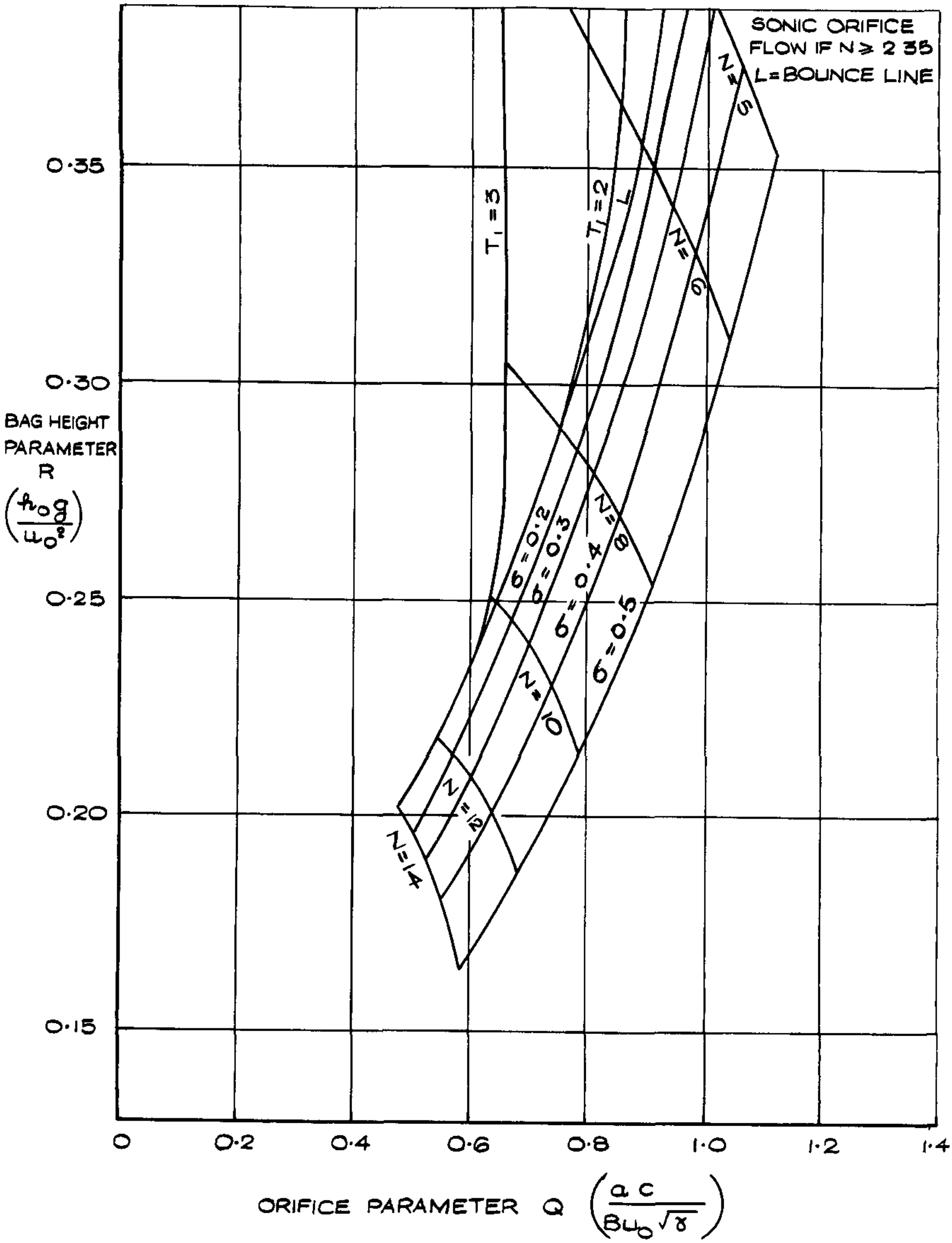


FIG. 15. DATA CHART No. 2E
EXTENSIBLE BAG, k = 0·25, S = 3·75

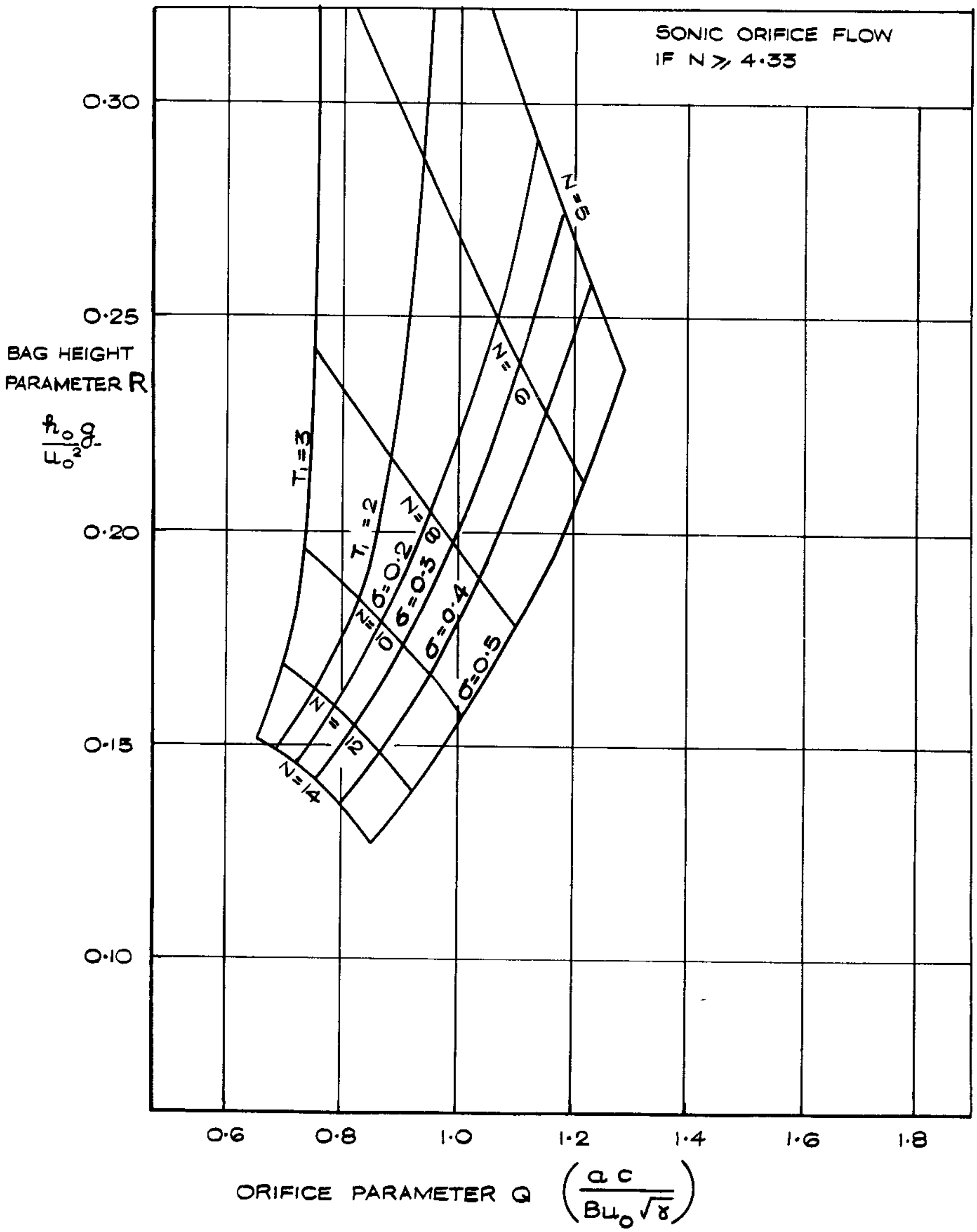


FIG.16. DATA CHART No.3E
EXTENSIBLE BAG, k = 0·25, S = 6

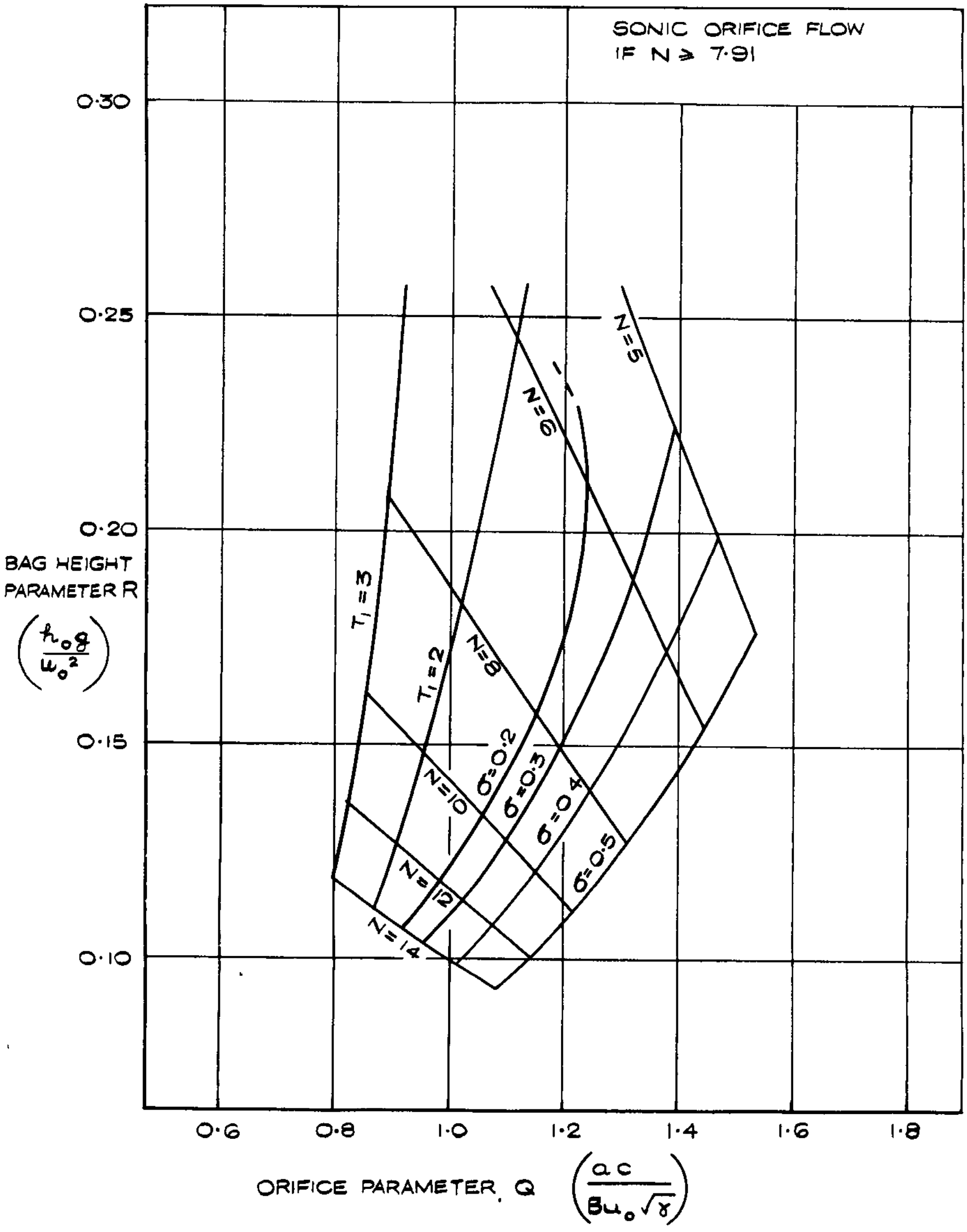


FIG. 17. DATA CHART No. 4 E
EXTENSIBLE BAG, k = 0·25, S = 10

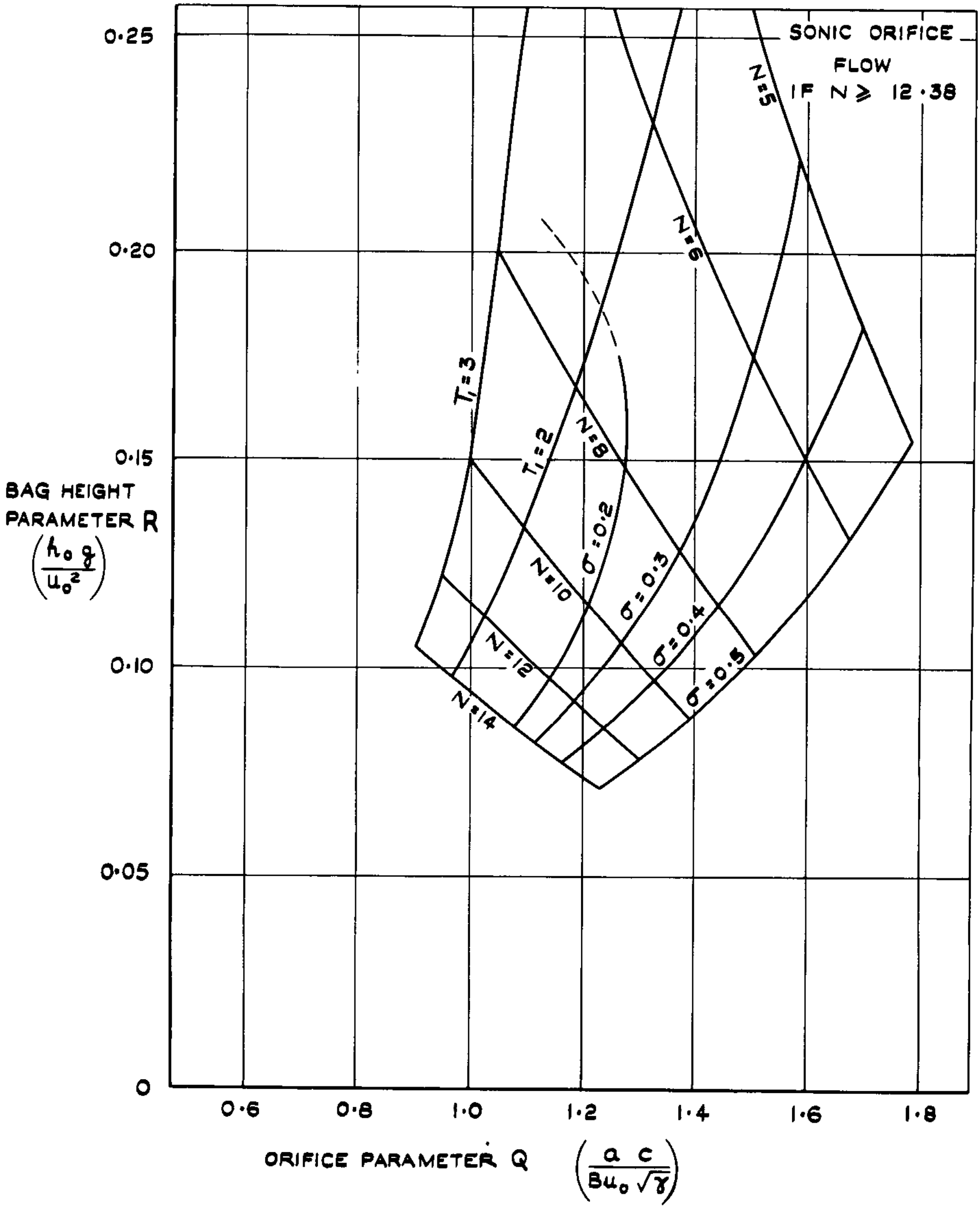


FIG. 18. DATA CHART No. 5 E

EXTENSIBLE BAG, K = 0·25, S = 15

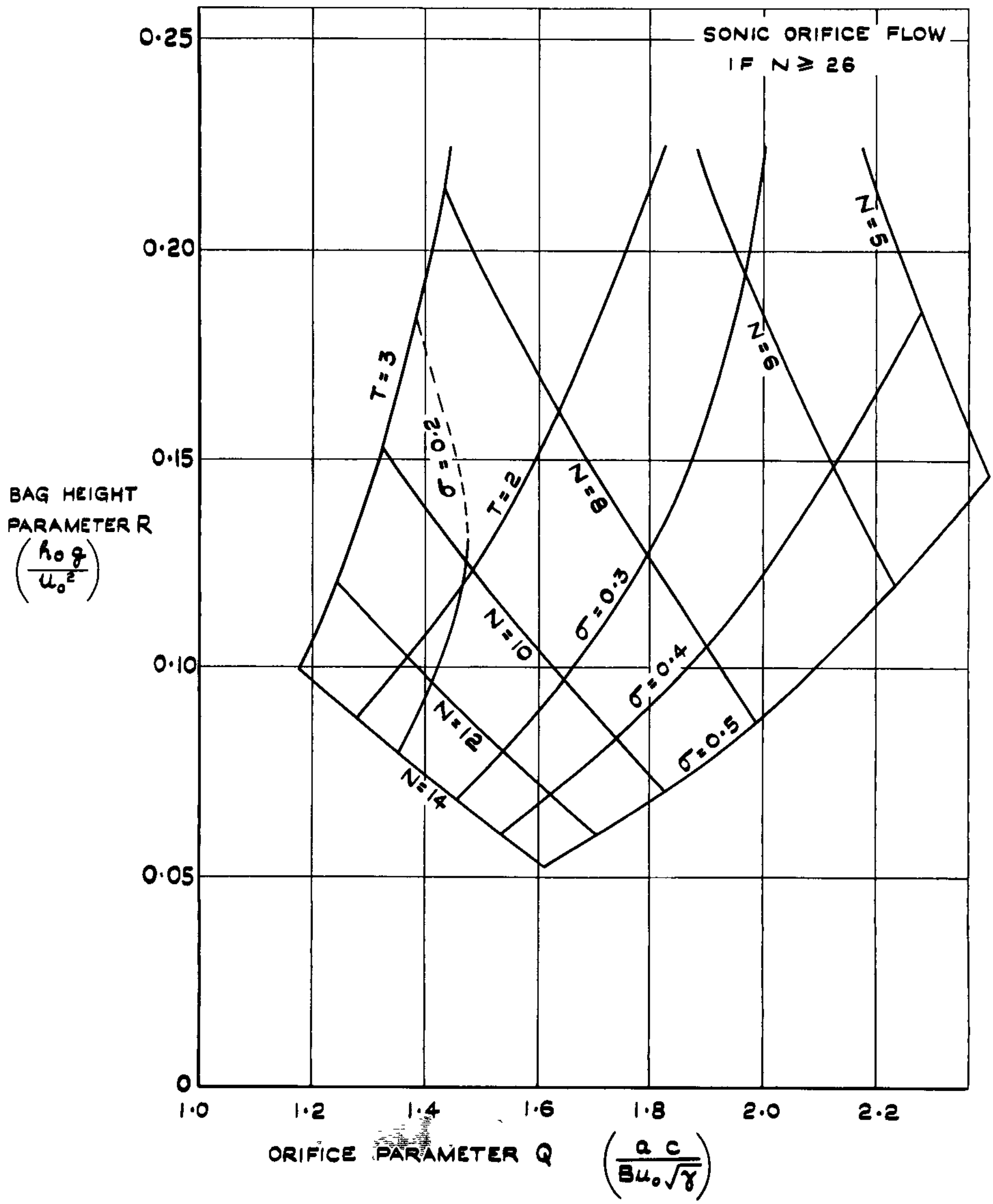


FIG. 19. DATA CHART No. 6E

EXTENSIBLE BAG, K=0·25, S=30

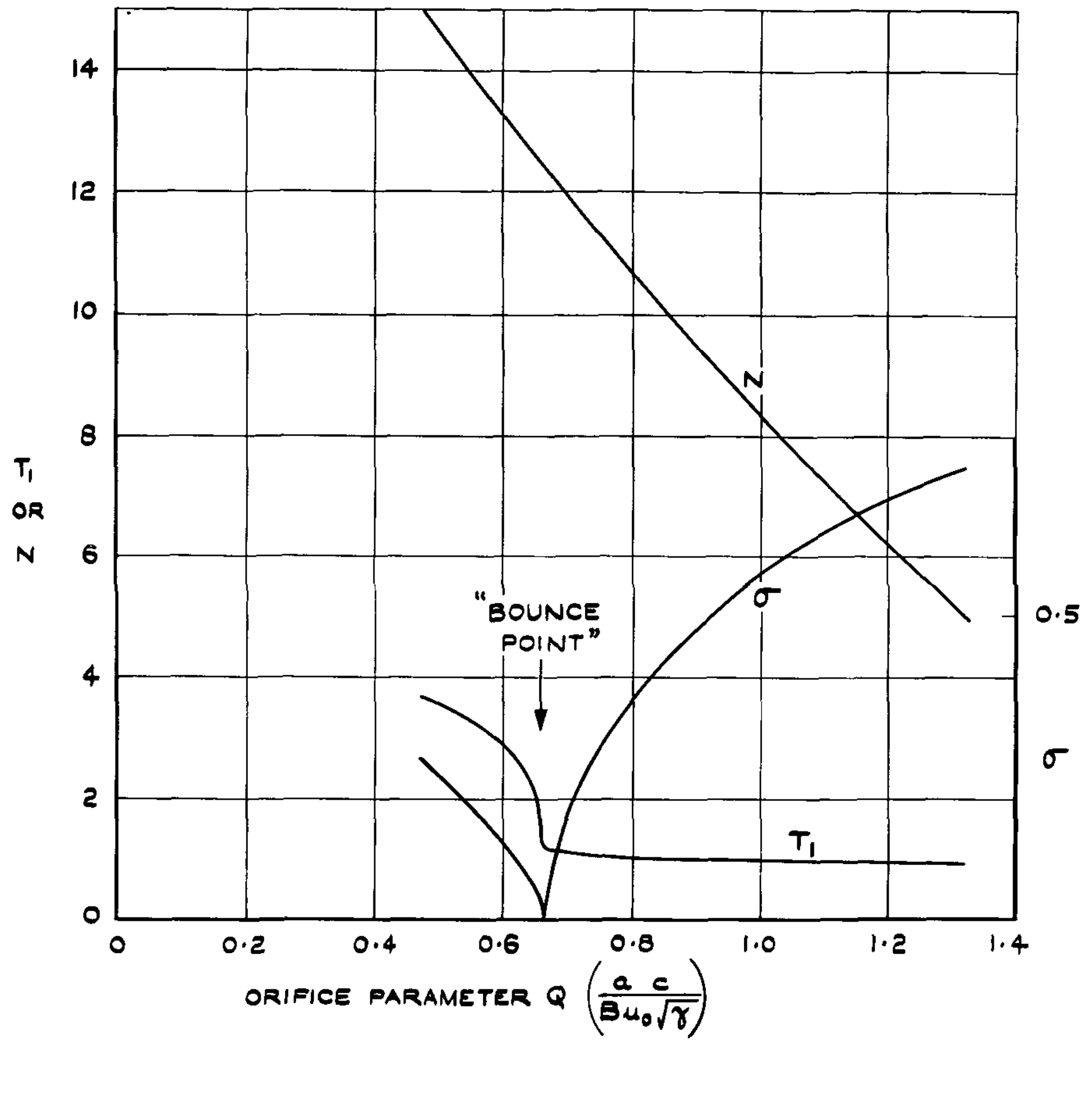


FIG. 20. VARIATION OF THE ORIFICE PARAMETER ONLY.
A MORE HEAVILY LOADED BAG (R=0·1288, S=6)

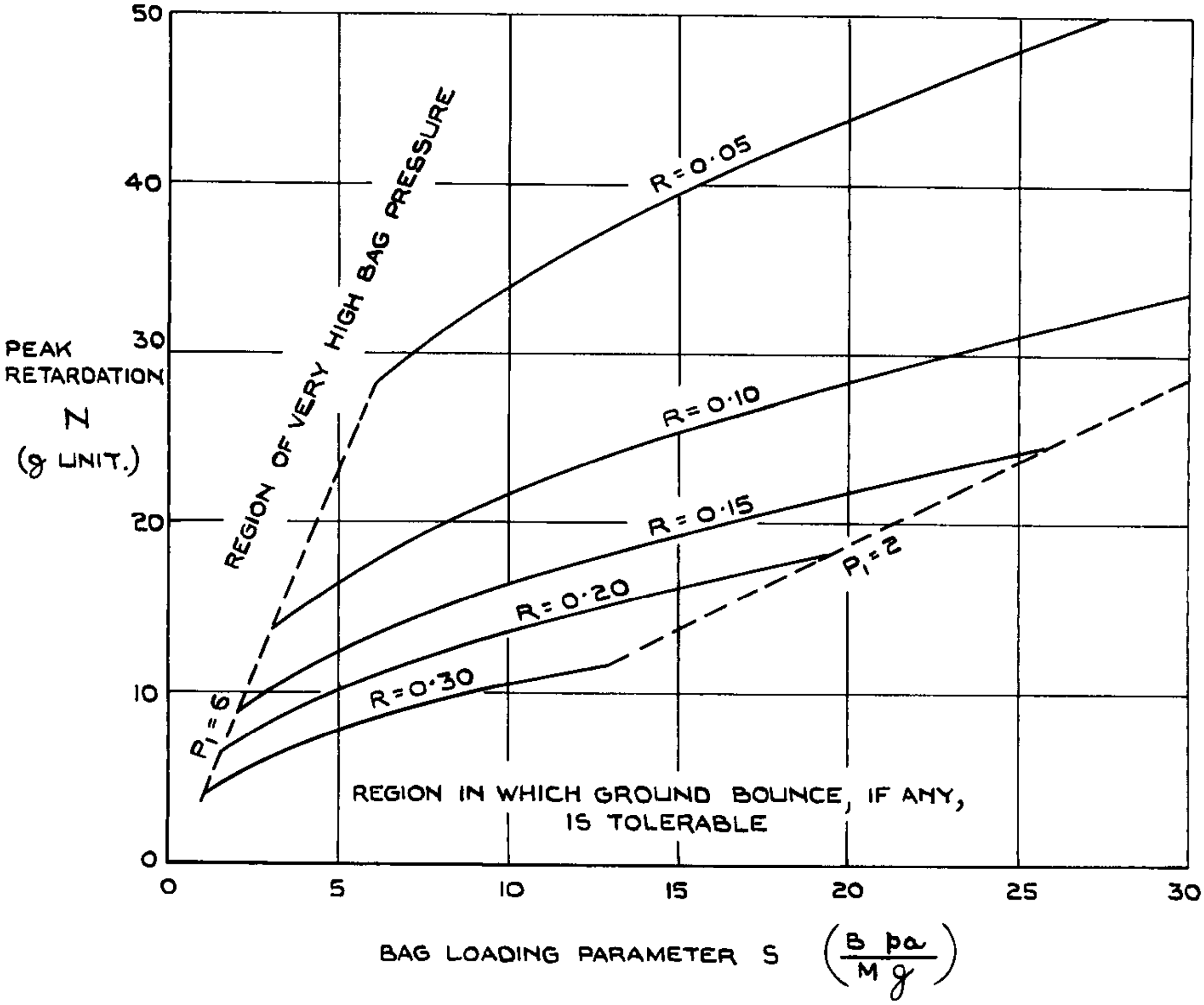


FIG. 21. CURVES SATISFYING THE CONDITION THAT THE AIR ENERGY IN THE BAG AT GROUND IMPACT IS 30% OF THE DESCENT ENERGY.

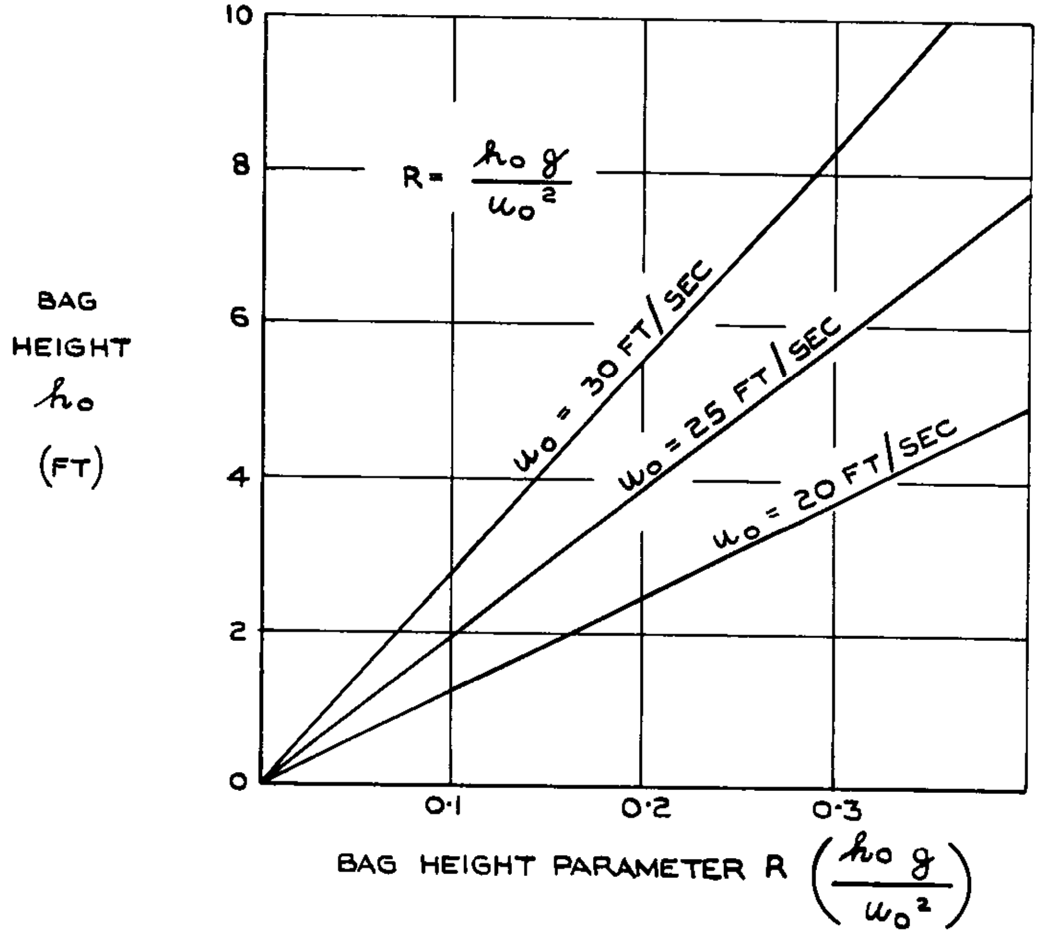


FIG. 22. BAG HEIGHT RELATED TO THE DESCENT SPEED AND THE PARAMETER R

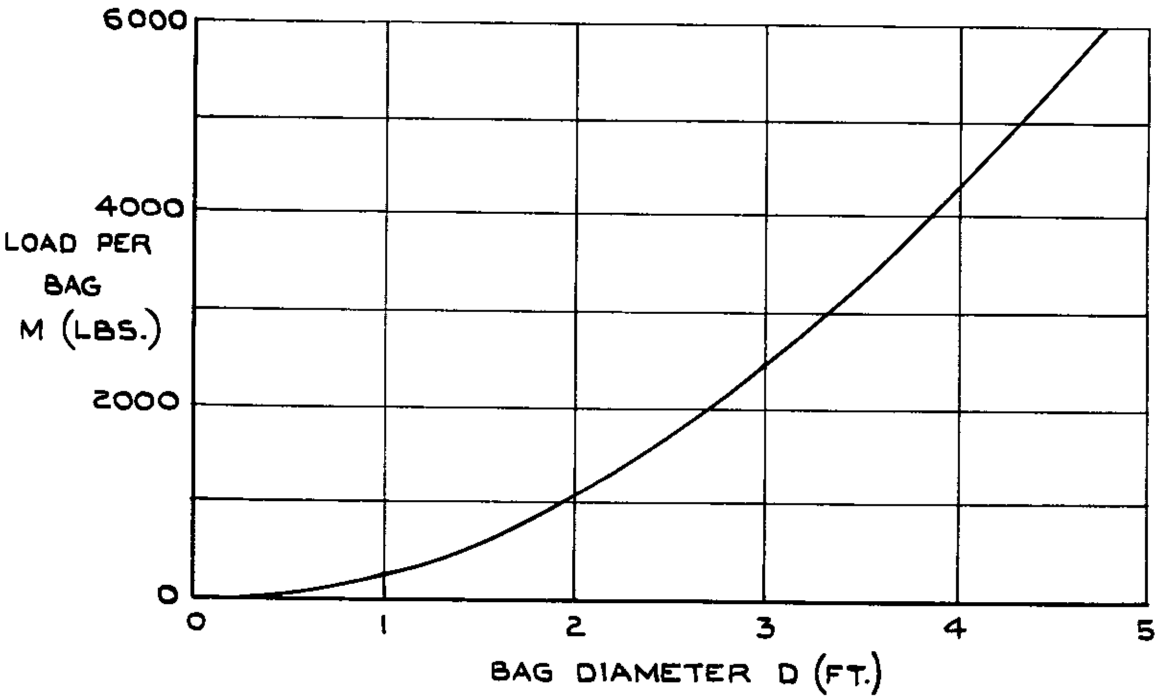


FIG. 23. THE RECOMMENDED MAXIMUM LOAD PER BAG (350 LB./SQ. FT.)

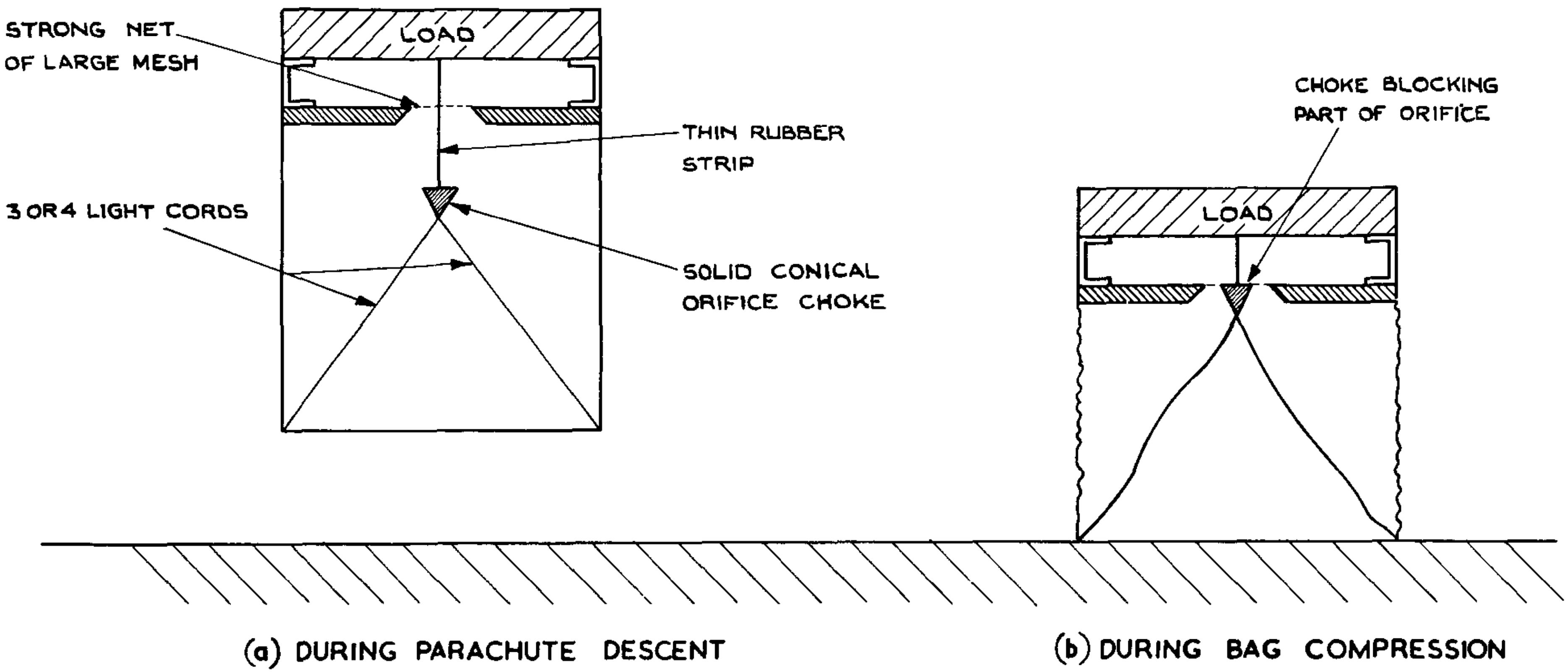


FIG. 24. (a & b) DOUBLE ORIFICE AIR BAG.

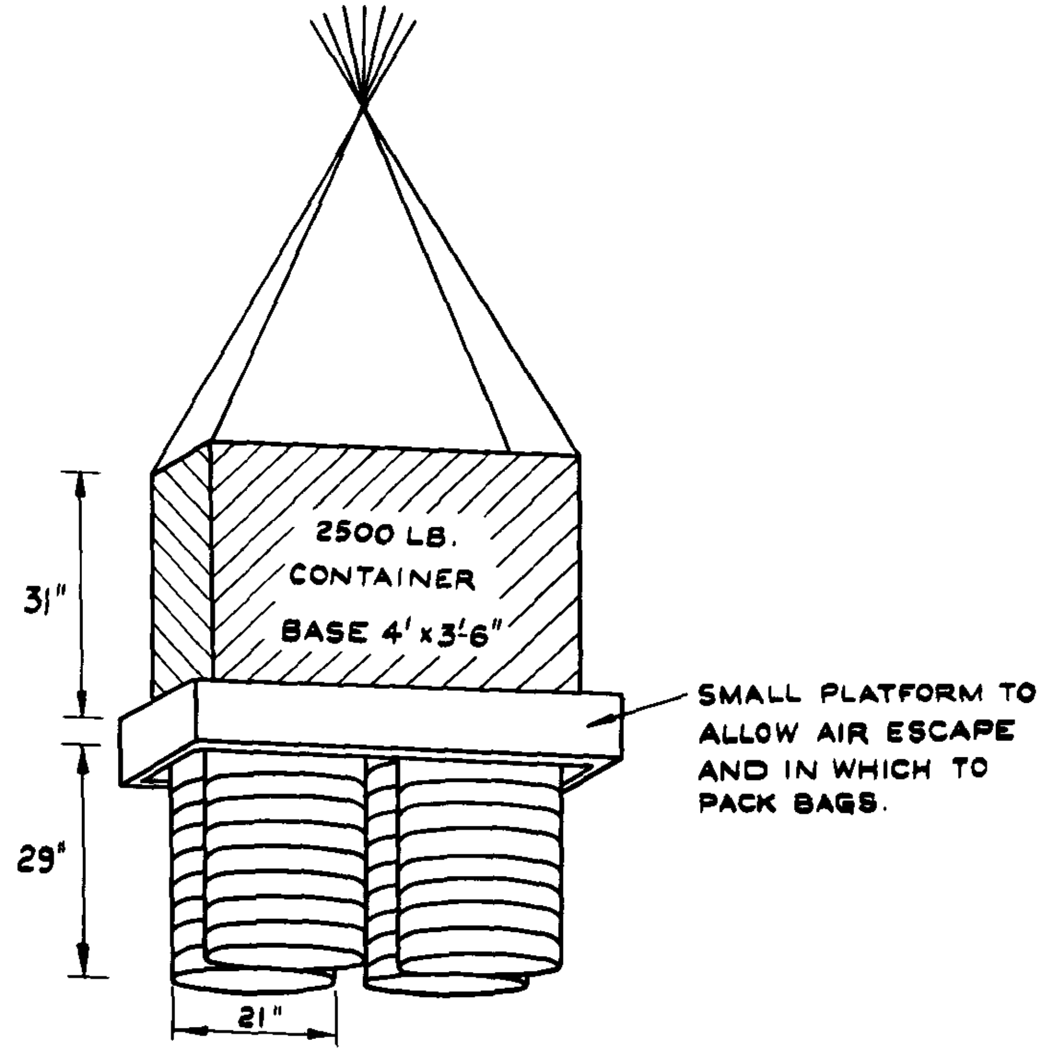


FIG. 25. A SKETCH OF THE AIR BAG SCHEME DISCUSSED IN THE DESIGN EXAMPLE. (SECTION 9.)

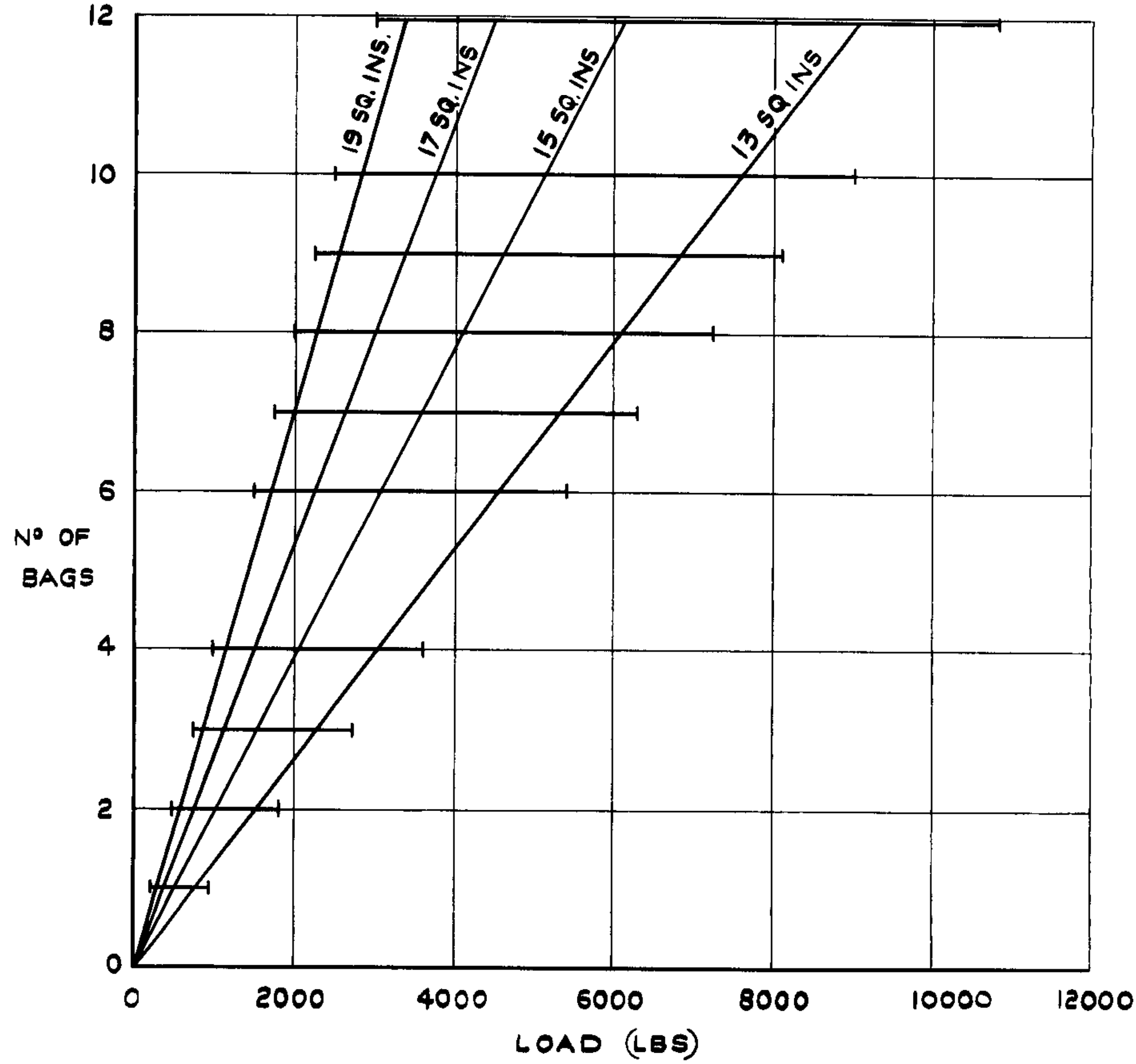


FIG. 26. THE LOAD CAPACITIES AND ORIFICE AREAS FOR SETS OF "STANDARD" AIR BAGS.

A.R.C. C.P. No. 751

A THEORETICAL APPROACH TO AIR BAG SHOCK ABSORBER DESIGN.
Browning, A.C. February, 1963.

A simple theory of the compression of a cylindrical air bag shock absorber has been studied in detail by means of over 1000 step-by-step integrations. Many features of practical air bag performance have been reproduced and data charts are given which indicate the design parameters for useful bags. From these charts the effect of variation of bag loading, height, orifice area and the speed of the descent can be appreciated. The use of a strong patch covering the orifice bursting at several pounds per square inch pressure has been investigated but gives little change in performance. If an extensible fabric is employed an increase in both bag height and orifice area is necessary. Bags of very high or very low loading are found to be inefficient and it is concluded that air bags are most suitable at a loading of 150 to 200 lb per square foot. The theory does not

P.T.O.

A.R.C. C.P. No. 751

A THEORETICAL APPROACH TO AIR BAG SHOCK ABSORBER DESIGN.
Browning, A.C. February, 1963.

A simple theory of the compression of a cylindrical air bag shock absorber has been studied in detail by means of over 1000 step-by-step integrations. Many features of practical air bag performance have been reproduced and data charts are given which indicate the design parameters for useful bags. From these charts the effect of variation of bag loading, height, orifice area and the speed of the descent can be appreciated. The use of a strong patch covering the orifice bursting at several pounds per square inch pressure has been investigated but gives little change in performance. If an extensible fabric is employed an increase in both bag height and orifice area is necessary. Bags of very high or very low loading are found to be inefficient and it is concluded that air bags are most suitable at a loading of 150 to 200 lb per square foot. The theory does not

P.T.O.

A.R.C. C.P. No. 751

A THEORETICAL APPROACH TO AIR BAG SHOCK ABSORBER DESIGN.
Browning, A.C. February, 1963.

A simple theory of the compression of a cylindrical air bag shock absorber has been studied in detail by means of over 1000 step-by-step integrations. Many features of practical air bag performance have been reproduced and data charts are given which indicate the design parameters for useful bags. From these charts the effect of variation of bag loading, height, orifice area and the speed of the descent can be appreciated. The use of a strong patch covering the orifice bursting at several pounds per square inch pressure has been investigated but gives little change in performance. If an extensible fabric is employed an increase in both bag height and orifice area is necessary. Bags of very high or very low loading are found to be inefficient and it is concluded that air bags are most suitable at a loading of 150 to 200 lb per square foot. The theory does not

P.T.O.

take account of the wind speed which, if more than about 6 ft/sec, could cause the load to drift partly off the bags, reducing the retardation.

take account of the wind speed which, if more than about 6 ft/sec, could cause the load to drift partly off the bags, reducing the retardation.

take account of the wind speed which, if more than about 6 ft/sec, could cause the load to drift partly off the bags, reducing the retardation.

C.P. No. 751

Published by
HER MAJESTY'S STATIONERY OFFICE

To be purchased from
York House, Kingsway, London w.c.2
423 Oxford Street, London w.1
13A Castle Street, Edinburgh 2
109 St. Mary Street, Cardiff
39 King Street, Manchester 2
50 Fairfax Street, Bristol 1
35 Smallbrook, Ringway, Birmingham 5
80 Chichester Street, Belfast 1
or through any bookseller

S.O. CODE No. 23-9015-51

C.P. No. 751