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The Development of a Dummy Bird for use in Bird Strike Research

By

A. W. R. Allcock and D. M. Collin

National Gas Turbine Establishment

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SUMMARY

The problems of using bird carcases in bird strike testing are mentioned and the development of a dummy bird is described. Dummies of wax, wood, flexalkyd foam, emulsion and gelatine were tested, first by impacts on very simple basic target shapes, and then on engine inlet guide vane assemblies. Comparison of the results with those from chicken carcases showed that the foam, emulsion and gelatine dummies were all realistic simulators. The gelatine dummy is recommended because of its successful history of use as a flesh simulator in other types of impact study and because of its cheapness and ease of manufacture.

The deflections measured using the special targets agreed quite well with simple theoretical calculations, and approximate values of the friction coefficient of the carcases and dummies were derived from high-speed films and the deflection measurements.

The tests on the inlet guide vanes showed that blade damage was approximately proportional to projectile momentum, and that rotation of the (variable) blades even 5° out of the projectile line of flight greatly reduced their damage resistance.

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*Replaces N.G.T.E. Report No. R.303 - A.R.C. 30697

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1.0 Introduction

Until 1965, engine bird ingestion tests in this country had been limited to a few proving tests of complete engines and a relatively small number of shots at inlet guide vane assemblies, etc. The carcases of chickens were usually used for the tests, but starlings, wood pigeon and a few other species were used occasionally. While dead birds were satisfactory for infrequent and fairly crude tests, the initiation of major bird ingestion research programmes on engines exposed significant problems in working with dead birds, viz:

(1) Severe hygienic difficulties associated with the high-speed impact of large quantities of dead tissue. The generally complex shape of engine parts, the presence of electronic and other instruments and the use of indoor facilities all combined to aggravate the problem. By contrast, tests on structures and windscreens mainly take place out of doors and in the absence of instrumentation, so that a general hosing-down of the test area and specimens is acceptable.

(2) Birds are not easily available in any desired weight or shape, and their somewhat irregular form raises doubts as to the exact position of the c.g. on impact, the cross-section at any particular point, etc., thus increasing the number of uncontrolled variables.

(3) The shape of a bird carcase, even when wrapped in a bag, is not good aerodynamically, and when shot from air guns at speeds near Mach 1 they can distort and tear. A smooth shape can avoid this, even if the body is no stronger mechanically.

It was therefore important to develop a dummy which gave realistic simulation and overcame the problems noted above. "Realistic simulation" was defined as the ability to produce exactly the same results during impact on engine blading as those produced by bird carcases. However, during the development programme, interesting evidence came to light on the quite separate question of whether a carcase fully simulates the impact properties of a living body. The evidence on this is discussed in Section 7.0.

While the objective of the experiments in no way depended on agreement with any theoretical results, it seemed profitable to make simple theoretical calculations of the quantities being measured experimentally. These were a useful indication of whether the experiments were producing the trends which might be expected, provided a check on the compatibility of measurements from two different instrumentation systems, and enabled useful data on impact loads to be obtained.

2.0 The dummy bird specification

A bird is obviously an extremely complex mechanical structure, and the degree of realism desirable in a dummy was difficult to decide. There was also a lack of reliable evidence on such matters as body density, percentage weight of skeleton, feathers, etc. for any bird species, nor was it known whether these quantities differed significantly between species. Hence there was no conclusive evidence as to whether a chicken adequately simulated a seagull, pigeon, etc. Some previous work on dummies was known to have been done with bags of chopped meat, soft wax, wet rags, etc., but no reports or comparative tests were available. It was also felt that strikes on engine blading would involve much more complex processes than strikes on windscreens, and that a more realistic form of dummy should be attempted. Ultimately it was decided that by far the most important contributor to the damage caused by a bird was the main mass of flesh and blood, and that for early trials at least, both the feathers and bones could be ignored (see below). The important features to simulate seemed to be:

(a) Density of flesh and blood.

(b) Tensile strength of flesh.

(c) Ratio of fluid/solid.

(d) Viscosity of blood.

The figures obtained for these quantities were as follows:

(a)	Specific gravity of chicken body[1]:	Cock 1·0418 to 1·0507 Hen 1·0480 to 1·0575
(b)	Tensile strength of muscles[2]:	85 to 142 lb/in²
	Collagen fibre strength[2]:	284 lb/in²
(c)	Body composition by volume[1]:	6 per cent whole blood 36 per cent extra-cellular water 58 per cent flesh tissue
(d)	Relative viscosity of chicken whole blood[1]:	Cock 4·0 to 5·2 Hen 3·1 to 3·9

However, the physiologists consulted agreed that it was very difficult to say what could be taken as a typical muscle or fibre strength, emphasising that bodies were highly non-homogeneous. It was also pointed out that no simple definition of fluid/solid ratio could be given, as this depended on whether only 'free' or also cellular fluids were considered, but the figures above were considered reasonably typical.

To check the data on overall density and to assess how the density varied for different parts of the body, some simple tests were done at N.G.T.E. on a plucked chicken carcase by weighing and measurement of volume by displacement. The results obtained also enabled the percentage weight of the limbs, etc. to be determined:

Part	Body	Wings	Upper legs	Lower legs	Head and neck	Overall
Relative density	1.03	1.07	1.08	1.15	0.9	1.02
Per cent weight	67	6.4	15.6	3.0	8.0	100

A specification based on the figures obtained for (a) to (d) above was therefore prepared, with the following additional features:

(a) The body to consist of a plastic or rubber foam, enclosed by an impermeable skin.

(b) All the materials to be non-toxic.

(c) Shelf life of at least three months.

(d) Shape to be a very short cylinder with hemispherical ends, of 5·6 in. diameter (to fit the R.A.E. air gun[3], which was used until an N.G.T.E. facility became available), and a volume appropriate to a weight of 4 lb.

The near-spherical shape was chosen to reduce the number of variables in the tests: a sphere can be considered as representing an average of the innumerable ways in which the elongated ellipsoidal body of a bird can strike engine blading.

Subsequently a more comprehensive programme of tests[4] covering several species was completed at the Ministry of Agriculture, Fisheries, and Food Infestation Control Laboratory at Worplesdon, Guildford. This confirmed the density figures used to specify the dummy, and provided much additional data on the percentage weight of feathers and skeleton, which supported the decision not to allow for them separately, but simply to treat them as part of the whole mass. The weights of the six species most relevant to the aircraft strike problem were all composed of at least 89 per cent at an average relative density of 0·98, which included an average of 6·3 per cent skeleton at an average relative density of 1·06. The remaining 11 per cent or less of weight was feathers.

3.0 Types of dummy bird

Several types of dummy were prepared, some representing detailed attempts to fulfil the specification, and others were included simply to provide a comparison with different materials. Manufacturing and other details for each type are given in Appendix II.

3.1 Flexalkyd foam

R.A.E. Chemistry, Physics and Metallurgy Department were given the original specification and prepared a number of experimental dummies. It proved impossible to obtain the desired ratio of liquid/solid weights without using a lead-impregnated foam, which was expensive and somewhat toxic. Large free spaces were also left after the liquid had been absorbed, so that the body was non-homogeneous. This was undesirable in itself and seemed to lead to difficulties during acceleration in the gun barrel. The fluid/solid ratio and any differentiation between blood and water was therefore dropped from the specification. The correct density was then achieved by almost complete filling of the foam pores with water, provided the basic foam had been 'densified' somewhat with barium sulphate.

3.2 Beechwood

Tests of solid wooden dummies seemed desirable to compare the effects of hard, rigid materials with those of soft substances.

3.3 Wax

The cheapness and ease of manufacture of paraffin wax dummies was a strong incentive to including them in tests, and there seemed some possibility that they would give acceptable simulation.

3.4 Gelatine/oil emulsion

Encouraging early tests with the foam dummy led to efforts to produce a cheaper and simpler substitute. An emulsion of oil and gelatine, mixed with sisal fibres, was therefore developed.

3.5 Gelatine

All the above dummies had been developed and partially tested before it was discovered* that gelatine had been used to simulate flesh in studies of ballistic wounding. Samples of this were therefore made and tested at a late stage in the programme. The background to the development of this material is given in Section 7.0.

4.0 Apparatus for tests on special targets

The damage caused by impact on a machine as complex as an aircraft engine is not easily quantifiable for comparison purposes, so it was decided to study the effects of bird carcases and dummies shot at three special targets, before studying damage to actual engine blading. The targets consisted of vertical plates at two extremes of sharpness - a flat plate and a sharp wedge - and an intermediate type with a semicircular nose section (Figures 1 and 2(a)). All three weighed 245 lb to facilitate comparisons, but later a lightened version of the knife-edge had to be used to obtain larger deflections. It weighed 59 lb. The targets were mounted on calibrated flexible beams (Figure 2(b)), the deflection of which could be measured (see Section 4.1).

The comparison of the impacts was to have been based on accelerometer readings, but initial tests showed that no commercially-available instruments were suitable for the very high accelerations occurring. A velocity transducer was therefore developed to overcome this difficulty. It was intended that the oscillographs obtained from this should be the main means of comparison, with target beam deflection separately measured by a mechanical method as a back-up. However, problems encountered in obtaining good and fully-comparative readings from the velocity transducers led to the deflection measurements becoming equally important in comparing the dummies.

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*Following a suggestion by the late Sir Walter Cawood, then Chief Scientist of the Ministry of Aviation.

4.1 Deflection measurement

Various methods of deflection measurement were tried, but much difficulty was caused by vertical vibration of the target during impact. The most satisfactory method proved to be one using a Duralumin rod mounted in two compressed rubber bushes, the rod just touching the target before impact. The horizontal movement after impact could be measured with a depth gauge to an accuracy of about ±0·002 in.

4.2 Velocity transducers

Two types are illustrated in Figure 3. A bar magnet attached to the target was driven through a stationary coil, thus generating an e.m.f. Originally the coil was fixed to a stand, but eventually its own inertia was found to be sufficient to keep it virtually stationary for the millisecond or so required. Axial vibration of the magnet could easily be detected and distinguished from gross target movement in the output, which consisted of a photographed trace on a Tektronix 551 oscilloscope.

The Mark I instrument was calibrated by a crank system driven by a vertical drill and the Mark II by drop tests, in both cases to the required maximum of 18 ft/s. The main differences between the two types were that the Mark II was much more robust mechanically and gave a stronger signal. However, most of the recordings ultimately obtained were with the Mark I, which was available much sooner.

The oscilloscope was triggered by fracture of a carbon rod placed some 18 in. in front of the target (Figure 4), after attempts at internal triggering by signal slope proved unreliable.

The Mark I transducer signals were amplified by a P.A.3 pre-amplifier to reduce the length of cable connected to the transducer, while allowing the oscilloscope to be moved further from the target area. It was also necessary to boost the very weak signals resulting from tests on the heavy knife-edge target. The Mark II transducer needed no pre-amplifier.

4.3 Projectile velocity before impact

Projectile velocity was measured by timing the interval between the breakages of two electrical conductors by the projectile as it travelled from the gun muzzle to the target.

At R.A.E. the system used two 0·003 in. diameter wires spaced 5 ft. apart and connected to a Chronotron[3]. The N.G.T.E. system used $\frac{1}{8}$ in. diameter carbon rods 3 ft apart and connected to a Venner digital time counter[5]. Calibrated high-speed films showed satisfactory breakage characteristics of the carbon rods and indicated speeds which agreed with the carbon rod system within ±4 per cent. The N.G.T.E. system was developed for use with guns with evacuated barrels[5] and is not satisfactory where the brittle rods are exposed to an air blast such as occurs with the R.A.E. gun, or any other air gun using a pressure reservoir.

The circuit block diagram is shown in Figure 4.

5.0 Results of tests on special targets

5.1 Blast deflection correction

The R.A.E. air gun[3] was used for two series of tests where speeds of over 400 ft/s with a 4 lb projectile were required, as a suitable N.G.T.E. high-speed vacuum gun[5] was not then available. It was also necessary for tests of chicken carcases, because it is an open air rig with good cleaning facilities. During an earlier series of tests using a different rig, a 0·25 in. sheet aluminium blast screen was erected in front of the target (Figure 5(a)) to prevent water vapour from the gun obscuring filming of the impact. This screen was subsequently omitted for those tests on the rig of Figure 2(b) for which no filming was planned, but it was realised after some time that air blast was actually causing appreciable target deflections, which had been fortuitously prevented by the screen in the earlier tests.

Time did not permit an adequate assessment of this effect, but the rudimentary calibration derived is shown in Figure 5(b). It was obtained by triggering the gun without a projectile, with and without a screen in position. Two of the shots used the light knife-edge target, and one the round-nose target. The latter was then corrected to be appropriate to the light knife-edge using Equation (7) of Appendix III.

The actual corrections applied in each case are discussed in the appropriate sections below.

5.2 Deflection measurements: flat plate

The results are shown in Figure 6. All were obtained with the blast guard in use, so no corrections were required.

The similarity of the results from all the dummies is evident. Only the two beechwood points lie consistently to one side of the general pattern, giving about 20 per cent less deflection than the chicken. The wax dummies appear to give smaller deflections than the chicken at low impact momentum, and slightly larger deflections at high momentum. The gelatine and emulsion dummies always tended to give smaller deflections.

The results of this test show little difference between the deflections caused by the various dummies on a flat surface. The instantaneous shock loads were very different, however, as described in Section 5.5.1.

5.2.1 Comparison with theoretical predictions

Simple momentum considerations were used to derive Equation (8) in Appendix III as an expression for deflection (δ), using measured load/deflection characteristics for the target beams. This equation may be re-expressed as:

$$\delta = \frac{mv}{1341} \text{ in.} \qquad \ldots.(1)$$

where m is the projectile mass in lb and v the impact velocity in ft/s.

This agrees with the experimental result that beam deflection is proportional to projectile momentum, and the theoretical line in Figure 6 is only a little to the left of a mean line through the experimental points. The agreement suggests that the static beam characteristic still applies even at the very high rates of strain occurring during impacts at over 900 ft/s.

5.3 Deflection measurements: round nose

The results are shown in Figure 7. The values requiring blast correction were obtained by using Figure 5(b), allowing for the fact that the round-nose target had a higher equivalent mass than the light knife-edge, by factoring the calibration values from the Figure in accordance with Equation (7) of Appendix III:

$$\text{deflection} \propto \sqrt{\frac{\text{equivalent mass for light knife-edge}}{\text{equivalent mass for round-nose target}}} = 0{\cdot}685$$

The resulting corrections appear to be rather too large, perhaps because when a projectile is present the target is shielded to some extent. A factor of 0·5 would give results closer to the lines suggested by the uncorrected data.

In contrast to the flat plate, most of the results fall on three distinct lines. All the soft dummies agreed closely with the chicken, although the one gelatine result was again rather low. The wax dummies caused about 42 per cent too much deflection, apart from the two highest results, and the wooden dummies about 145 per cent too much.

5.3.1 Comparison with theoretical predictions

Equation (9) in Appendix III may be re-expressed as:

$$\delta = \frac{mv \sin^2\theta}{1400} \text{ in.} \qquad \ldots.(2)$$

where θ = angle from the line of flight through which the debris was deflected (i.e. $\theta = 90^\circ$ for a flat plate), m is the projectile mass in lb and v its velocity in ft/s.

The proportionality to momentum is again confirmed, but a value for θ is needed to compare absolute values. Tests were therefore done in which θ was measured for gelatine, wax and wooden dummies. The results were as follows:

Dummy	θ^{o}
Gelatine	21
Wax	21
Wood	30

Substitution of these values in Equation (2) gives the following results at mv = 3220 ft lb/s (100 slug ft/s):

Dummy	δ (Theory) in.	δ (Experiment) in.
Gelatine	0.285	0.51
Wax	0.285	0.73
Wood	0.582	1.22

The results are seen to be very low when compared with Figure 7. Friction is unlikely to be responsible, because the wood result would be unaffected by this (the wood split up and did not flow around the nose). The most probable cause of the discrepancy is that there was much more loss of momentum in the direction of flight than that indicated simply by the angle through which the projectile was turned. If it is assumed that a slice of the projectile of width equal to the width of the target (2 in.) is stopped completely as if it had struck a flat plate, and the rest is assumed to be deflected as above, then approximately half the mass is deflected and half stopped, so that from Equations (1) and (2) the deflection would be given very roughly by an expression of the form:

$$\delta = \frac{mv}{2}\left(\frac{1}{1341} + \frac{\sin^2\theta}{1400}\right) \text{in.} \qquad \text{....(3)}$$

The results are then:

Dummy	δ (Theory)	δ (Experiment)
Gelatine	0.97	0.51
Wax	0.97	0.73
Wood	1.12	1.22

The discrepancies are reduced and the postulated impact behaviour seems plausible. The improvement for the gelatine dummy would be expected to be least, because it flows most easily, and with the wood most, as shown by the table above.

5.4 Deflection measurements: knife edge

The results for the original target are shown in Figure 8. The deflections were clearly very small, and all the results obtained without the blast screen had to be omitted, as the corrections involved were many times larger than the deflection due to impact of the projectiles. However, some points on the Figure are shown as being affected by blast, but uncorrected. These were tests with the blast screen in place, but it can be seen from Figure 5(b) that even in this case there would be significant blast effects. The only points which can be accepted without reservation are those obtained with the N.G.T.E. vacuum gun, which has virtually no blast.

The excessively small deflections shown in Figure 8 led to the testing of a lightened target weighing only about a quarter as much as the original target. However, the large contribution of the beams to the equivalent mass (Appendix III, Section 2.2) was overlooked, and the deflections with the lightened target were only slightly increased. The results are shown in Figure 9. A more satisfactory picture may be obtained if the results of Figures 8 and 9 are combined, and the blast corrections from the lower part of Figure 5(b) included at the same time. This has been done in Figure 10 by factoring the results of Figure 8 in accordance with Equation (7) of Appendix III.

From this Figure it is evident that all the dummies gave higher deflections than the chicken carcases, except for the gelatine and foam types.

The larger deflections from the emulsion dummies probably resulted from a high coefficient of friction (see next section).

5.4.1 Comparison with theoretical predictions

From Figures 20 and 21, it appeared that the soft projectiles were not disintegrating or being thrown clear of the wedge surfaces on impact, but that they applied a substantial force normal to the sloping faces. This seemed particularly evident in the third frame of Figure 21, where a layer of material next to the surface seemed to be being squeezed out from under the main hemispherical bulk on top of it. Thus the friction between the wedge surface and the missile was clearly involved, and Equation (17) of Appendix III was therefore derived with the effect of friction coefficient (μ) included. The Equation may be re-expressed as:

$$\delta \;=\; mv(1 + 5{\cdot}98\mu)\; 2{\cdot}60 \cdot 10^{-5}\text{ in.} \qquad \ldots.(4)$$

with m in lb, and v in ft/s. Thus once again the deflection is proportional to projectile momentum. If the slope of the chicken line in Figure 10 is substituted in the equation, the value obtained for μ is 0·09.

Measurements from Figures 20 and 21 were also used to deduce friction coefficients, as shown in Appendix III Section 4.0. The results were:

$$\mu = 0 \cdot 35 \text{ for the chicken carcase}$$

$$\mu = 0 \cdot 23 \text{ for the foam dummy}$$

The discrepancy between these results and μ from Equation (4) is substantial, but neither method of calculating μ is very accurate. The measurement of the deflections was clearly approximate in view of the somewhat ill-defined effect of blast, and accurate measurement of the velocities from the high-speed films was very difficult. However, it is clear that Figure 10 displays the expected trend with momentum and the absolute values imply a friction coefficient of the same order as those derived from the high-speed films. Further estimates of μ are discussed in Section 5.5.5.

5.5 Transducer results

It was realised from the outset that it might be difficult to relate the transducer results quantitatively to the nature of the impact, and their primary purpose was envisaged as providing a qualitative comparison of the time/velocity history of impacts on different targets. It was considered that traces which were very similar implied that the impact processes had also been very similar, whatever the traces actually represented, and however contaminated by vibrations within the target, beams, etc. they might be. Some quantitative data were, however, successfully derived (Section 5.5.4).

For most of the tests, two transducers were used, one mounted onto the rear face of the target and one on top (referred to as the 'rear' and 'upper' transducers respectively). Their results were generally similar, but the rear one usually exhibited more high-frequency vibration.

The results for nominally identical tests on the knife-edge and round-nose targets are shown in Figure 11. The repeatability is seen to be good, both as regards peak amplitude and detail shape of the trace.

The "driving plug" referred to in this and Figures 12 to 16 is the foam cylinder which forms part of the projectile when using the R.A.E. gun[3].

Comparisons between different dummies are shown in Figures 12 to 16. Many experimental problems were encountered in triggering the oscilloscope, usually in conjunction with a high-speed camera, and not many fully comparable records were obtained. Only on the round-nose target can the dummies be compared with the chicken, and no results with gelatine were obtained. However there is enough material to contribute worthwhile evidence, which is considered below.

5.5.1 Flat-plate target (Figure 12)

No comparison with a chicken carcase is available, but the different characteristics of the beech, wax and gelatine/oil dummies are well brought out. The beechwood applied a severe acceleration which caused an initial velocity peak some three times greater than in the other cases. The oscillations are more severe, and die away more rapidly. All these facts are consistent with a hard material. The wax and gelatine/oil dummies gave similar peak values, the wax having slightly less severe oscillations immediately after initial impact. These observations are consistent with the deflection results.

5.5.2 Round-nose target (Figures 13 to 15)

The differences between the trace characteristics for the different projectiles are quite clear. The beech dummy clearly caused a much higher initial peak than any of the others. The flexalkyd dummy gave rather inconsistent results (Figures 13 to 15) for which the most likely cause would be an inaccurate shot only partially striking the target in Figure 14(b). The flexalkyd gave similar peak amplitudes to the chicken but the very sharp initial peak and larger subsequent oscillations are significantly different from the chicken traces. The only emulsion dummy comparison was unfortunately indirect, due to the different transducer and gain settings used. However, the comparison in Figure 14 indicates that it simulated the chicken carcase better than any of the other dummies.

5.5.3 Knife-edge target (Figure 16)

The only results available were all for the heavy version and are shown in Figure 16. As might be expected from the deflection results, there is little difference in peak amplitude. However, the beech again produced a very sharp initial peak, while the emulsion dummy trace took five times as long to reach the same amplitude.

5.5.4 Comparison of deflections as measured and as derived from transducer results

Although the primary purpose of the oscillograph traces was qualitative comparison, some calculations were made from the rear transducer recordings. A typical result is shown in Figure 17(a). In general, there were two frequencies of 2000 c/s and 10,000 c/s superimposed on the trace of gross target movement. The 2000 c/s was the natural frequency of the rear of the target when struck on the front, but the origin of the higher frequency is not known. However, a smooth curve can be drawn through the mean points of the oscillations to give the line shown in Figure 17(b), which enables impact duration and smoothed peak velocity to be calculated. From this, the beam deflection can be calculated by substituting in Equation (6) of Appendix III. The comparison with the directly-measured deflections is shown in Figure 18. The generally good agreement shows that the transducers were giving a good indication of target velocity.

Further evidence for this came from a comparison of the instantaneous peak amplitudes on Figures 13 to 15. This was straightforward for the chicken carcase and foam and emulsion dummies where projectile weight and velocity were reasonably consistent (3·03 to 3·75 lb, and 481 to 505 ft/s respectively):

		Mean peak amplitude
Chicken carcase	(Figures 13(a) and 14(a))	17·6 mm
Flexalkyd foam	(Figures 13(b) and 14(b))	16·0 mm
Wax	(Figure 13(c))	25·0 mm

However, the only beechwood or emulsion results were in a significantly lower speed range. Values comparable to the above table were therefore obtained by noting that the projectile weight and velocity for Figures 14(c) and 15(b) were fairly comparable to those for the wax in Figure 15(a), which could itself be related to the wax result in Figure 13(c). The ratios of the peak amplitudes in Figures 14(c) and 15(b) were 1·75 for the beechwood and 0·52 for the emulsion, relative to the wax value of Figure 15(a). The value for wax (25·0 mm) already obtained for the higher speed range (Figure 13(c)) was then factored by 1·75 to give a value of 43·7 mm for beechwood, and by 0·52 to give a value of 13 mm for the emulsion. The relative values can then be compared using the chicken carcase as a yardstick:

Ratios of peak amplitudes

chicken carcase	gelatine/oil emulsion	flexalkyd foam	wax	beechwood
1.0	0.74	0.91	1.42	2.48

Now from Equation (6) of Appendix III, $V_{max} \propto \delta_{max}$, and so the relative deflections in Figure 7 can be compared with the peak target velocities above:

Ratios of beam deflections (Figure 7)

chicken carcase	gelatine/oil emulsion	flexalkyd foam	wax	beechwood
1.0	0.97	1.0	1.42	2.44

Agreement is clearly fairly good.

5.5.5 Comparison of transducer results with calculated average impact forces

The average impact force was defined with reference to Figure 17(b) as that constant force which would produce V_{max} in time Δt, i.e. assuming uniform acceleration of the target. Then:

$$\bar{F} = \frac{M_e}{32 \cdot 2}\left(\frac{V_{max}}{\Delta t}\right) \qquad \ldots.(5)$$

where M_e is the equivalent mass of the target and beams in lb, V_{max} the maximum (smoothed) velocity in ft/s, and Δt the impact time in seconds.

Δt is very difficult to determine accurately, as may be appreciated from Figures 11 to 16, and the original estimates of average impact force from the oscillographs were very scattered. However, this scatter was greatly reduced by obtaining a mean value for the product of projectile velocity and impact time for each type of projectile on a given target. This mean value was then divided by each measured projectile velocity to get the impact time in individual cases. These impact times and values of V_{max} measured in each case were then used with Equation (5) to calculate average impact force and the results are shown in Figure 19.

Although there is considerable scatter, a definite trend with momentum is discernible, particularly for the knife-edge and flat-plate targets. The results for the latter draw attention to the huge impact forces occurring, the highest value for a chicken carcase being 290 ton.

The theoretical curves for the knife-edge target struck by a 4 lb projectile were derived using Equation (13) of Appendix III, re-expressed as:

$$\bar{F} = 0 \cdot 0068\ v^2\ (1 + 5 \cdot 98\mu)\ \text{lb} \qquad \ldots.(6)$$

where v is impact velocity in ft/s and μ the coefficient of friction, for which values of 0·1 and 0·35 were assumed. The soft projectile results show some tendency to follow the line having $\mu = 0 \cdot 1$, which agrees very closely with the value of 0·09 derived from Figure 10 in Section 5.4.1. The assumption that

$$\Delta t = \frac{2r}{v} \qquad \ldots.(7)$$

(where r = projectile radius in ft and v is impact velocity in ft/s) is involved in Equation (6), and errors in this could affect the calculated forces materially. However, measurements from Figure 16(c) indicated that Equation (7) was quite a good approximation for the knife-edge.

The theoretical curve for the round-nose target struck by a 4 lb projectile was derived using Equation (4) of Appendix III, re-expressed as:

$$\bar{F} = 0{\cdot}031\ v^2\ \text{lb} \qquad \ldots.(8)$$

where v is impact velocity in ft/s and a value of θ of 21° was assumed. The experimental points follow the same trend, but much higher forces are indicated, probably for the reasons already discussed in Section 5.3, but in this case, a value of Δt only about half that given by Equation (7) is suggested by measurements from Figures 13 to 15, and this fact would also mean that Equation (8) gave values which were too small.

The theoretical curve for the flat plate struck by a 4 lb projectile was also derived using Equation (4) of Appendix III, re-expressed as:

$$\bar{F} = \frac{v^2}{4}\ \text{lb} \qquad \ldots.(9)$$

where v is impact velocity in ft/s. Agreement with the experimental points is quite good, but the calculated forces are again too low. Measurements from Figure 12 indicate that again Equation (7) gives too great an impact time. The peak forces occurring in the first few tenths of a millisecond are of course much larger than the values shown in Figure 19, but their significance as regards damage is greatly reduced by their very brief duration.

5.6 High-speed films

A number of high-speed films was taken during the special target tests in the hope that data on deceleration, fragmentation, etc. could be obtained from them. In fact it proved very difficult to obtain successful films, and frames from the only examples available are shown in Figures 20 to 23. The essence of the problem was the need to coincide the impact of the projectile with the last two or three hundred milliseconds of the high-speed camera run. The total run was only about 1 sec, and only in the last part had the film been accelerated to full speed. Various methods of triggering were tried, and ultimately the camera was used to fire the gun, with a variable delay for different projectile velocities. However, variations in projectile drag, etc. still varied the time taken for the projectile to travel from the breech to the target, and the cameras themselves developed faults and caused electrical interference with the gun circuits which resulted in many blank films.

5.6.1 Chicken carcase on knife-edge target (Figure 20)

This shot took place using the R.A.E. gun, where the chicken and the cylindrical driving plug are enclosed in a nylon bag[3].

The most striking feature of the sequence is the aerodynamic distortion of the projectile, in spite of the relatively low speed (274 kt); this clearly illustrates the difficulty with carcases mentioned in Section 1.0. It would be impossible to guarantee an accurate impact point, and the drag of the body would be variable and high. The contrast with Figure 21 is striking. The aerodynamic distortion clearly had negligible importance with this type of test, but where an accurate strike was required it could invalidate the result.

The full film of this test was used to determine the friction coefficient of the carcase (see Section 5.4.1 and Appendix III, Section 4.0).

5.6.2 Flexalkyd foam dummy on knife-edge target (Figure 21)

The dummy has retained its spherical shape, the only slight defect being that a horizontal slit appears to have occurred in the nylon bag at the nose. As with the chicken carcase, the knife-edge causes no shattering of the dummy, which is split into two apparently equal portions of hemispherical shape.

The full film of this test was used to determine the friction coefficient of the dummy (see Section 5.4.1 and Appendix III, Section 4.0).

5.6.3 Wax dummy on knife-edge target (Figure 22)

No bag or driving plug was necessary with this dummy. The results differ from the previous two in that some fragmentation of the dummy took place, due to the brittle nature of the material. Difficulty in measuring the speeds before and after impact unfortunately made it impossible to derive a friction coefficient.

5.6.4 Wax dummy on flat-plate target (Figure 23)

The shot was fired at N.G.T.E., and the central core of the foam plastic sabot[5] from the vacuum gun can be seen following the dummy. The vertical rod for triggering the oscilloscope (Figure 4) can be seen just in front of the plate. The impact process is clearly shown, particularly the development of circumferential cracks after the initial contact.

6.0 Tests on inlet guide vane assemblies

It was clearly necessary to amplify the basic work on special targets by some comparisons of actual damage to engine blading. There were no facilities for shooting at rotating stages at N.G.T.E., and in any case static blades greatly reduce the number of variables involved (e.g. by enabling an exact point of impact relative to the blade geometry to be consistently maintained). Scrap Rolls-Royce Avon i.g.v. assemblies were readily available and so it was decided to test these. Sufficient blades of the same mark of engine were not available, so both light alloy and steel had to be used. The blade setting angle was variable from 0° to 35° at mid-span (referred to as 'fully-open' and 'fully-closed' respectively), as shown in Figure 24.

6.1 Damage assessment criterion

To introduce some quantitative criterion on which to base damage comparisons, it was decided to use a points system as follows:

3 points per blade completely broken off,

2 points per blade bent so that it pulled out at the tip, but did not break off,

1 point per blade bent but not pulled out at the tip.

The numbers were arrived at arbitrarily, but seemed to give useful results in practice. (Fractional scores were used in borderline cases, e.g. 1·5 for a blade severely bent, but not quite pulled out, 0·5 for a slight bend, etc.)

Figure 24 shows the outlines of three sizes of dummy superimposed on the aluminium i.g.v. assembly. From an examination of the marks on the blades, it appeared that in practice the impact point was held within a circle of about half an inch radius around the nominal aiming point.

From the Figure it may be postulated that the maximum damage that could occur would be when all the blades covered by the cross-section of a given projectile were removed. This could be regarded as defining a 'maximum damage rating'. However, it is possible that sideways deflection of debris from the projectile and/or blades could damage blades not in the direct line of flight. Hence the maximum damage rating was defined in each case by deciding the most likely damage additional to that resulting from removal of blades which lay in the flight path of the projectile. This resulted in the following values:

	Maximum damage rating	
Projectile weight	Blades fully-closed	Blades fully-open
1 lb	10	8
2 lb	10	9
4 lb	11	10

The experimental results suggested that these values were realistic.

6.2 Tests on aluminium alloy blades

Figure 25(a) shows results with blades fully-open and 1·5 to 2 lb projectiles. There is great scatter, as might be deduced from a study of the effect of small errors in aim on the geometry of Figure 24: even the small aiming scatter mentioned in the previous Section allowed considerable variation of potential damage with the smaller projectiles. However, the possible trend with momentum which may be deduced is consistent with the results in Figure 25(b). Here the consistency is remarkably good, with the unexplained exception of one emulsion dummy which did some damage. It is clear that the wax dummies were much too severe, while there was good agreement between the chicken carcase and the emulsion and flexalkyd types, at least as far as tested. Figure 26 shows photographs of the contrast in damage at around 390 ft/s. Higher speeds did not become experimentally feasible until after the light alloy i.g.v. assemblies had been used up.

With blades fully-closed (Figure 27) the weakest bending axis of the blade was exposed to the impact, and the damage was not surprisingly very much greater; it was again proportional to momentum. There was no detectable difference between the two types of dummy tested, and unfortunately no other types of dummy were available for these tests, and chicken carcases could not be used on the enclosed rig.

Frames from high-speed films of two shots are shown in Figures 28 and 29. They represent points from Figure 25, and although not comparable because of the very different weights used, they showed that it was possible to film the impact process usefully. Trials have since been conducted on devices to prevent the interference of so much sabot debris, which obscured the photographs although it had a negligible effect on damage. The film in slow motion clearly showed the rapid torsional oscillations of the blades during the strike in Figure 28.

6.3 Tests on steel blades

The next set of i.g.v. assemblies to become available had hollow steel blades, so the results are not directly comparable to those already discussed. They appeared to be rather weaker than the solid alloy blades (compare Figures 25(b) and 30 with soft dummies at a momentum of 50 slug ft/s), but this was affected by a slight difference in the definition of damage rating. Because the ductile steel blades rarely broke off cleanly, it was decided that where they were laid right back and severely cracked at the root, as in Figure 31, they would score 3 points, as for a complete break.

Adequate speeds were available to cause maximum damage, and Figure 30 shows that the emulsion and gelatine types agreed quite closely with the chicken carcase up to just beyond the momentum for maximum damage. A comparison is illustrated in Figure 31.

6.4 Effect of blade incidence

The greatly increased damage when the blades were 'closed' has already been noted (Section 6.2). Tests at various intermediate incidences were therefore proposed, but it was immediately found that turning the blades only 5° from fully-open altered the damage rating from zero to maximum (see Figure 32). A further test at 15° also produced maximum damage.

7.0 Discussion and conclusions

The most obvious conclusions from the tests were that the hard dummies had impact characteristics which differed widely from those of the chicken carcases or the soft dummies, and that the differences between the soft dummies and the chicken carcases in all the types of test were small. The special target deflection measurements provided little evidence for an order of merit for the soft dummies but the flexalkyd foam appeared to have a slight advantage over the emulsion type, which gave deflections which were too high.

The transducer oscillographs again showed close agreement between the soft projectiles, but the high initial acceleration with the flexalkyd foam dummy suggested that the emulsion type was a little more realistic. The impact forces derived from the oscillographs showed that the one result with an emulsion dummy on the knife-edge target gave too high a force. This agreed with the finding mentioned above for the deflection measurements. The i.g.v. tests did not show any significant differences between the soft dummies, but a lack of flexalkyd dummies weakened the comparison.

It was unfortunate that the gelatine dummy was introduced into the programme so late, but it was quite thoroughly assessed in the most important case - the inlet guide vanes, and the three results available with the special targets agreed well with the chicken carcase.

In making a choice between the three soft dummies, the flexalkyd foam type is to be preferred to the emulsion dummy because it can simulate density correctly (Appendix II). It is also much more robust, an important factor when shooting at high velocities. The choice between the gelatine and flexalkyd foam dummies is not clear on the evidence of the tests described, but the case for the gelatine type is greatly strengthened by its proved success as a simulator in the ballistic studies mentioned below.

Discovery of the gelatine gave rise to the interesting question of whether a chicken carcase itself is a satisfactory simulator of a living bird. The original reason for development of the gelatine had been that studies of ballistic wounding[6] had shown that dead tissue did not adequately simulate living tissue, a conclusion also reached in studies of vehicle accident injuries[7]. Hence there is reason to suppose that the gelatine may actually be a better simulator of a living bird than is a dead bird. However, the closely similar results obtained with chicken carcases and the gelatine dummies indicate that in impact studies the differences between living and dead tissue are much less important than in cases where the penetration of small objects into tissue is being considered. It also seems theoretically reasonable that the bulk characteristics such as density, coefficient of restitution, and momentum are the really influential variables in impact of the whole body on other bodies.

However, where the impact behaviour of the gelatine dummies differs from bird carcases, there is reason to suppose that the gelatine may actually be the more realistic simulator of a living bird. There is no doubt that caution should be exercised when interpreting the results of tests using carcases, and only freshly-killed birds should be used whenever possible. The deterioration of cell structure which takes place after death, and which changes the mechanical properties of the tissue, is not prevented by freezing. Any departure from normal body temperature at the time of use also affects mechanical properties.

Thus it may be concluded that for bird ingestion research, the best projectile material is the gelatine specified in Appendix II. This conclusion is indeed fortunate, because the gelatine dummy was the cheapest and easiest to make, and had sufficient strength to survive the high acceleration in air guns. Extensive testing at N.G.T.E. and elsewhere has highlighted the advantages of using dummies and several hundred have been fired at N.G.T.E. and Rolls-Royce. The gelatine can, of course, be moulded to any desired shape.

The only circumstances in which a carcase would still seem to be preferable to a dummy are as follows:

(a) When a proving test on a complete engine is being done. The dummy would not represent secondary effects, such as blockage of bleed valves by feathers, etc.

(b) When impact speeds are very low, say less than 100 kt. The tough covering of feathers may then have a significant effect, but there is no definite evidence on this point.

The wax dummy might find a use as a cheap and convenient "slave" for proving rigs, etc., because in general it causes a more severe impact than do the soft dummies.

The comparative tests resulted in considerable secondary information which may be summarised thus:

(a) Damage to inlet guide vanes is very sensitive to the incidence of the blades to the projectile flight path.

(b) The forces due to friction are significant when sharp objects are struck at small angles. Friction coefficients between about 0·1 and 0·35 for soft dummies or chicken carcases were indicated.

(c) The forces resulting from impact on flat or rounded surfaces are extremely high. Values of up to 290 ton at about 1000 ft/s were produced on a flat plate by chicken carcases weighing 4 lb.

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APPENDIX I

List of symbols

$\bar{F}$	average force of impact along original line of flight of projectile
$\bar{F}_f$	average force of impact along original line of flight of projectile due to frictional forces
$\bar{F}_m$	average force of impact along original line of flight of projectile due to deflection of projectile debris
k	beam spring constant
m	mass of projectile
M_e	equivalent mass of target and beams
r	radius of projectile
v	velocity of projectile immediately prior to impact
v_1	component of velocity along original line of flight of projectile debris leaving target after impact
V_{max}	maximum target velocity from smoothed oscilloscope trace
δ	beam deflection
Δt	time duration of impact
θ	angle between line of flight of debris leaving target and original line of flight of projectile
μ	coefficient of friction of projectile debris on target surface
ρ	density of projectile

APPENDIX II

Description of dummy birds

1.0 Flexalkyd foam

1.1 Mould

This was made in glass fibre laminate, in two equal parts, flanged at the centre line, and with clamps or bolts to hold the halves together. A hole of about $\frac{1}{8}$ in. diameter was bored in the top half for venting.

The mould was lined with a thin coat of stearate grease, (Ralli Bondtite EL.50 Release Agent).

1.2 Foam manufacture

Formula:

200 g	Flexalkyd resin (modified)
113 g	Barium sulphate precipitated
2 ml	N.COCO morpholine
1·3 ml	Armeen DMCD
2 ml	Water
53 ml	Tolnylene diisocyanate Desmodur T.65

The mix was first poured into the lower half of the mould, and then the top half clamped on while pouring continued.

After pouring, the mould was left at room temperature for 5 hr and then post-cured at 60°C overnight. The foam had a bulk specific gravity of about 0·18 and the specific gravity of the matrix itself was about 1·18.

1.3 Water-filling

The completed core was evacuated and filled with water as follows:-

1. A vacuum chamber was made, consisting of a section of water pipe about 10 in. diameter, flanged so that it could be sealed with a transparent diaphragm at one end, the other end being closed. A vacuum pump connection was attached.

2. The cores were checked to see if a thin skin had formed on them, and if so this was lightly rubbed off with coarse sandpaper. They were then put into the vacuum chamber and water added to virtually fill the chamber. A metal weight was used to keep the buoyant cores under water.

3. After sealing, the chamber was evacuated to the residual vapour pressure of the water, and then the pump shut off to prevent it taking in too much vapour.

4. Air continued to bubble out of the cores for some time, and when this ceased, the chamber was opened to the atmosphere and left for about 24 hr. The cores, which shrank and wrinkled when evacuated, gradually took up their original shape as they absorbed water.

5. The cores were gently squeezed until a weight was obtained giving the desired relative density before skinning.

1.4 Skinning

The skin consisted of 100 g Silcoset 101 and 2 g Accelerator A. It was applied as one coat, with the dummy spitted on a $\frac{1}{8}$ in. diameter steel rod. The skin thickness was about $\frac{1}{16}$ in., and the dummy rotated slowly on the spit until the skin set. The skin was then cured for 5 hr at room temperature.

1.5 Characteristics

The dummies could have any density between about 0·2 and just over 1·0, depending on the water content, but below a relative density of about 1 there were substantial air spaces. The desired density could be obtained within about ±0·5 per cent.

There were negligible short-term ageing effects and the debris after a strike was non-toxic and inorganic.

The dummies felt resilient and the foam strongly resisted manual tearing.

2.0 Beechwood

2.1 Manufacture

Three planks of beechwood were glued together with P.V.A. adhesive, and turned to the desired size and shape with the grain along the major axis. No finish was applied.

2.2 Characteristics

The density was 0·721 ±2 per cent and could not be varied.

There were negligible short-term ageing effects and debris after a strike was of course harmless and non-putrefying.

3.0 Wax

3.1 Manufacture

Paraffin wax was poured into a suitable mould and allowed to set. The need for continual topping-up to compensate for shrinkage could be avoided by filling the mould initially with broken lumps of solid wax before pouring in molten wax, which then melted the solid lumps and mixed with them to form a homogeneous body.

3.2 Characteristics

The density was 0·886 ±2 per cent and could not be varied more than about ±10 per cent.

There were negligible short-term ageing effects and debris after a strike was of course harmless and non-putrefying.

4.0 Gelatine/oil emulsion

4.1 Mould

The mould could be of any material. It was lined with a thin layer of MS.4 silicone compound. This could last for two or three mouldings.

4.2 Dummy materials (quoted for 4 lb bird)

270 g	Decorators size
1320 g	Tap water
60 g	Zal Pine Disinfectant (in neat form)
910 g	OM 108 machine oil
50 g	Sisal string, shredded into the separate fibres and cut to about 3 in. lengths

4.3 Manufacturing method

1. All the size was put into 320 g cold water in a large (3 to 4 litre) glass beaker and left for 5 min while it swelled.

2. The beaker was placed on a hotplate at 60 to 70°C for all the following stages, until ready for moulding.

3. One litre of hot water was added and stirred with an emulsifier until all the size disappeared and a creamy liquid was obtained.

4. All the disinfectant was added and stirred until fully mixed in.

5. All the oil was poured in while continuing emulsification until a thick creamy substance was obtained.

6. The emulsifier was removed and 40 g of the string gradually added while stirring with a spatula to ensure it was thoroughly mixed in.

7. The lower half of the mould was filled, taking care to exclude air bubbles.

8. The top half of the mould was then put on and the rest of the mix pushed in with a stick. The remaining 10 g of string was added when the mould was nearly full, and about the last 100 cc of liquid put in with a syringe. (The 10 g of string put in by itself allowed for the fact that the syringe tended to inject only the liquid, leaving the already-mixed string behind.)

9. The mould was left for at least 4 hr.

4.4 Characteristics

The dummies had a density of 0·8 ±5 per cent which could not be varied more than a few per cent. There were minor ageing effects when stored in a sealed bag, but exposure to air allowed a skin to form, which eventually deepened to at least 0·25 in. and could crack. After several weeks the original dead feel was replaced by a more resilient one. The dummies had little mechanical strength. If no skin were allowed to form, a mould developed after a few days, and the debris could also go mouldy eventually, if not removed after a strike.

5.0 Gelatine

5.1 Manufacture

Acid-processed pigskin gelatine was dissolved in hot tap water to make a 20 per cent solution by weight. After standing to allow bubbles to surface, it was poured into any suitable mould and allowed to set. There was virtually no volume change when cold.

5.2 Characteristics

The density was 1·02 ± about 2 per cent and could be varied a small amount. The dummy would grow a heavy mould if left exposed for more than about 48 hr, but this could easily be prevented by keeping it in a plastic bag. Debris from a strike was non-toxic but could eventually go mouldy. The dummy was fairly resilient, semi-transparent and difficult to tear.

APPENDIX III

Estimation of forces and deflections for special target tests

1.0 Assumptions

The assumptions were chosen to be appropriate to the characteristics of the carcases and soft dummies. Hence the wooden projectile results were unlikely to be predicted at all accurately, while the wax results might be expected to form an intermediate case. The approximations involved were substantial even for the soft dummies, but the calculations formed an adequate basis for comparison with the experimental results. The assumptions were as follows:

(a) Coefficient of restitution zero, i.e. all momentum normal to a target surface destroyed on impact.

(b) Projectile spherical, and effective duration of impact given by ratio of projectile diameter to velocity.

(c) Projectile homogeneous. This was true in practice for all cases except the chicken carcases.

(d) Target movement during impact negligible, i.e. maximum target velocity was reached in zero deflection distance.

2.0 Calculations for the flat-plate and round-nose targets

2.1 Force

In these cases friction between the projectile and the target surface could clearly play little or no part, so momentum forces only are considered.

The average force parallel to the original flight-path of the projectile due to deflection of the mass is given by:

$$F = \frac{mv}{\Delta t}(1 - \cos^2\theta) = \frac{mv \sin^2\theta}{\Delta t} \qquad \text{....(III.1)}$$

where F is average force along target axis (lb)

m is mass of projectile (slug)

v is velocity of projectile (ft/s)

Δt is duration of impact (sec)

θ is angle from initial line of flight through which projectile is deflected ($^\circ$)

Now it is assumed that $\Delta t = \frac{2r}{v} = \frac{1 \cdot 24}{v}\left(\frac{m}{\rho}\right)^{\frac{1}{3}}$ sec ....(III.2)

for a spherical projectile,

where r is projectile radius (ft)

ρ is projectile density (slug/ft^3)

$\therefore$ from Equations (III.1) and (III.2)

$$F = \frac{mv^2 \sin^2\theta}{1 \cdot 24}\left(\frac{\rho}{m}\right)^{\frac{1}{3}}. \qquad \text{....(III.3)}$$

If m is assumed to be 0·124 slug (4 lb), and ρ is taken as 1·935 slug/ft^3 (62·35 lb/ft^3, i.e. a relative density of 1·0), Equation (III.3) becomes

$$F = \frac{v^2 \sin^2\theta}{4} \text{ lb}. \qquad \text{....(III.4)}$$

2.2 Beam deflection

By conservation of momentum along the line of flight,

$$M_e\, V_{max} = mv \sin^2\theta \qquad \text{....(III.5)}$$

where M_e is equivalent mass of the target and mounting beams (slug)

V_{max} is maximum velocity of target (ft/s)

Equating the kinetic energy of the target to the strain energy of the beams,

$$\tfrac{1}{2} M_e\, V_{max}^2 = \tfrac{1}{2} k\, \delta^2 \qquad \text{....(III.6)}$$

where k is load/unit deflection of the beams (lb/ft)

δ is deflection of target beams (ft)

$\therefore$ from Equations (III.5) and (III.6)

$$\delta = \frac{mv \sin^2\theta}{(k\ M_e)^{\frac{1}{2}}} \cdot ft \qquad \text{....(III.7)}$$

The beam load/unit deflection curve was not quite linear, particularly at the start, but the following values are very good approximations for deflections generally falling in the ranges shown.

$\delta > 0{\cdot}1$ ft	$k = 23{,}000$ lb/ft
$0 < \delta < 0{\cdot}1$ ft	$k = 25{,}200$ lb/ft
$0 < \delta < 0{\cdot}017$ ft	$k = 30{,}000$ lb/ft

Now $M_e = 10{\cdot}84$ slug (349 lb), made up of the target mass of $7{\cdot}61$ slug (245 lb) and $\frac{17}{35}$ of the mass of the beams[7]. Hence for the flat plate, where $\theta = 90^\circ$ and the deflections are generally more than $0{\cdot}1$ ft

$$\delta = \frac{mv}{499}\ ft. \qquad \text{....(III.8)}$$

For the round nose the deflection angle is not self-evident, and the beam deflections lay in the range from about $0{\cdot}017$ to $0{\cdot}1$ ft. Thus $k = 25{,}200$ and

$$\delta = \frac{mv \sin^2\theta}{521}\ ft. \qquad \text{....(III.9)}$$

3.0 Calculations for the knife-edge targets

3.1 Force

The average component of force due to the deflection of the projectile debris is given by Equation (III.1). The average component arising from friction may be calculated thus:

$$\text{average force normal to the surface} = \frac{mv \sin\theta}{\Delta t} \text{ lb}$$

$$\therefore \quad \text{average force parallel to the surface} = \frac{\mu\, mv \sin\theta}{\Delta t} \text{ lb}$$

which defines a coefficient of friction μ between the halves of the projectile and the surfaces of the wedge.

$$\therefore \qquad F_f = \frac{\mu\, mv \sin\theta \cos\theta}{\Delta t} \text{ lb} \qquad \text{....(III.10)}$$

where F_f is the average force of impact along the original line of flight of the projectile due to frictional forces

and $$F = F_m + F_f$$

where F_m is the average force of impact along the original line of flight of the projectile due to deflection of projectile debris.

$\therefore$ from Equations (III.1) and (III.10):

$$F = \frac{mv \sin^2\theta}{\Delta t} + \frac{\mu\, mv \sin\theta \cos\theta}{\Delta t}$$

$$\therefore \qquad F = \frac{mv \sin\theta}{\Delta t}(\sin\theta + \mu\cos\theta). \qquad \text{....(III.11)}$$

Then, taking Equation (III.2) for the effective duration of impact

$$F = \frac{mv^2 \sin\theta}{1.24}\left(\frac{\rho}{m}\right)^{\frac{1}{3}}(\sin\theta + \mu\cos\theta) \qquad \text{....(III.12)}$$

and substituting the same values for m and ρ as in Equation (III.4) and putting $\theta = 9{\cdot}5^{0}$,

$$F = 0{\cdot}0068\ v^2\ (1 + 5{\cdot}98\mu)\ \text{lb.} \qquad \ldots.(III.13)$$

3.2 Beam deflection

Equation (III.5) is modified by the addition of the impulse from the frictional force.

$\therefore$ from Equations (III.5) and (III.10)

$$M_\theta\ V_{max} = mv \sin^2\theta + \mu\ mv \sin\theta \cos\theta$$

$$= mv \sin\theta\ (\sin\theta + \mu \cos\theta) \qquad \ldots.(III.14)$$

$\therefore$ from Equations (III.6) and (III.14),

$$\delta = \frac{mv \sin\theta\ (\sin\theta + \mu\cos\theta)}{(k\ M_\theta)^{\frac{1}{2}}}. \qquad \ldots.(III.15)$$

For the original knife-edge target, $\theta = 9{\cdot}5^{0}$, $M_\theta = 10{\cdot}84$ slug (349 lb) and $0 < \delta < 0{\cdot}017$ in., so a k of 30,000 lb/ft was appropriate. Hence

$$\delta = mv\ (1 + 5{\cdot}98\mu)\ 4{\cdot}78 \cdot 10^{-5}\ \text{ft.} \qquad \ldots.(III.16)$$

For the light knife-edge the only change is that M_θ was 5·09 slug (164 lb), hence

$$\delta = mv\ (1 + 5{\cdot}98\mu)\ 6{\cdot}97 \cdot 10^{-5}\ \text{ft.} \qquad \ldots.(III.17)$$

4.0 Estimation of friction coefficient

The films from which Figures 20 and 21 were obtained were unfortunately the only successful ones on which velocity before and after impact could be measured with tolerable accuracy. They were analysed as follows:

$$\left.\begin{array}{l}\text{Initial velocity of projectile} = v \\ \text{Velocity of projectile immediately after} \\ \text{strike} = v_1\end{array}\right\} \text{measured from film}$$

v_1 as measured is parallel to the initial line of flight.

$\therefore$ final velocity along surface of wedge $= \dfrac{v_1}{\cos\theta}$.

If there were no friction,

$$v \cos\theta = \frac{v_1}{\cos\theta}$$

so the loss of velocity along the wedge surface due to friction is given by

$$v \cos\theta - \frac{v_1}{\cos\theta}.$$

Now the frictional force parallel to the surface is

$$\frac{\mu\, mv \sin\theta}{\Delta t}.$$

So $$\frac{\mu\, mv \sin\theta}{\Delta t} = \frac{m}{\Delta t}\left(v \cos\theta - \frac{v_1}{\cos\theta}\right)$$

$$\therefore \qquad \mu = \frac{1}{v \sin \theta}\left(v \cos \theta - \frac{v_1}{\cos \theta}\right)$$

$$= \cot \theta - \frac{v_1}{v \sin \theta \cos \theta}$$

$$\mu = \cot \theta - \frac{2v_1}{v \sin 2\theta}. \qquad \text{....(III.18)}$$

For $\theta = 9{\cdot}5^{\circ}$,

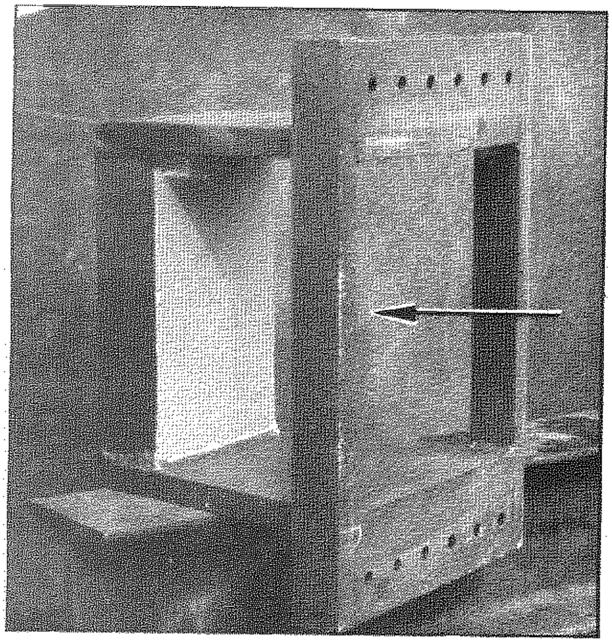
$$\mu = 5{\cdot}976 - \frac{6{\cdot}14\ v_1}{v}. \qquad \text{....(III.19)}$$

For the chicken carcase in Figure 20, measurements from the film gave $v = 500$ ft/s, $v_1 = 458$ ft/s

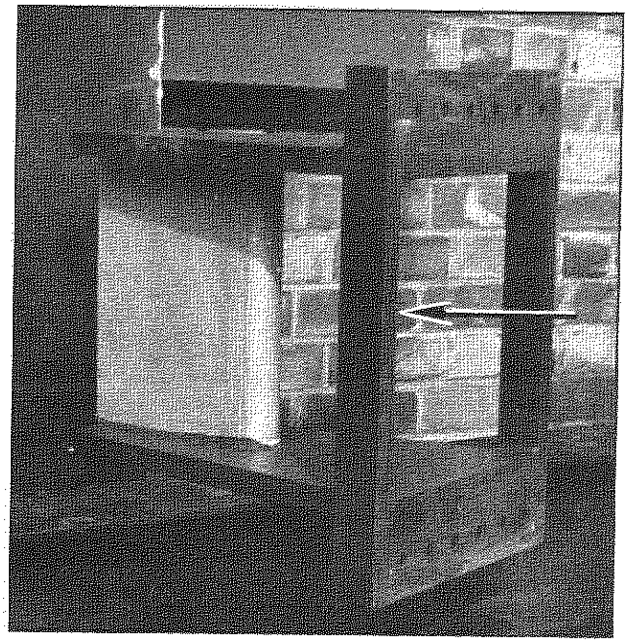
$$\therefore \qquad \mu = 5{\cdot}976 - 5{\cdot}63 = \underline{\underline{0{\cdot}346}}.$$

For the flexalkyd foam dummy in Figure 21, $v = 488$, $v_1 = 457$

$$\therefore \qquad \mu = 5{\cdot}976 - 5{\cdot}75 = \underline{\underline{0{\cdot}226}}.$$

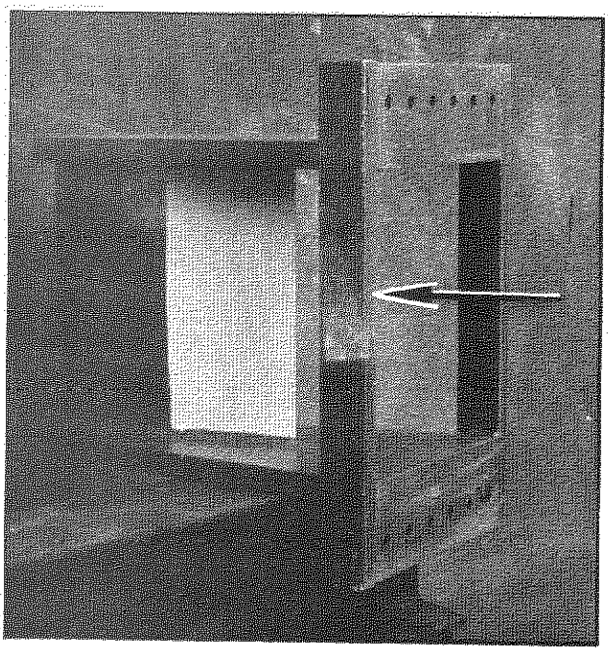


(a) FLAT PLATE

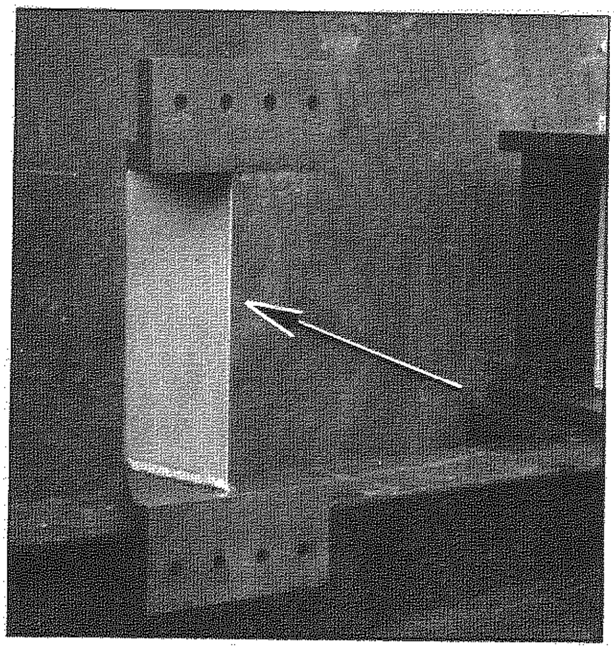


(b) ROUND NOSE

ARROWS SHOW LINE OF FLIGHT OF PROJECTILE

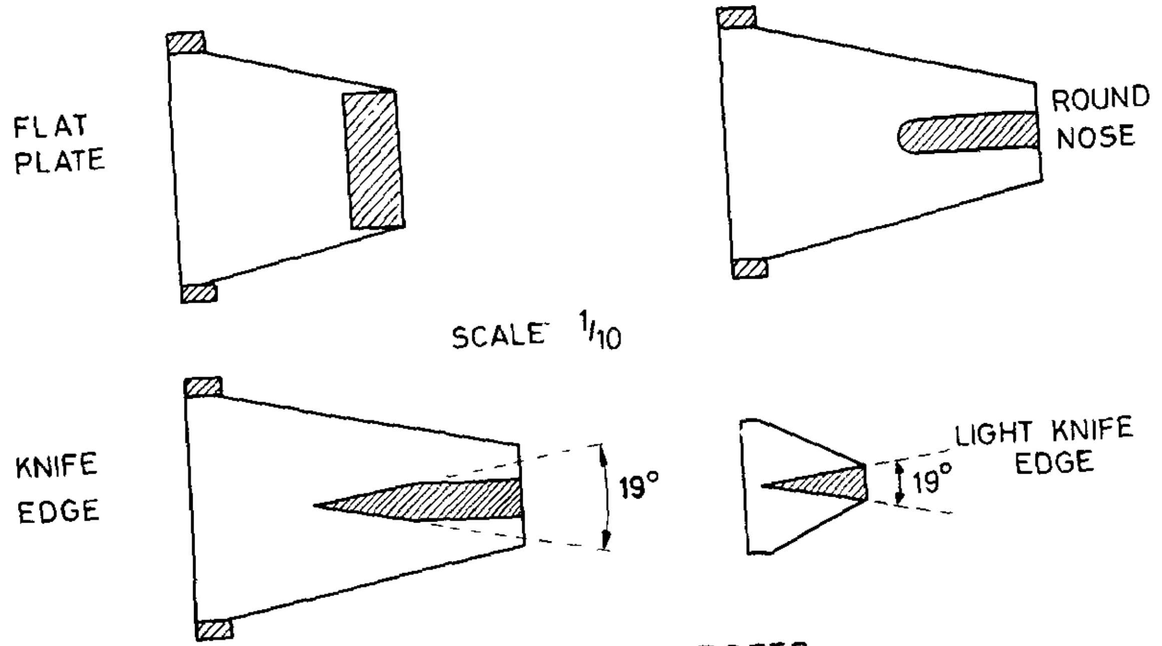


(c) KNIFE EDGE

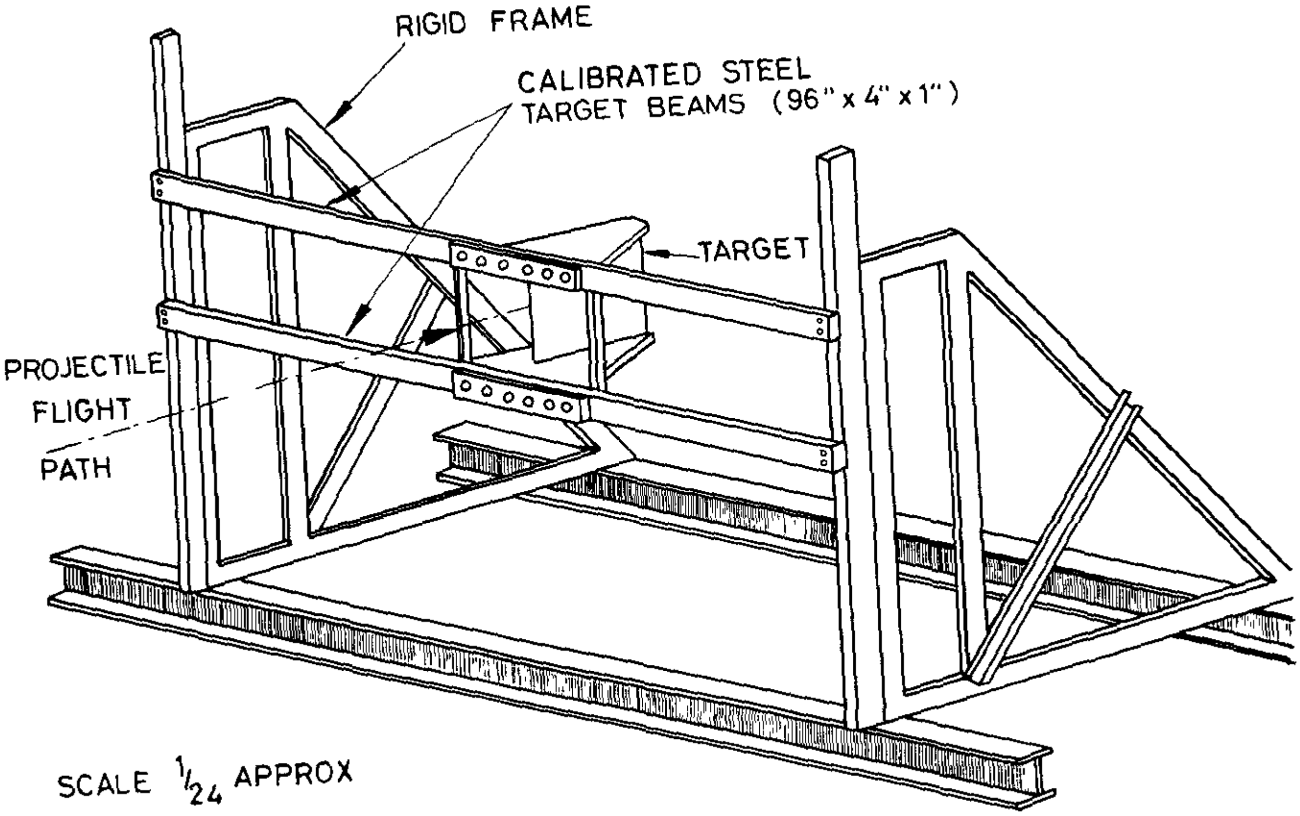


(d) LIGHT KNIFE EDGE

FIG. 1 SPECIAL TARGETS



(a) SECTIONS THROUGH TARGETS



(b) SKETCH OF SPECIAL TARGET RIG

FIG. 2 SPECIAL TARGETS AND RIG

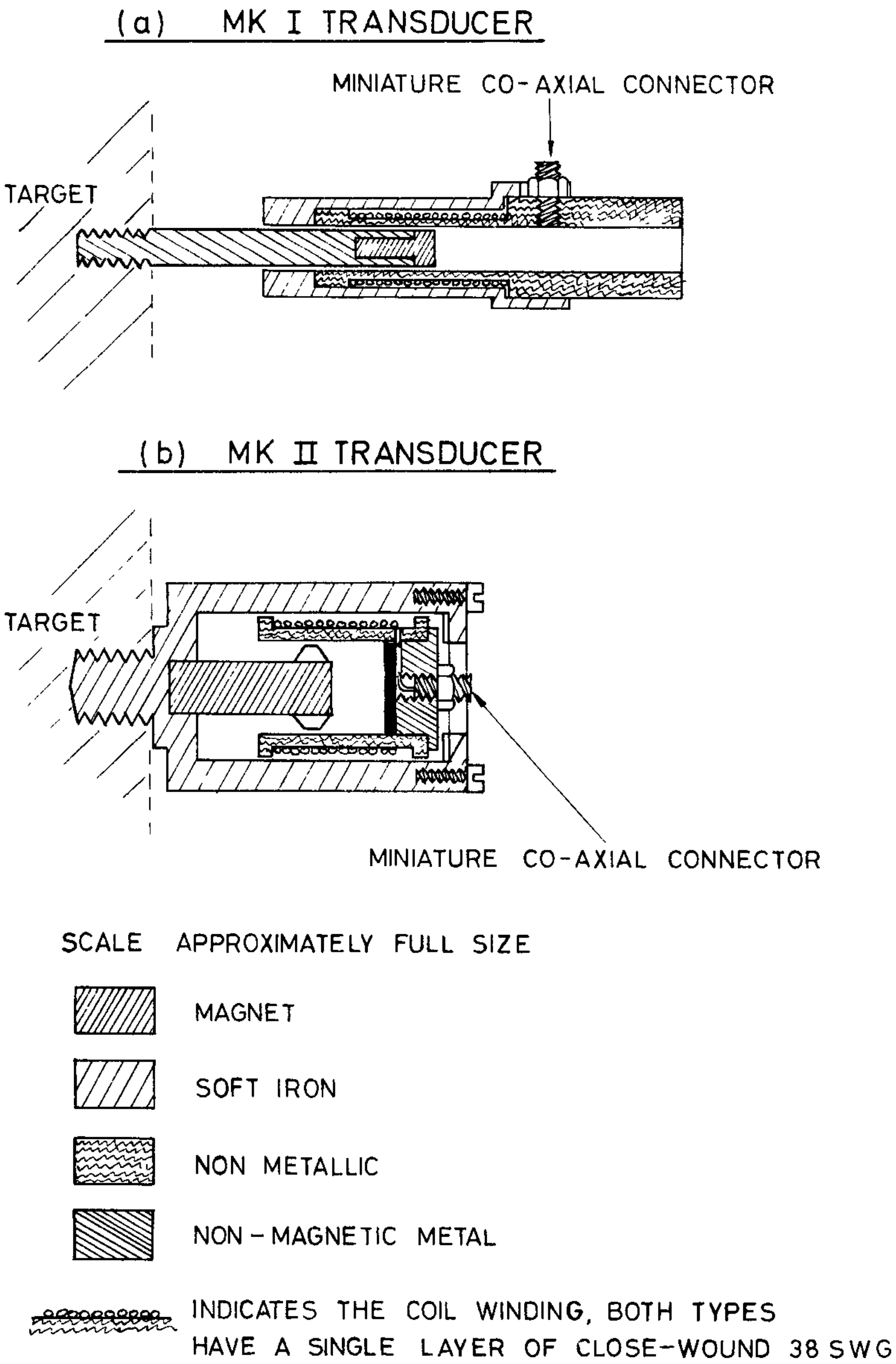


FIG. 3 CROSS-SECTIONS OF VELOCITY TRANSDUCERS

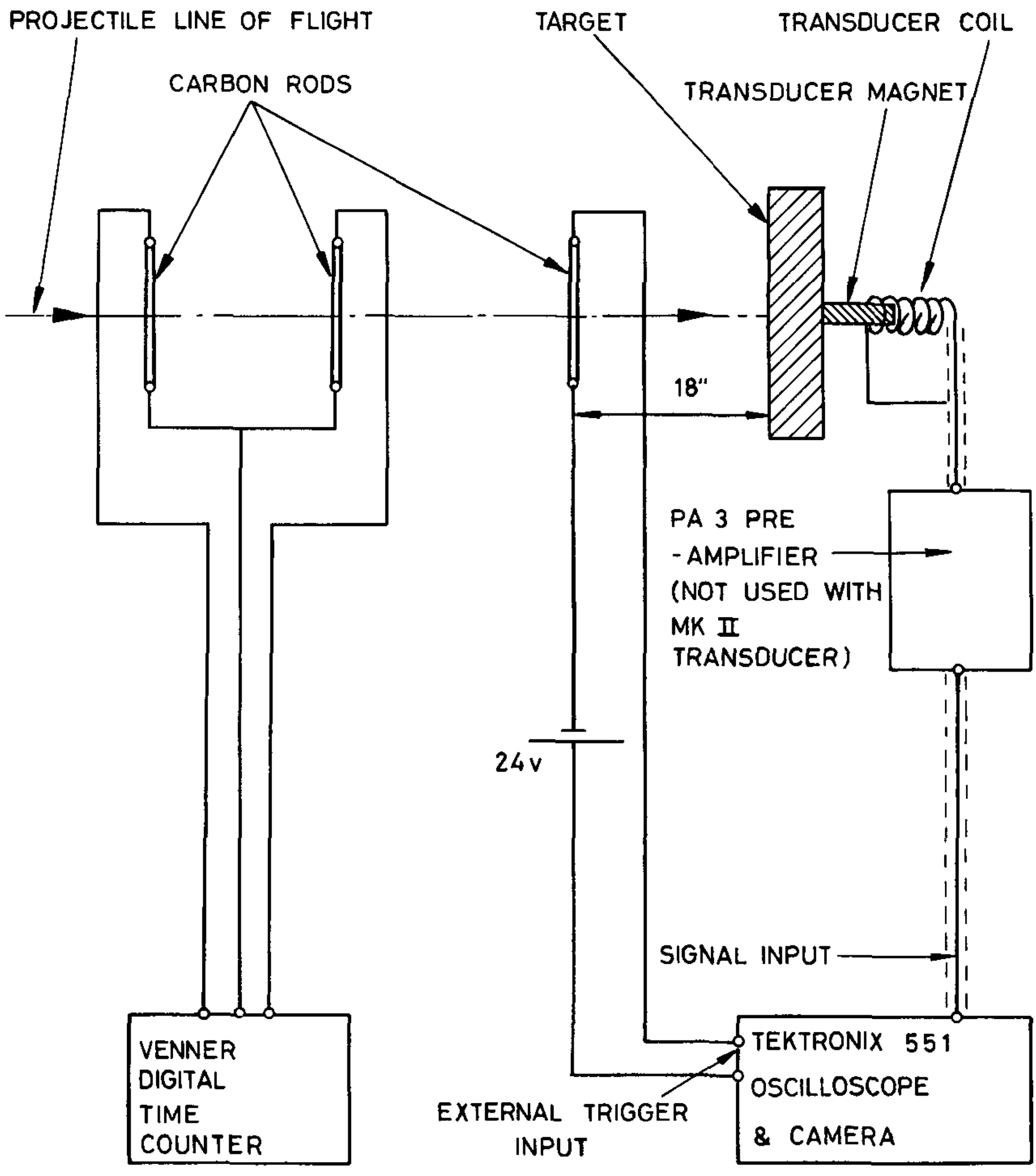
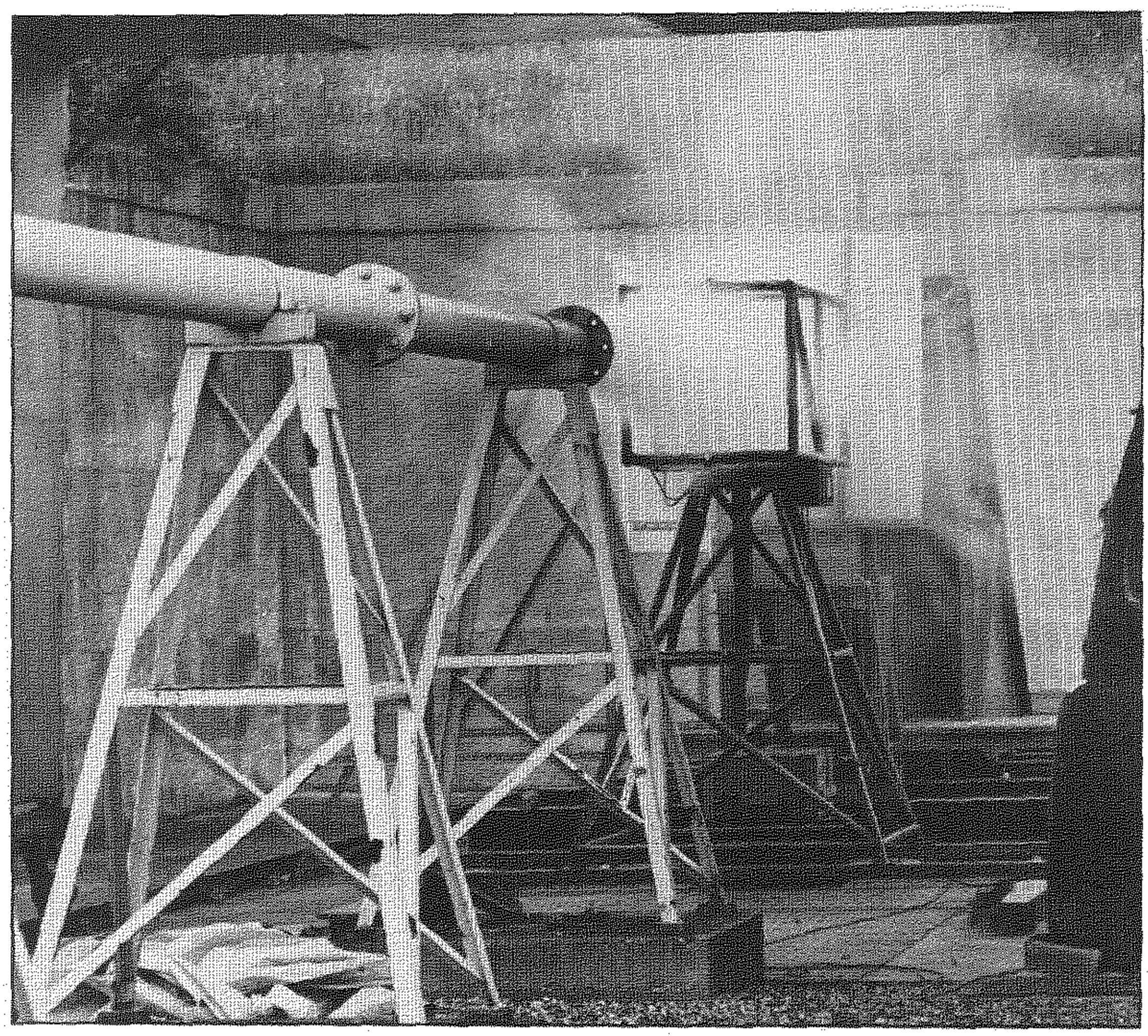
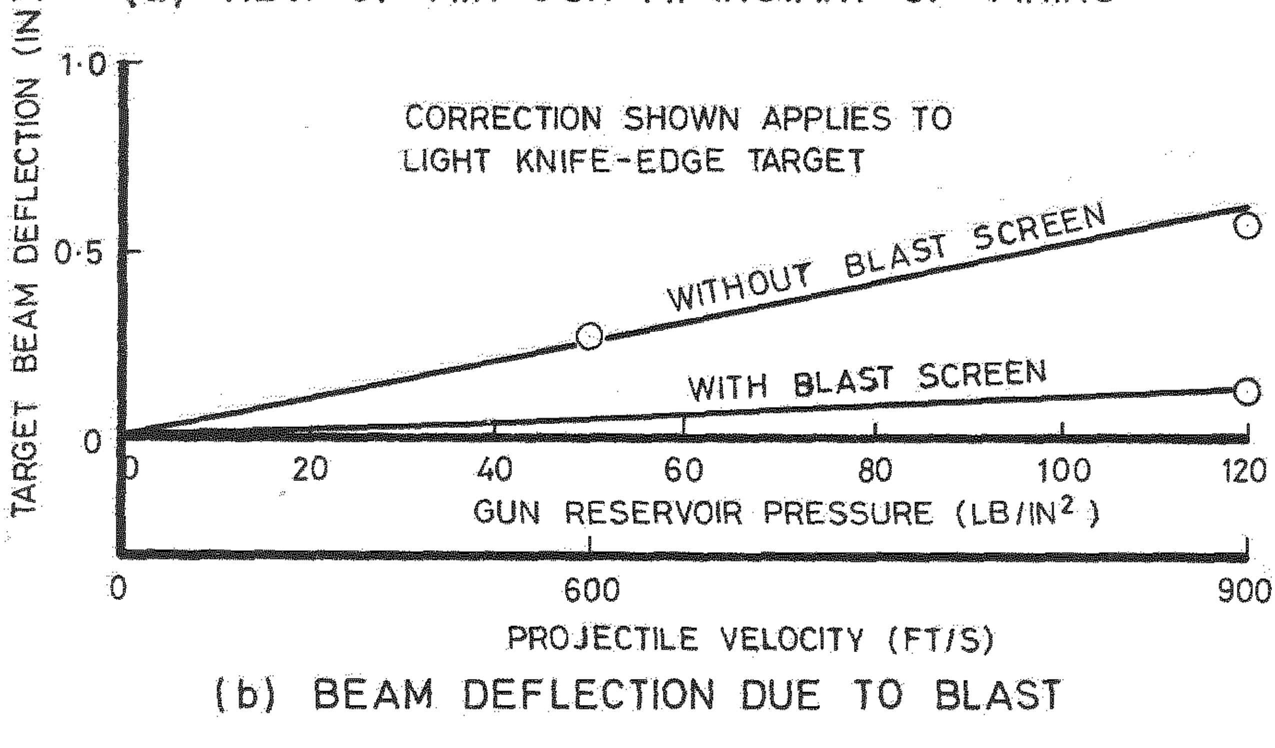


FIG. 4 ELECTRICAL CIRCUITS FOR SPECIAL TARGET TESTS



(a) VIEW OF AIR GUN AT INSTANT OF FIRING



(b) BEAM DEFLECTION DUE TO BLAST

FIG. 5 AIR GUN BLAST EFFECTS

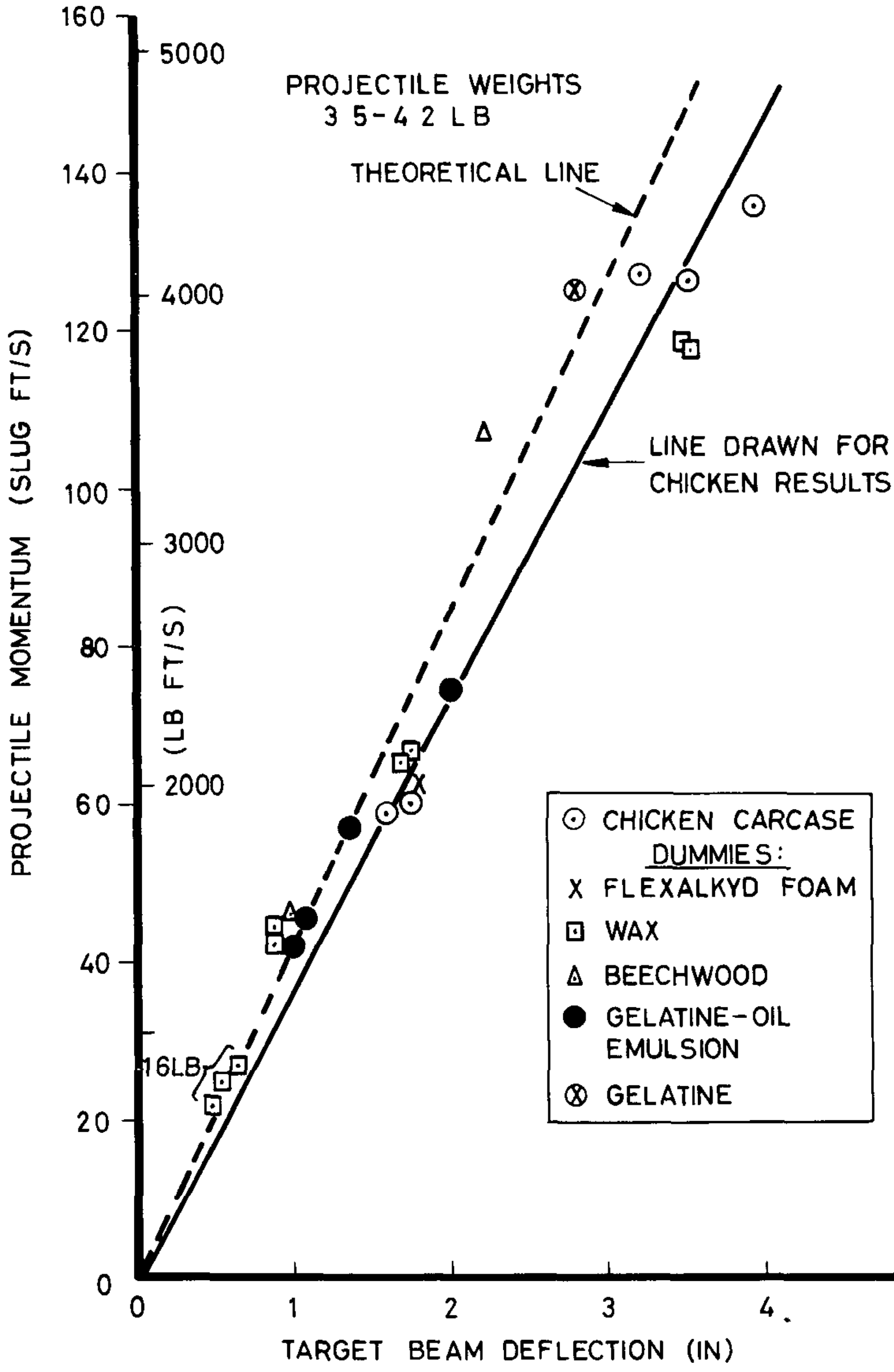


FIG. 6 TARGET BEAM DEFLECTIONS: FLAT PLATE

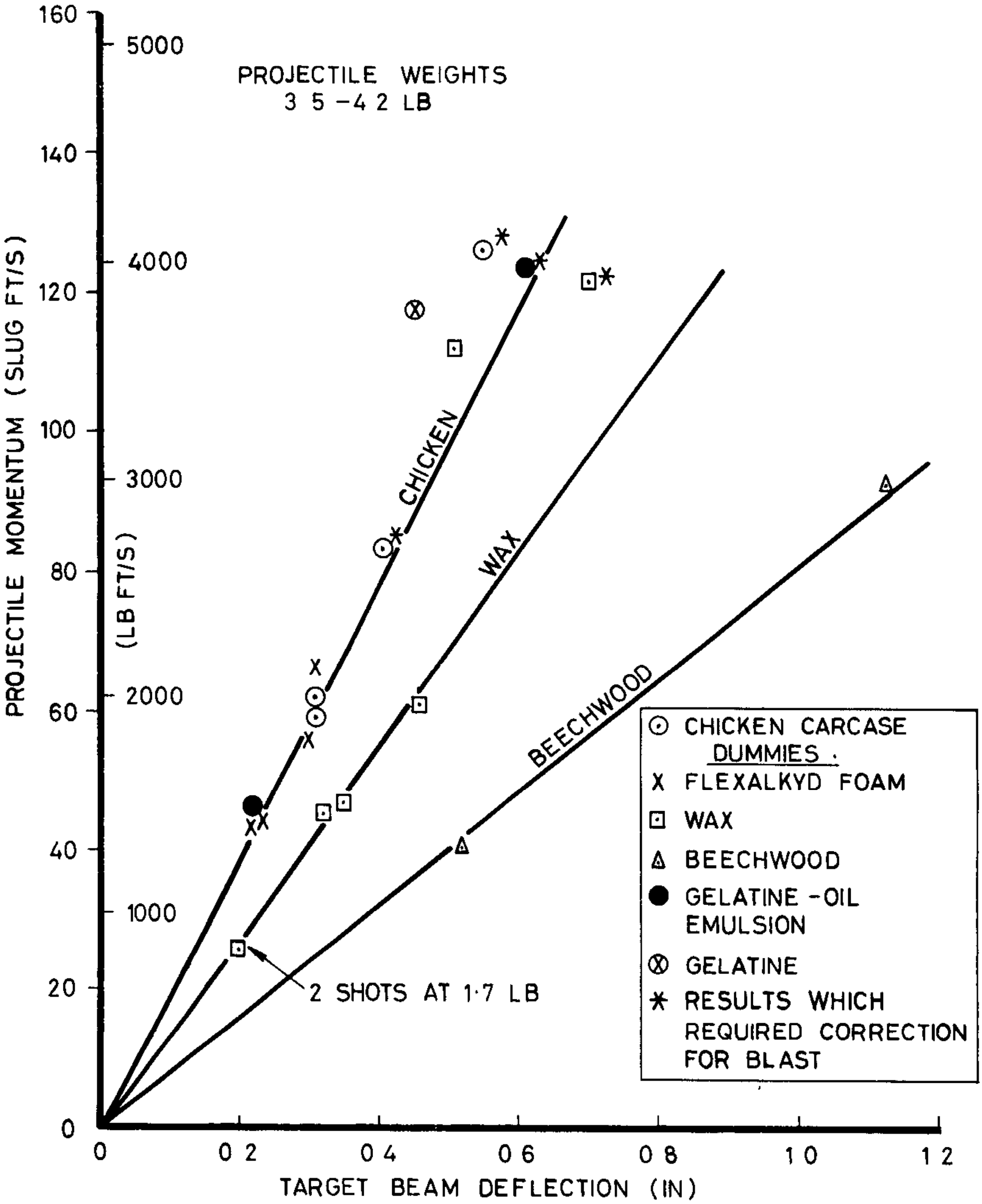


FIG. 7 TARGET BEAM DEFLECTIONS: ROUND NOSE

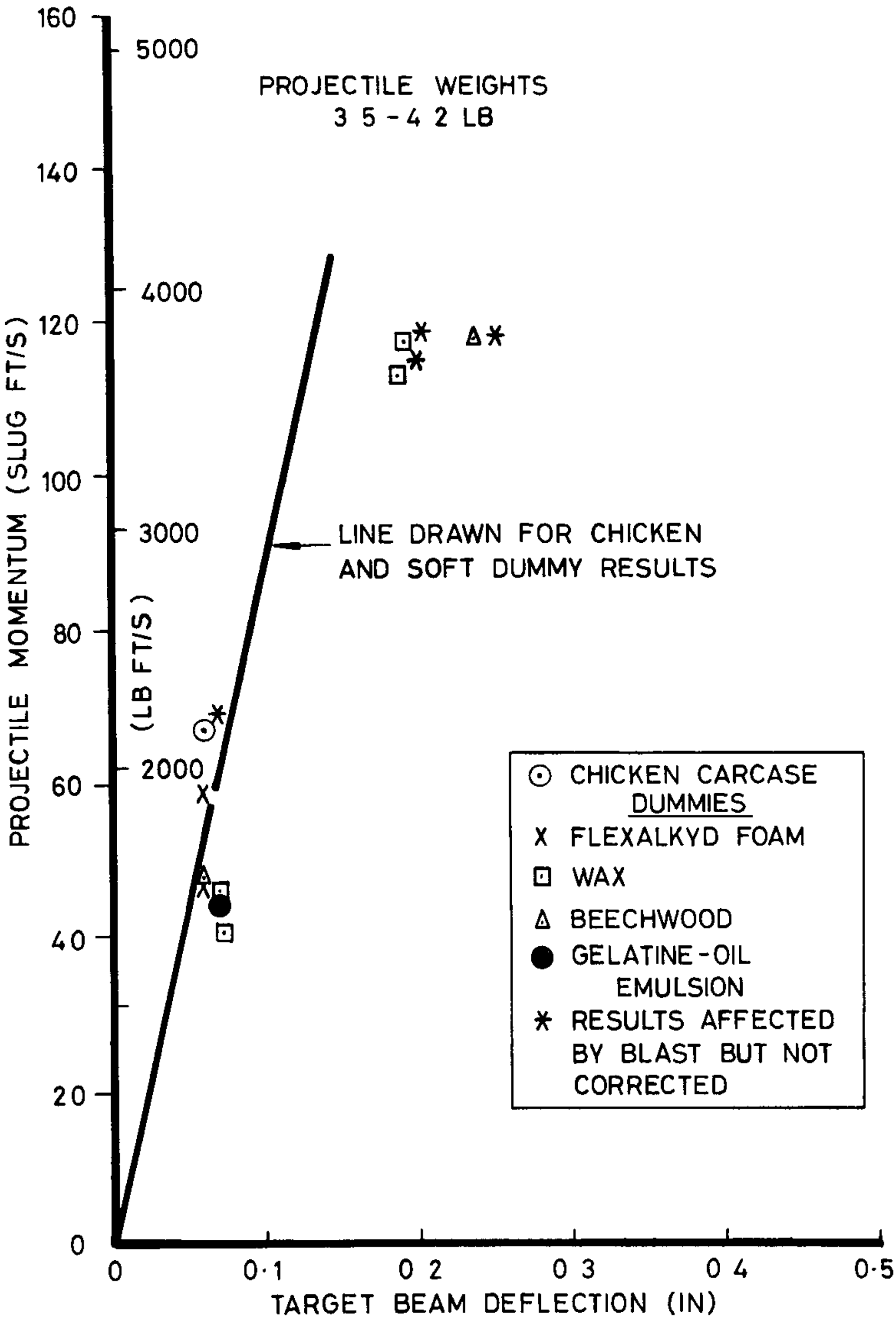


FIG. 8 TARGET BEAM DEFLECTIONS: KNIFE EDGE

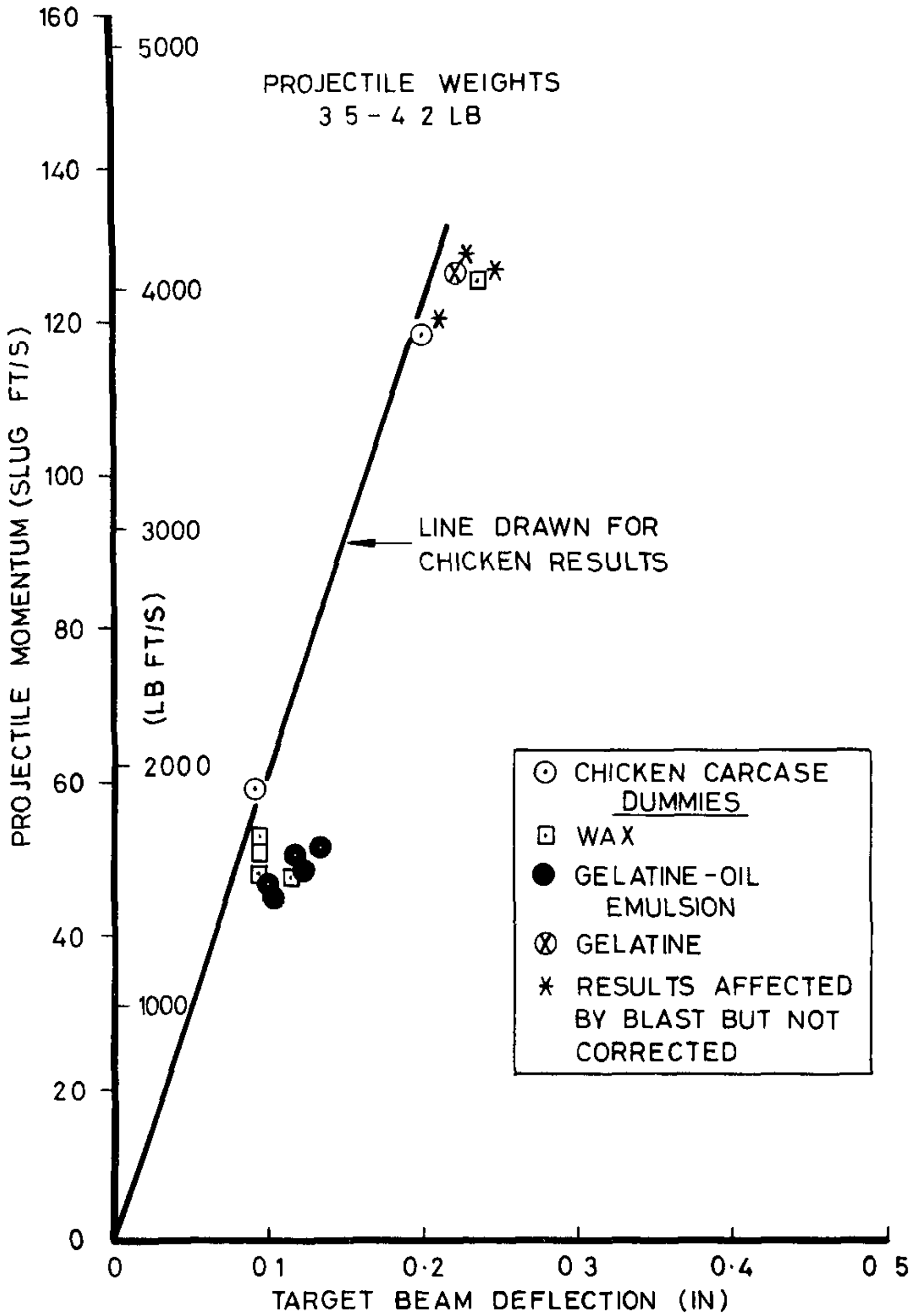
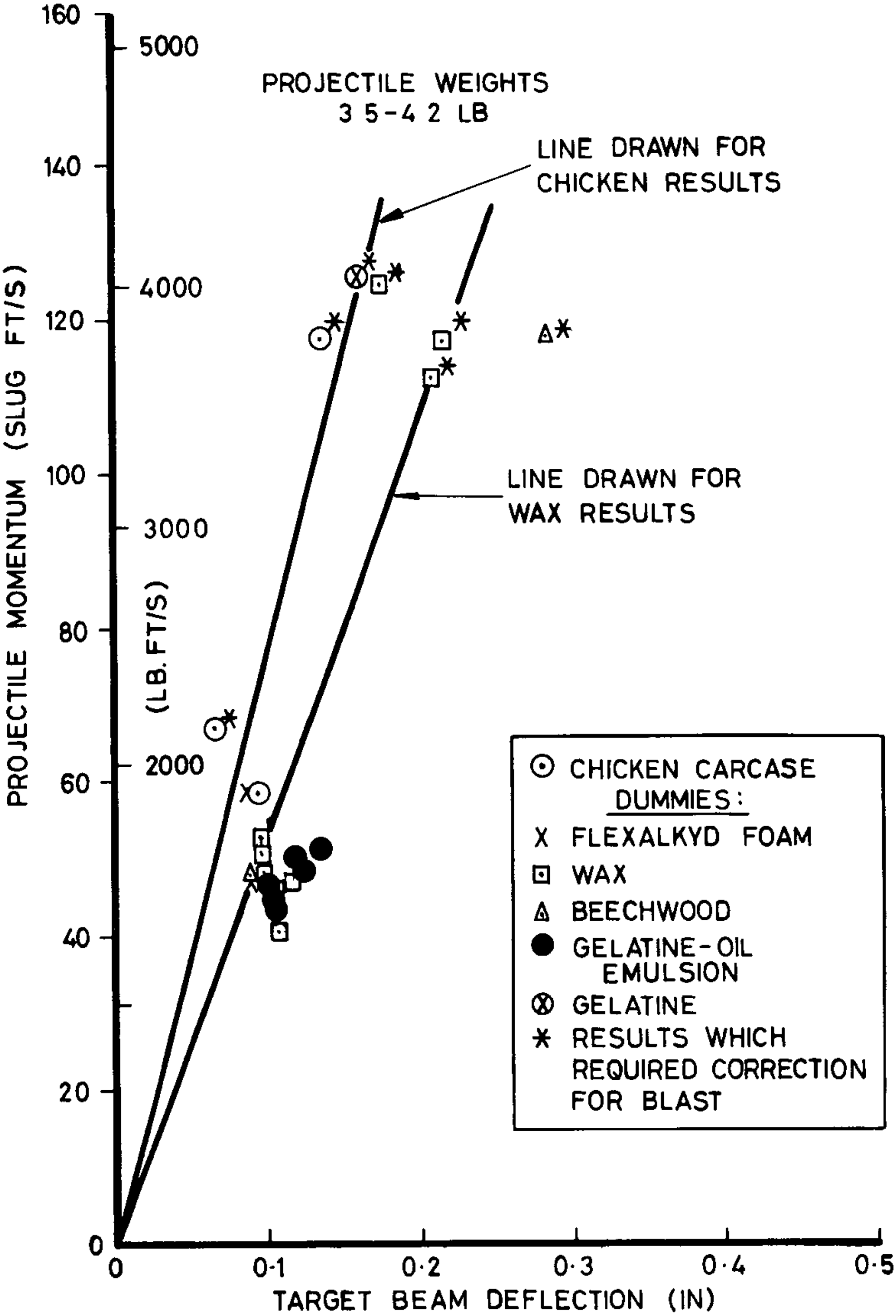


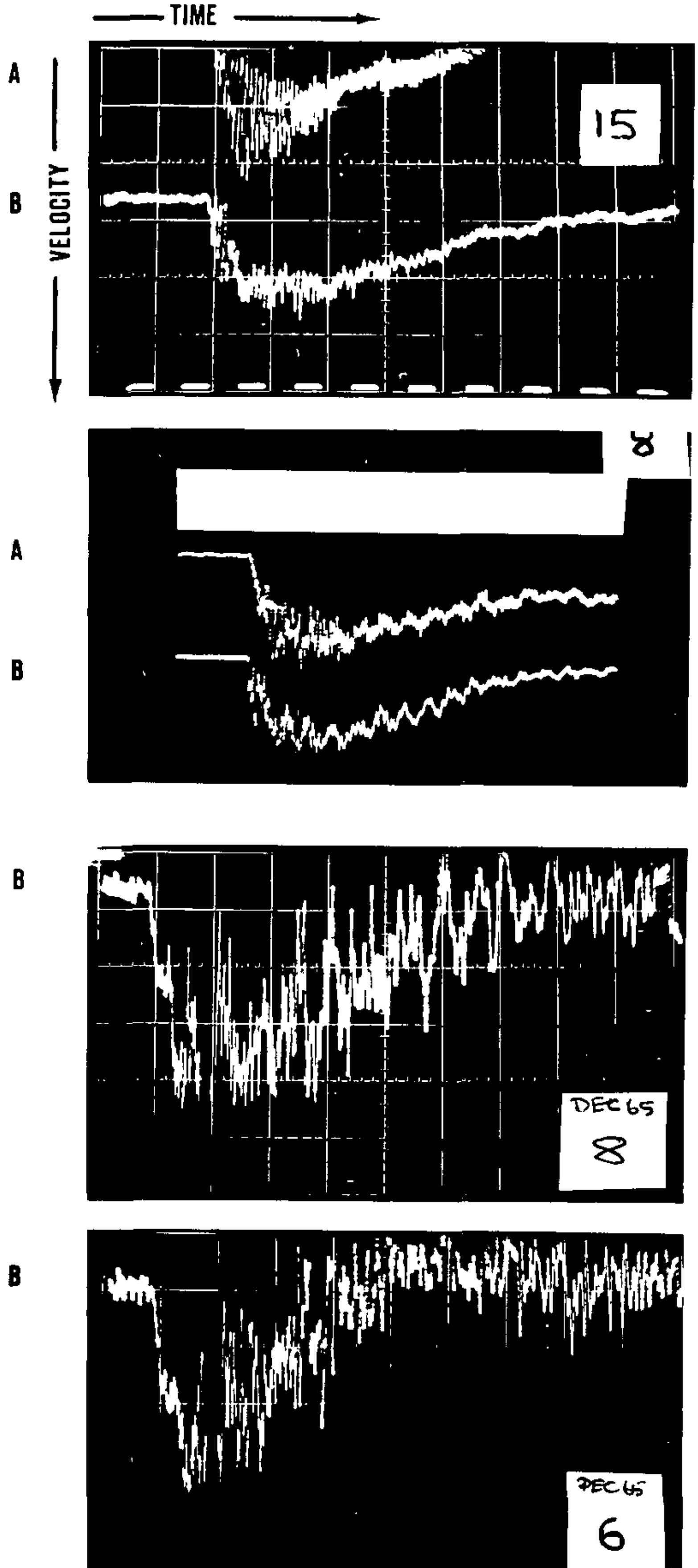
FIG. 9 TARGET BEAM DEFLECTIONS: LIGHT KNIFE EDGE



NB DEFLECTIONS SCALED TO LIGHT KNIFE EDGE

FIG. 10 COMBINED RESULTS FOR KNIFE-EDGE TARGETS

VERTICAL AND HORIZONTAL SCALES SAME IN EACH CASE



(a)
3 66 lb CHICKEN CARCASE
(plus 0 28 lb DRIVING PLUG)
AT 481 ft/sec

ROUND-NOSE TARGET

(b)
3·63 lb CHICKEN CARCASE
(plus 0·44 lb DRIVING PLUG)
AT 491 ft/sec

(c)
3 63 lb WAX DUMMY
(NO DRIVING PLUG)
AT 405 ft/sec.

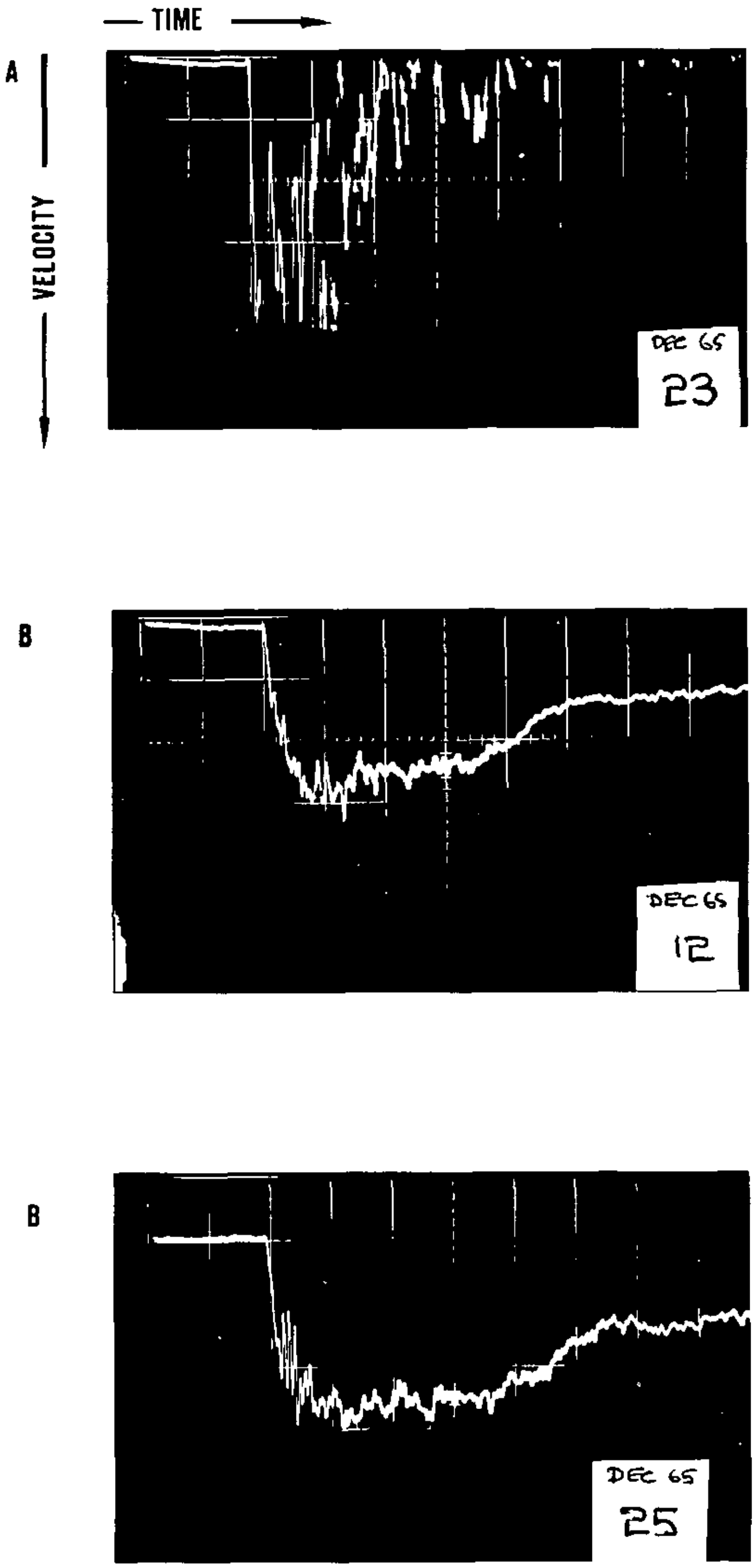
KNIFE-EDGE TARGET

(d)
3·56 lb WAX DUMMY
(NO DRIVING PLUG)
AT 422 ft/sec.

'A' INDICATES UPPER TRANSDUCER TRACE
'B' INDICATES REAR TRANSDUCER TRACE

FIG. 11 REPEATABILITY OF OSCILLOGRAPHS

VERTICAL AND HORIZONTAL SCALES SAME IN EACH CASE



(a)
3·83 lb BEECHWOOD DUMMY
(NO DRIVING PLUG)
AT 397 ft/sec.

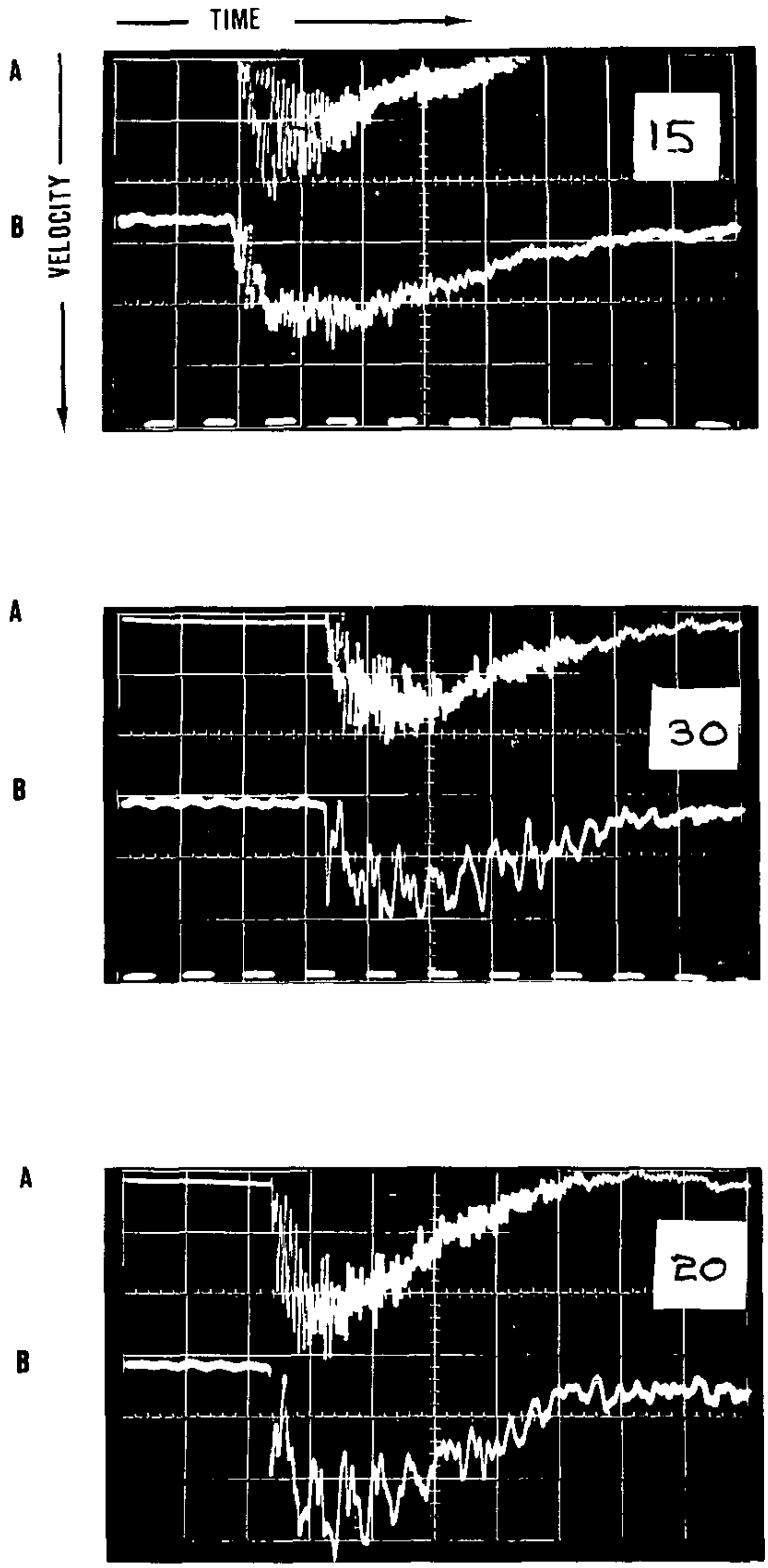
(b)
3 59 lb WAX DUMMY
(NO DRIVING PLUG)
AT 383 ft/sec.

(c)
3·74 lb EMULSION DUMMY
(NO DRIVING PLUG)
AT 362 ft/sec.

'B' INDICATES REAR TRANSDUCER TRACE

FIG. 12 OSCILLOGRAPHS OF IMPACTS ON FLAT-PLATE TARGET

VERTICAL AND HORIZONTAL SCALES SAME IN EACH CASE



(a)
3 66 lb CHICKEN CARCASE
(plus 0 28 lb DRIVING PLUG)
AT 481 ft/sec.

(b)
3-47 lb FLEXALKYD DUMMY
(plus 0-28 lb DRIVING PLUG)
AT 481 ft/sec

(c)
3 63 lb WAX DUMMY
(plus 0 28 lb DRIVING PLUG)
AT 505 ft/sec.

'A' INDICATES UPPER TRANSDUCER TRACE
'B' INDICATES REAR TRANSDUCER TRACE

FIG. 13 OSCILLOGRAPHS OF IMPACTS ON ROUND-NOSE TARGET

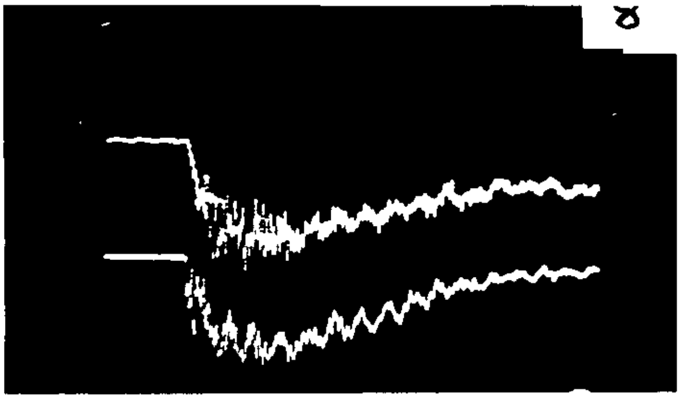
VERTICAL AND HORIZONTAL SCALES SAME IN EACH CASE

——— TIME ———→

A

VELOCITY

B

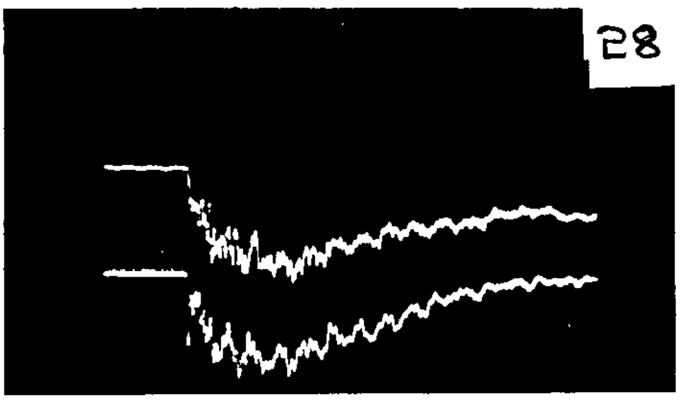


(a)

3 63 lb CHICKEN CARCASE
(plus 0 44 lb DRIVING PLUG)
AT 491 ft/sec

A

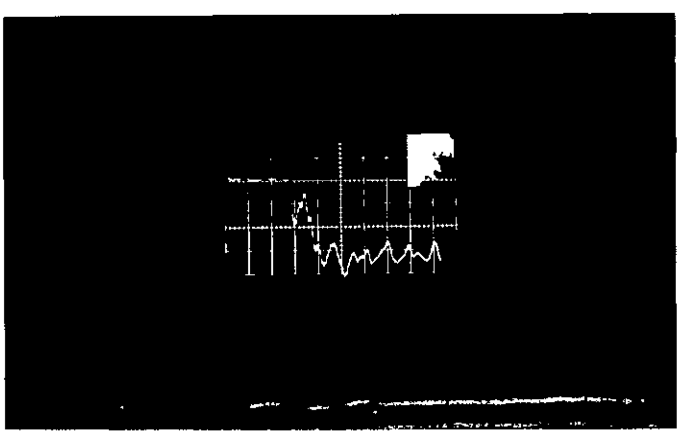
B



(b)

3·75 lb FLEXALKYD DUMMY
(plus 0 44 lb DRIVING PLUG)
AT 500 ft/sec.

B



(c)

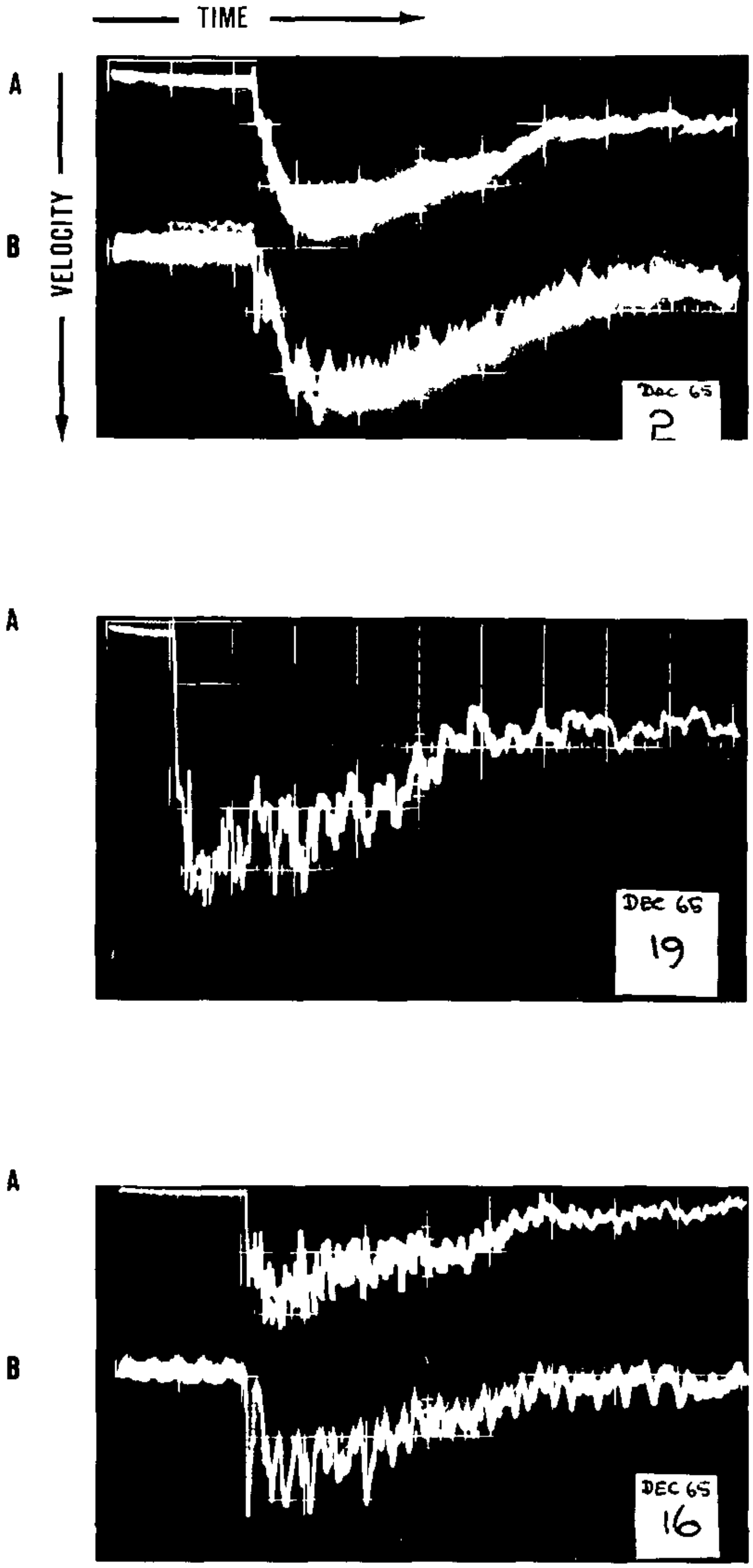
3·53 lb EMULSION DUMMY
(NO DRIVING PLUG)
AT 418 ft /sec

'A' INDICATES UPPER TRANSDUCER TRACE
'B' INDICATES REAR TRANSDUCER TRACE

HORIZONTAL SCALE IS
0 67 OF (a) AND (b)

FIG. 14 OSCILLOGRAPHS OF IMPACTS ON ROUND-NOSE TARGET (CONTD.)

VERTICAL AND HORIZONTAL SCALES SAME IN EACH CASE



(a)

3 64 lb WAX DUMMY
(NO DRIVING PLUG)
AT 405ft/sec.

(b)

3 50 lb BEECHWOOD DUMMY
(NO DRIVING PLUG)
AT 378 ft/sec.

(c)

3·03 lb FLEXALKYD DUMMY
(NO DRIVING PLUG)
AT 456ft/sec.

'A' INDICATES UPPER TRANSDUCER TRACE

'B' INDICATES REAR TRANSDUCER TRACE

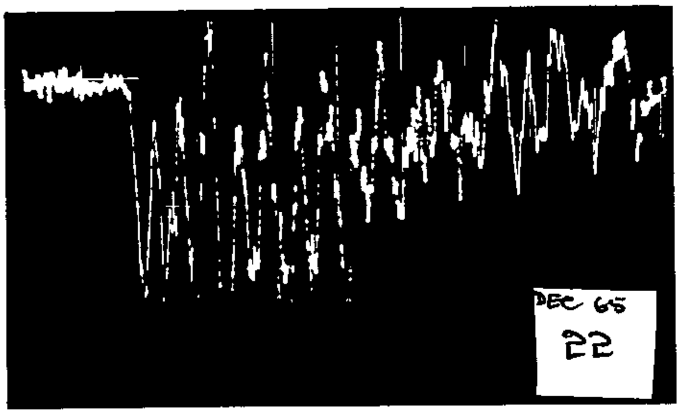
FIG. 15 OSCILLOGRAPHS OF IMPACTS ON ROUND-NOSE TARGET (CONTD.)

REP 13 68

VERTICAL AND HORIZONTAL SCALES SAME IN EACH CASE

—— TIME ——→

VELOCITY

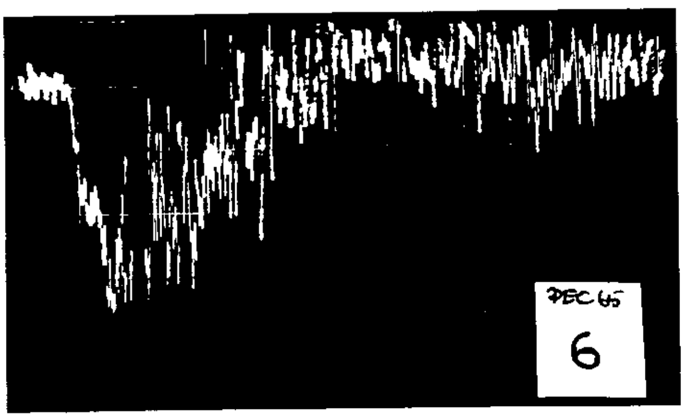


(a)

3·78 lb BEECHWOOD DUMMY

(NO DRIVING PLUG)

AT 403 ft/sec.

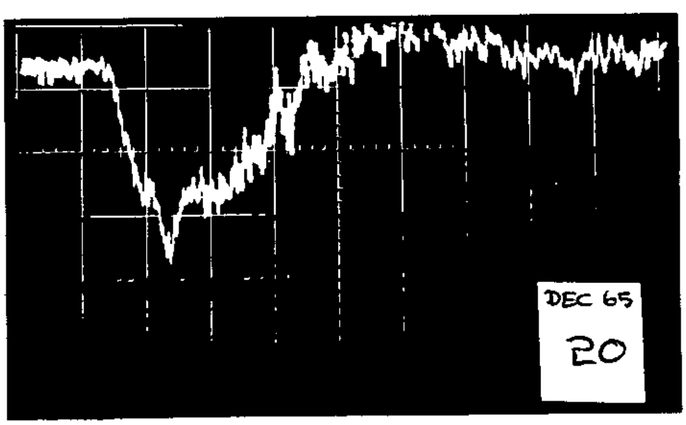


(b)

3·56 lb WAX DUMMY

(NO DRIVING PLUG)

AT 422 ft/sec.



(c)

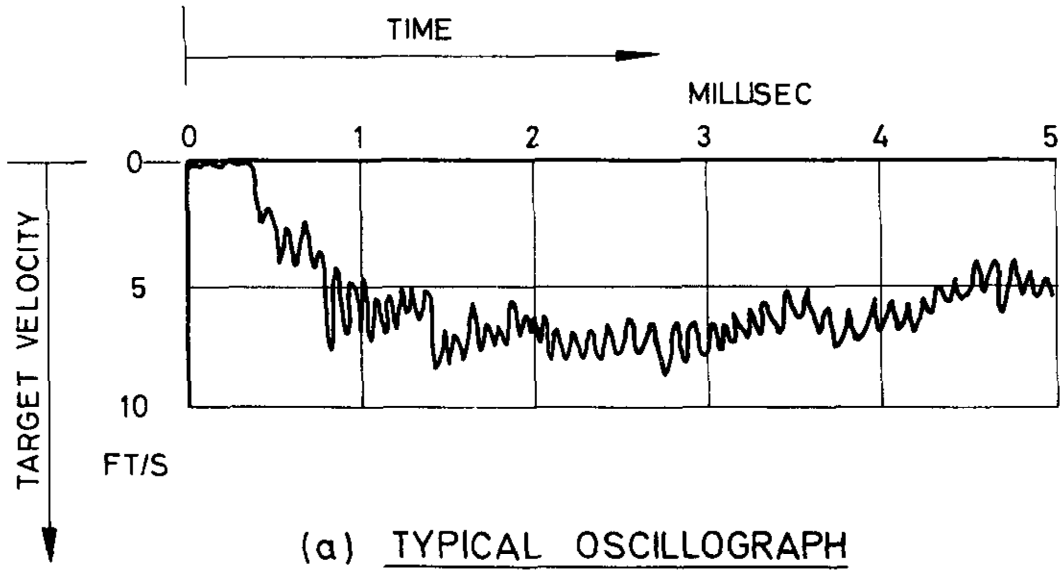
3·84 lb EMULSION DUMMY

(NO DRIVING PLUG)

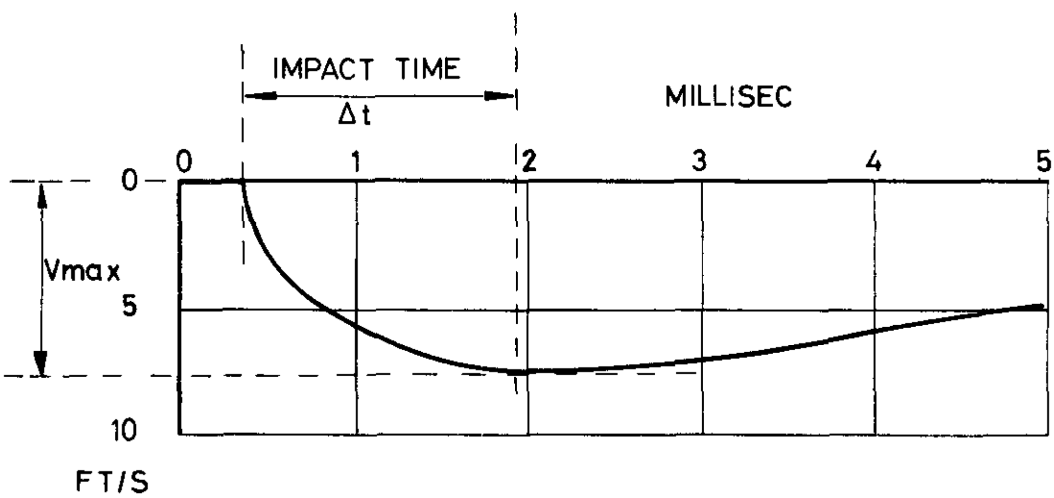
AT 372 ft/sec

REAR TRANSDUCER USED IN EACH CASE

FIG. 16 OSCILLOGRAPHS OF IMPACTS ON KNIFE-EDGE TARGET



(a) TYPICAL OSCILLOGRAPH



(b) SMOOTHED VELOCITY / TIME CURVE

FIG. 17 INTERPRETATION OF TYPICAL OSCILLOGRAPH

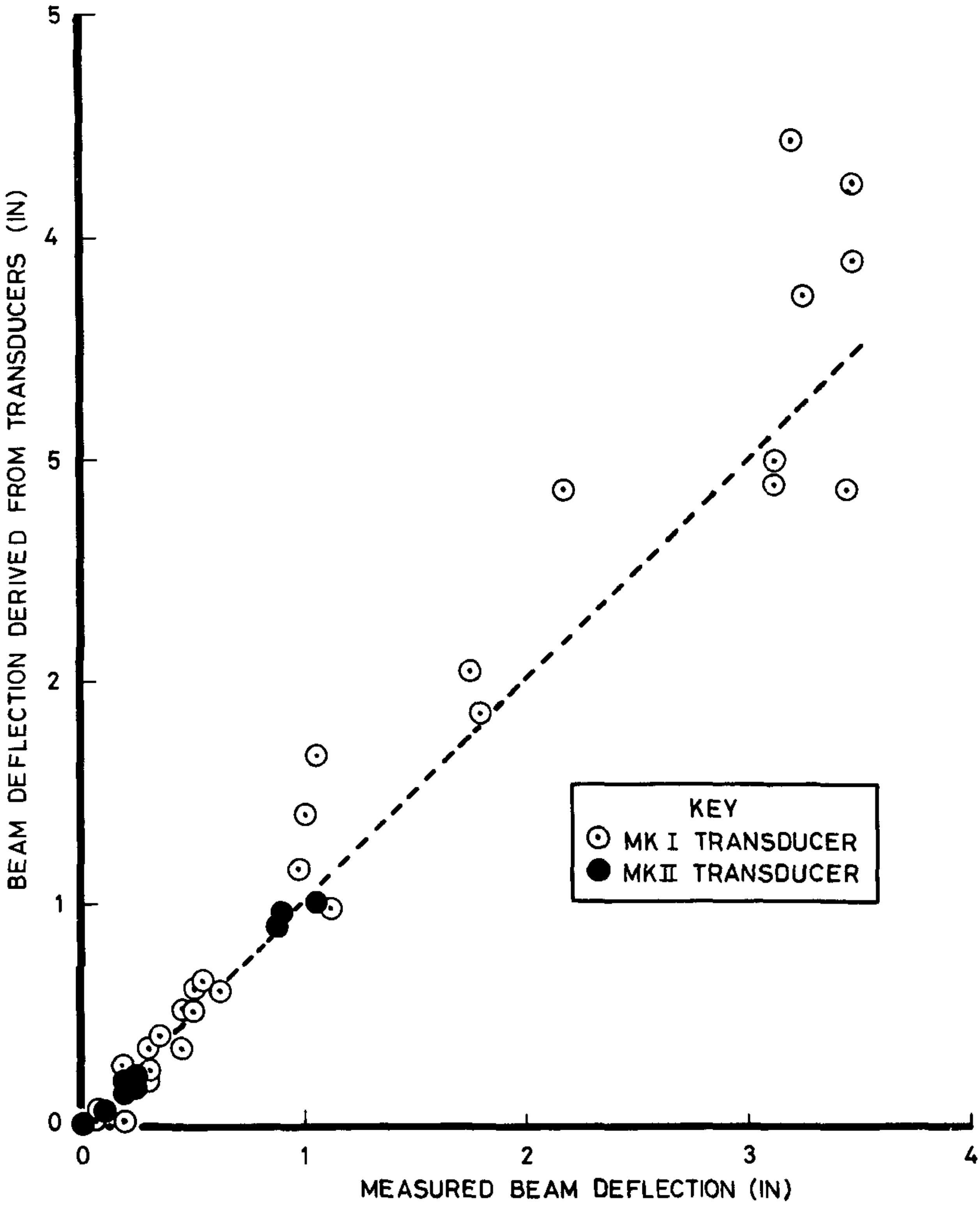


FIG. 18 COMPARISON OF DEFLECTION RESULTS

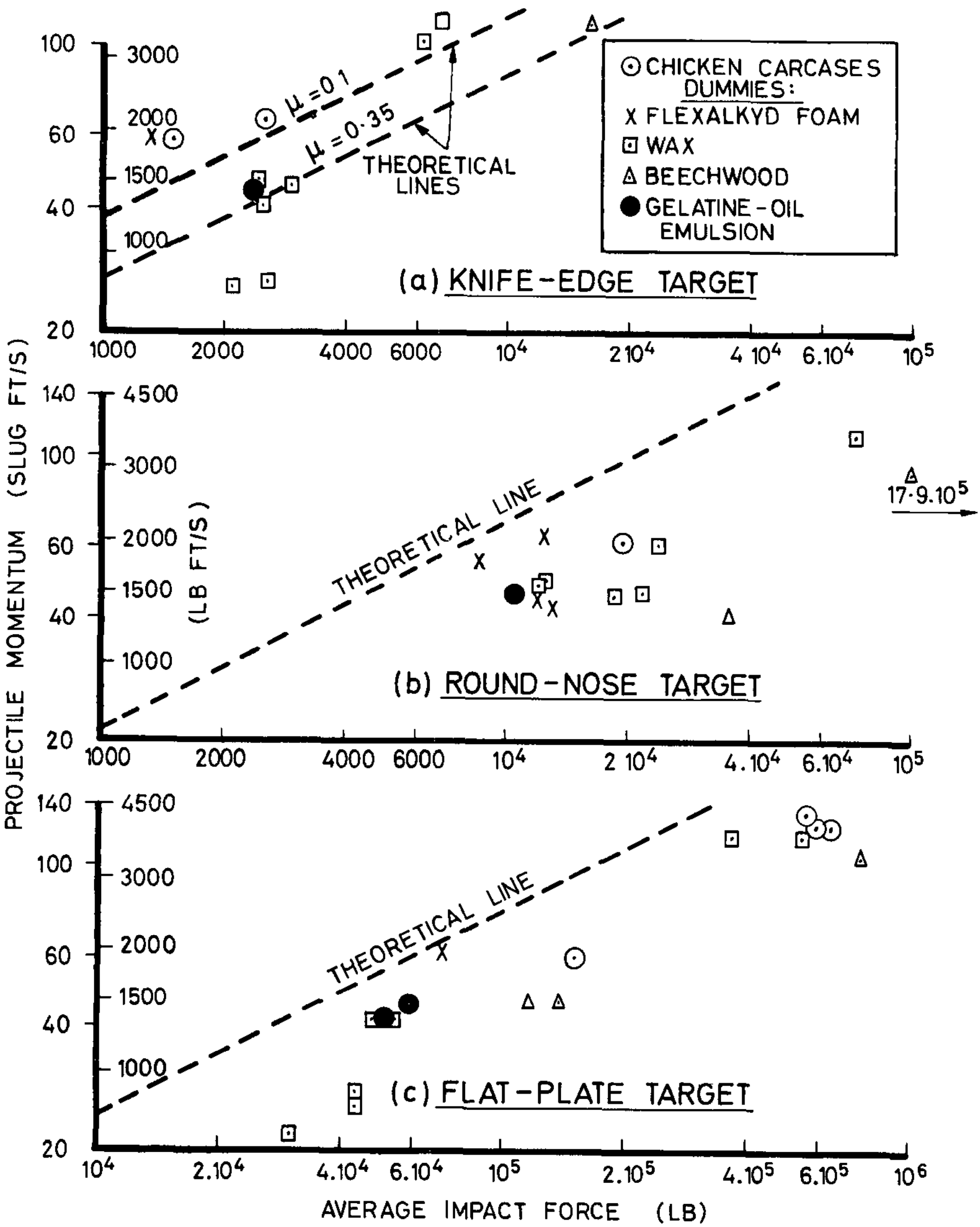
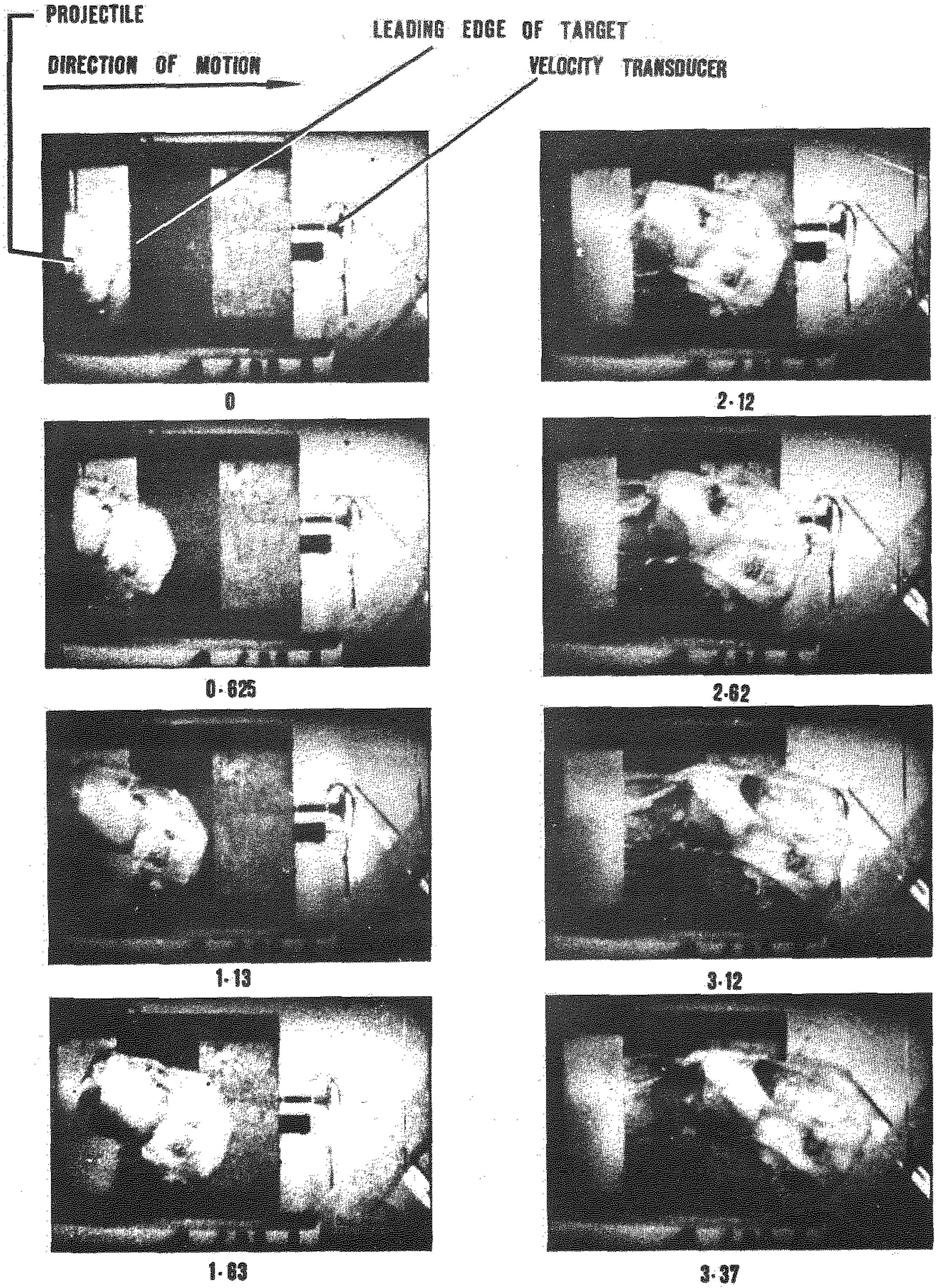


FIG. 19 IMPACT FORCES

FIGURES SHOW TIME IN MILLISECONDS RELATIVE TO FIRST PICTURE
(FILM SPEED 8000 PICTURES PER SEC.)

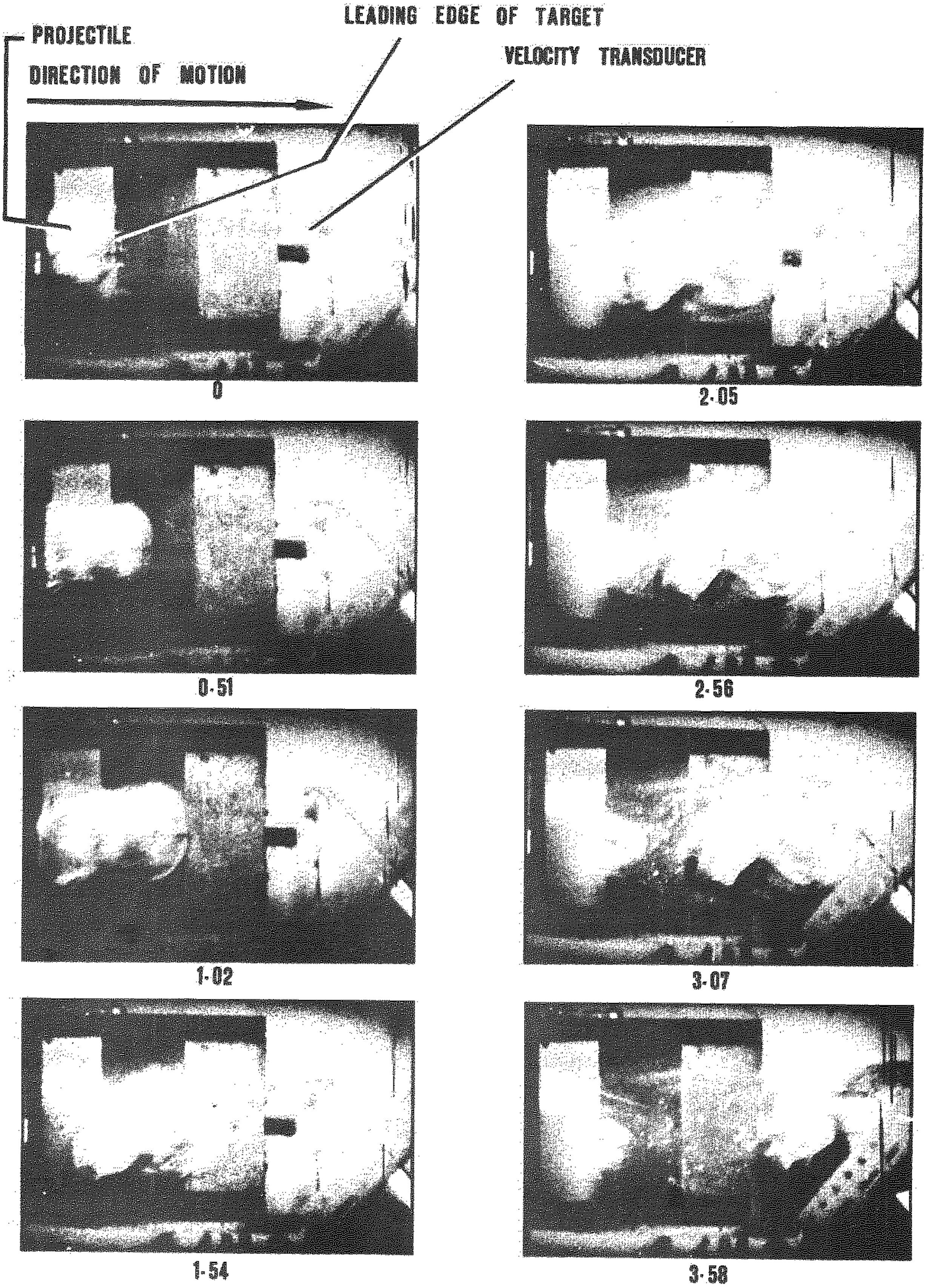


4·3lb CHICKEN CARCASE plus 0·29lb DRIVING PLUG AT 463ft/sec.

FIG.20 CHICKEN CARCASE STRIKE ON KNIFE-EDGE TARGET

FIGURES SHOW TIME IN MILLISECONDS RELATIVE TO FIRST PICTURE

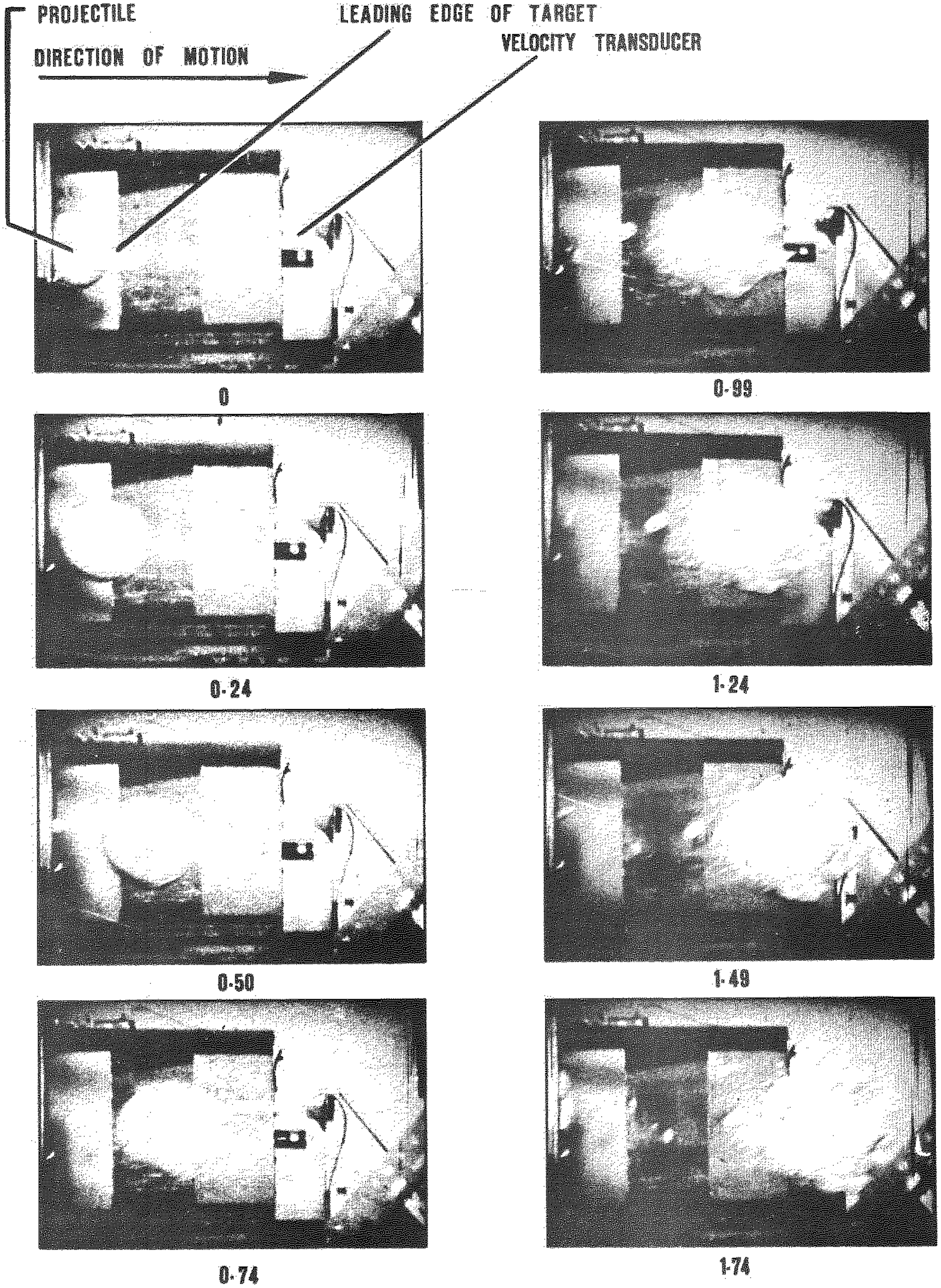
(FILM SPEED 7810 PICTURES PER SEC.)



3·55 lb FLEXALKYD DUMMY plus 0·36 lb DRIVING PLUG AT 491 ft/sec.

FIG.21 FLEXALKYD DUMMY STRIKE ON KNIFE-EDGE TARGET

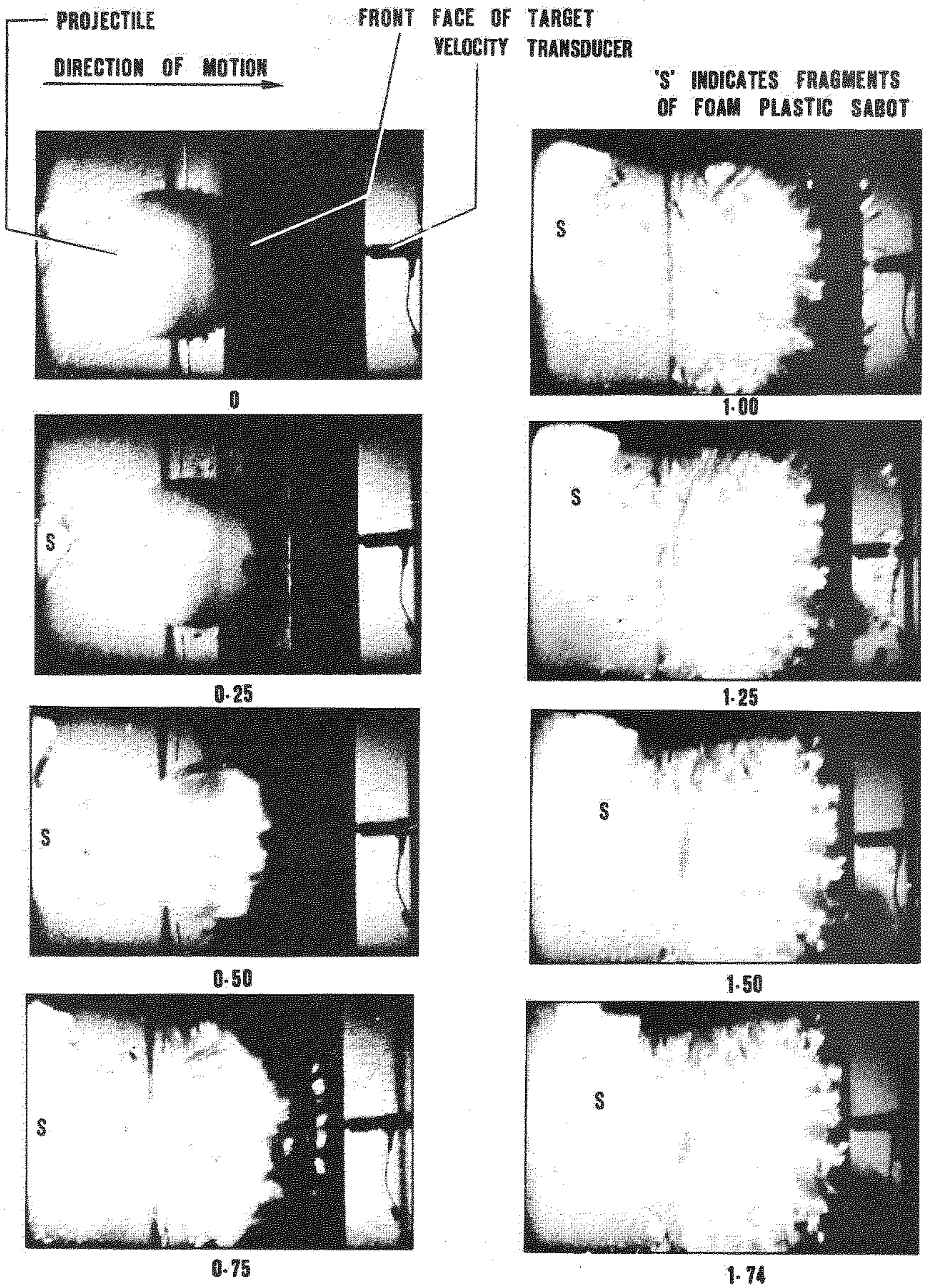
FIGURES SHOW TIME IN MILLISECONDS RELATIVE TO FIRST PICTURE
(FILM SPEED 8060 PICTURES PER SEC.)



3·69 lb WAX DUMMY plus 0·28 lb DRIVING PLUG (FOLLOWING BEHIND) AT 944ft/sec.

FIG.22 WAX DUMMY STRIKE ON KNIFE-EDGE TARGET

FIGURES SHOW TIME IN MILLISECONDS RELATIVE TO FIRST PICTURE
(FILM SPEED 8000 PICTURES PER SEC.)



4·0 lb WAX DUMMY AT 450 ft/sec.

FIG.23 WAX DUMMY STRIKE ON FLAT-PLATE TARGET

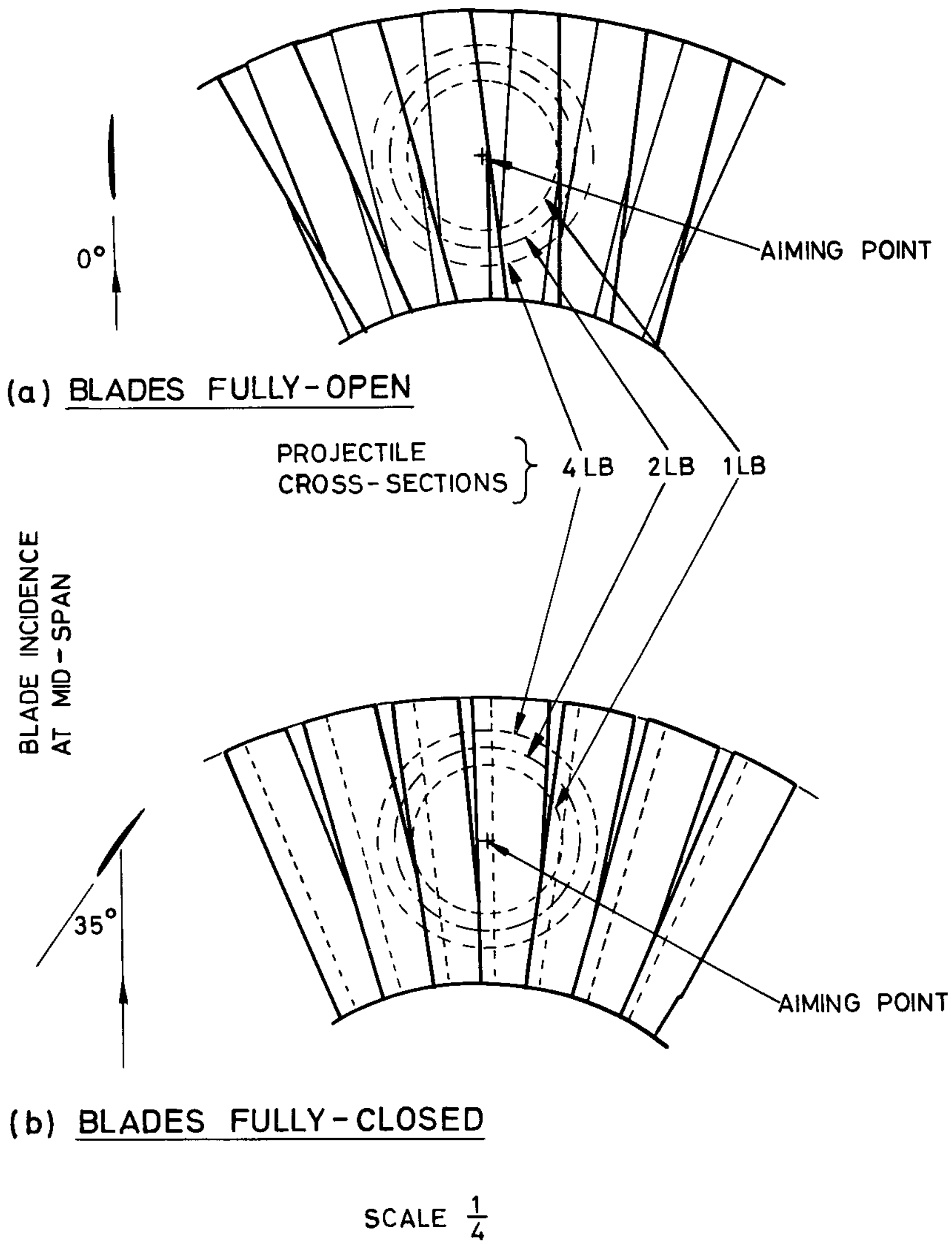


FIG. 24 PROJECTILE CROSS-SECTIONS ON ALUM. ALLOY I.G.V.

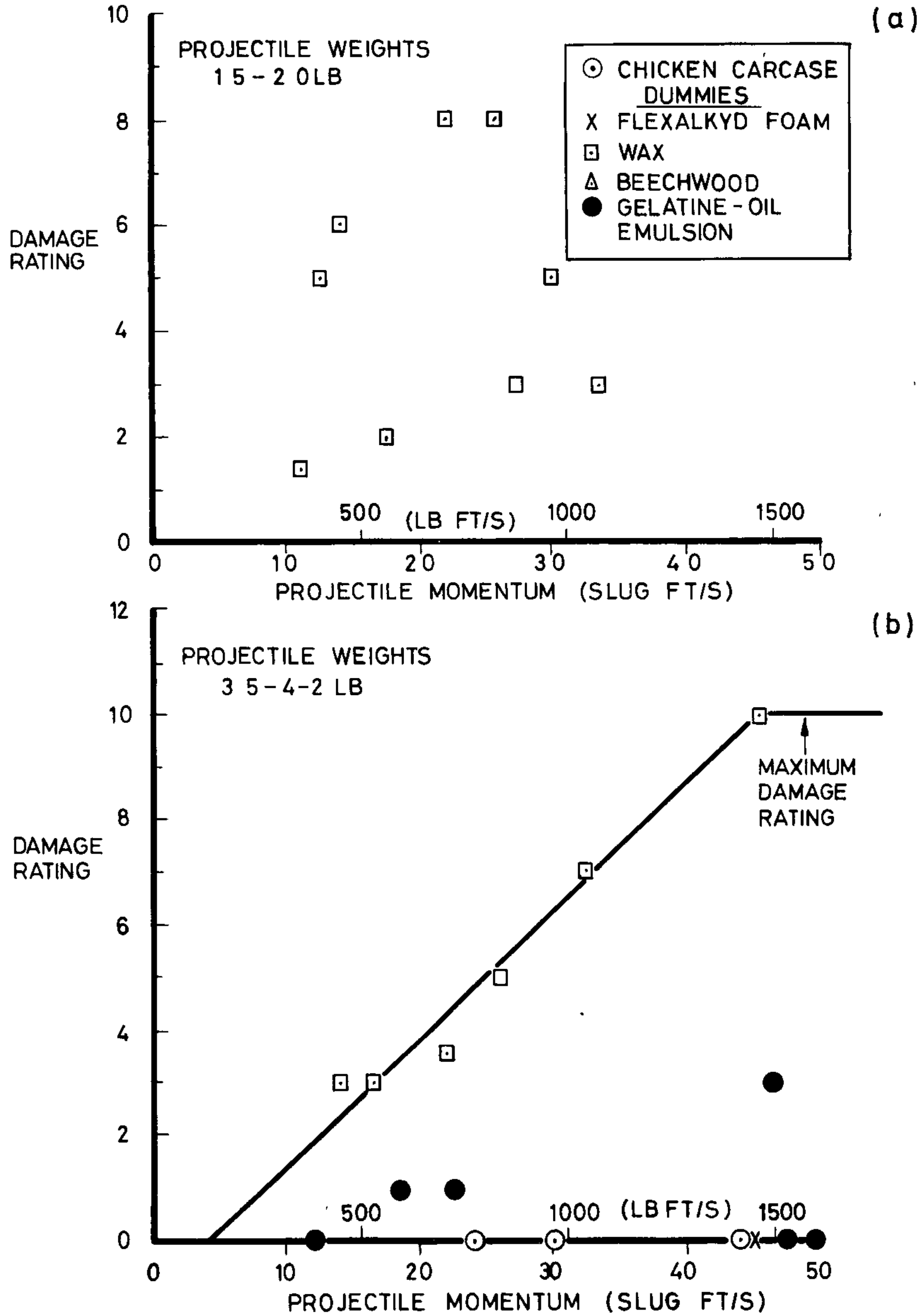
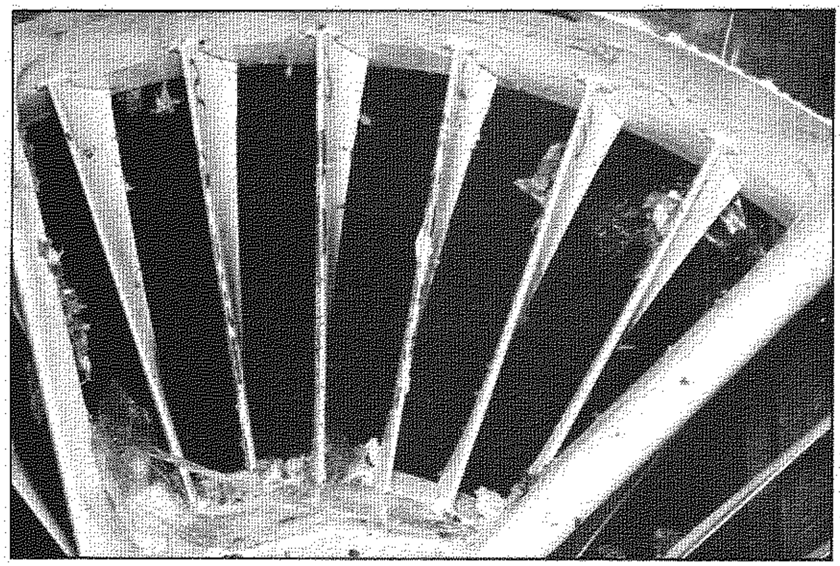


FIG. 25 ALUM ALLOY I.G.V. DAMAGE: BLADES FULLY-OPEN

BLADES FULLY-OPEN IN EACH CASE

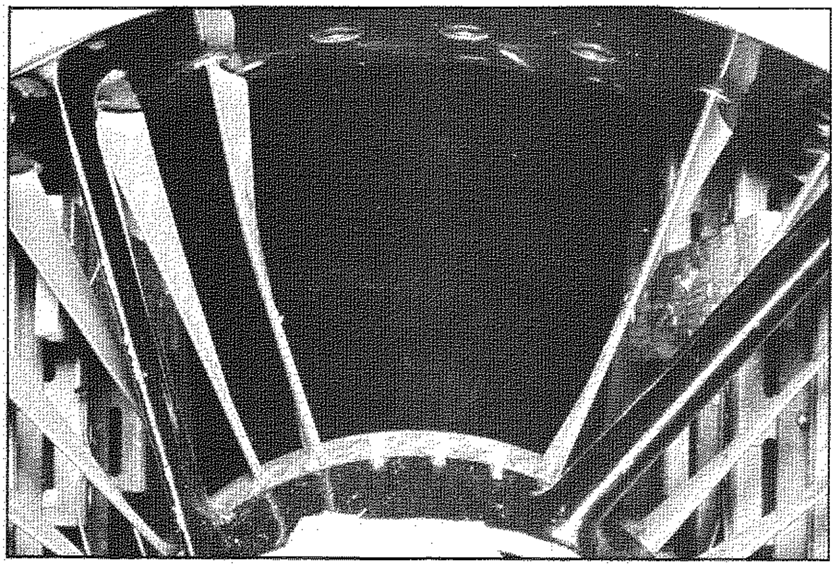


(a)

3·7 lb. CHICKEN CARCASE

AT 382 ft/s

DAMAGE RATING = 0

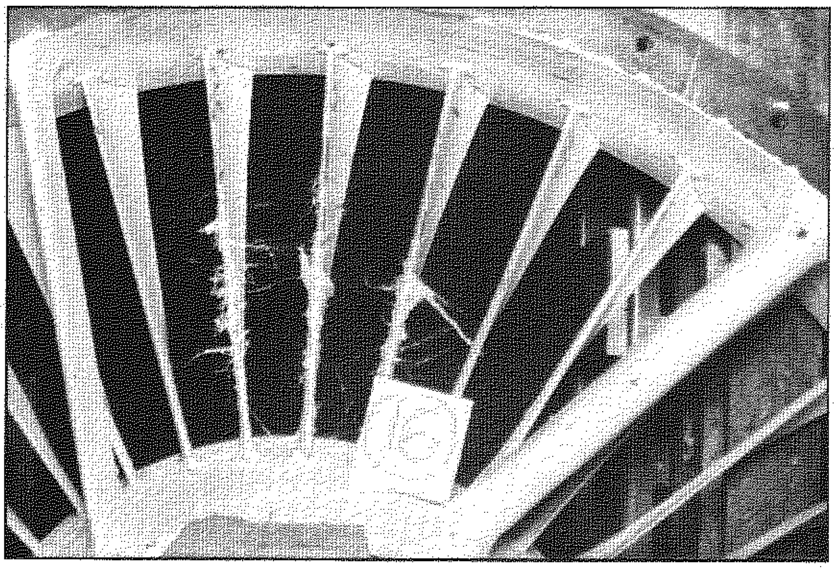


(b)

3·75 lb. WAX DUMMY

AT 388 ft/s

DAMAGE RATING = 10



(c)

3·77 lb. GELATINE-OIL

EMULSION DUMMY

AT 403 ft/s

DAMAGE RATING = 0

FIG. 26 DAMAGE COMPARISON WITH ALUM. ALLOY I. G. V.

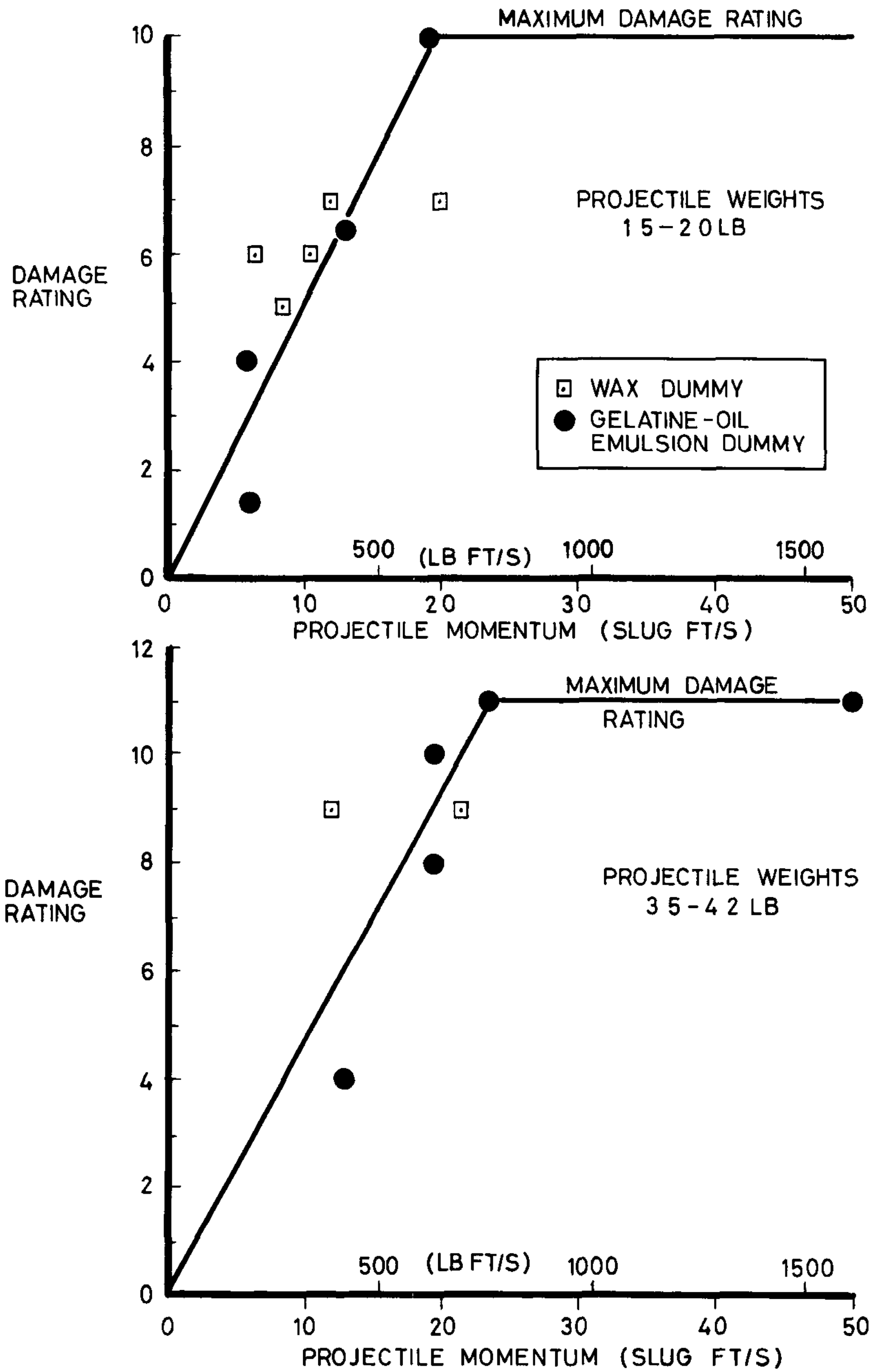
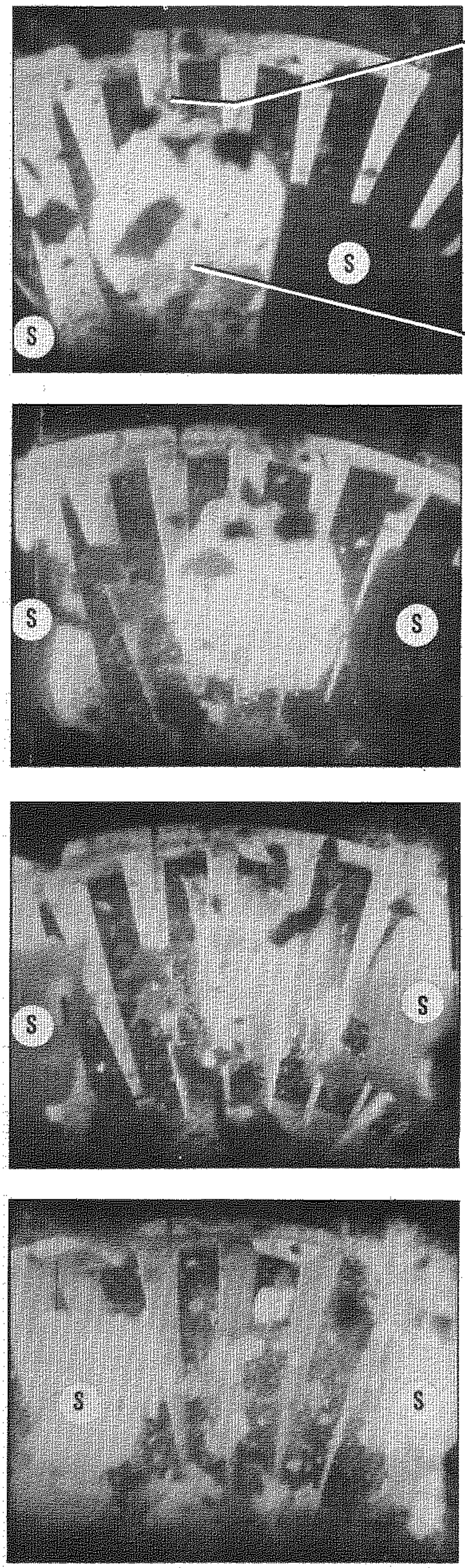
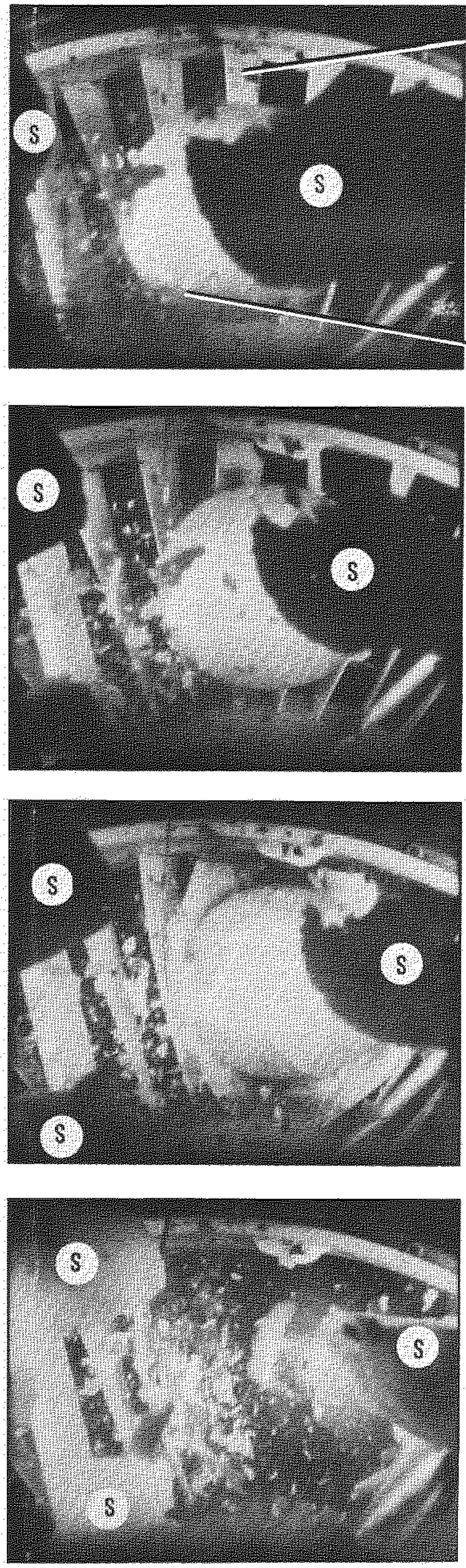


FIG. 27 ALUM. ALLOY I.G.V. DAMAGE : BLADES FULLY-CLOSED



1·09lb EMULSION DUMMY AT 577ft/sec.
I.G.V. FULLY OPEN

FIG. 28 EMULSION DUMMY STRIKE ON ALUMINIUM ALLOY I.G.V.



INLET GUIDE VANES (VIEW IS OBLIQUE FROM FRONT)

'S' INDICATES FRAGMENTS OF FOAM PLASTIC SABOT NOT RETAINED BY GUN

DUMMY

4·17lb WAX DUMMY AT 394ft/sec.
I.G.V. FULLY OPEN

FIG.29 WAX DUMMY STRIKE ON ALUMINIUM ALLOY I.G.V.

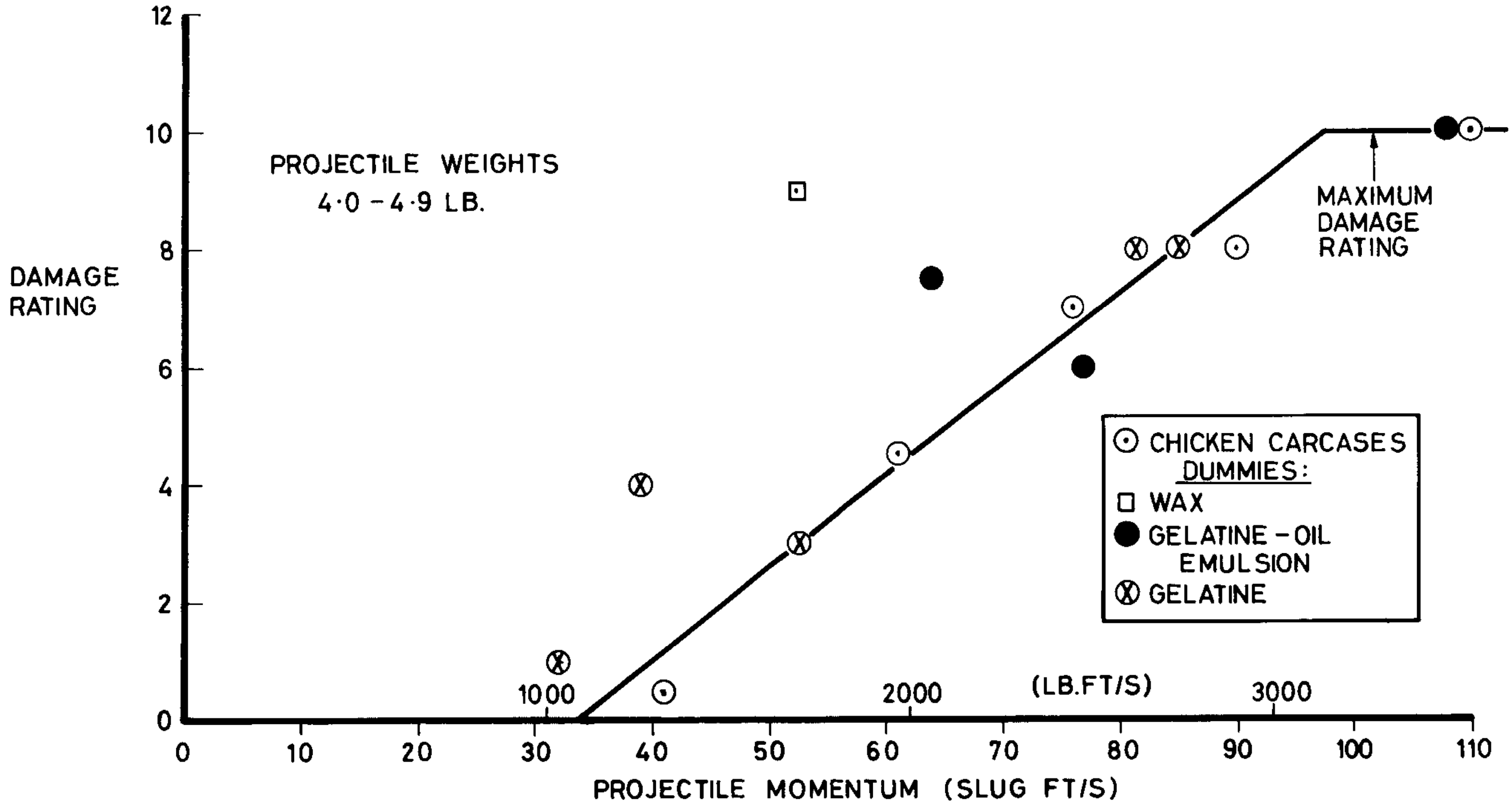
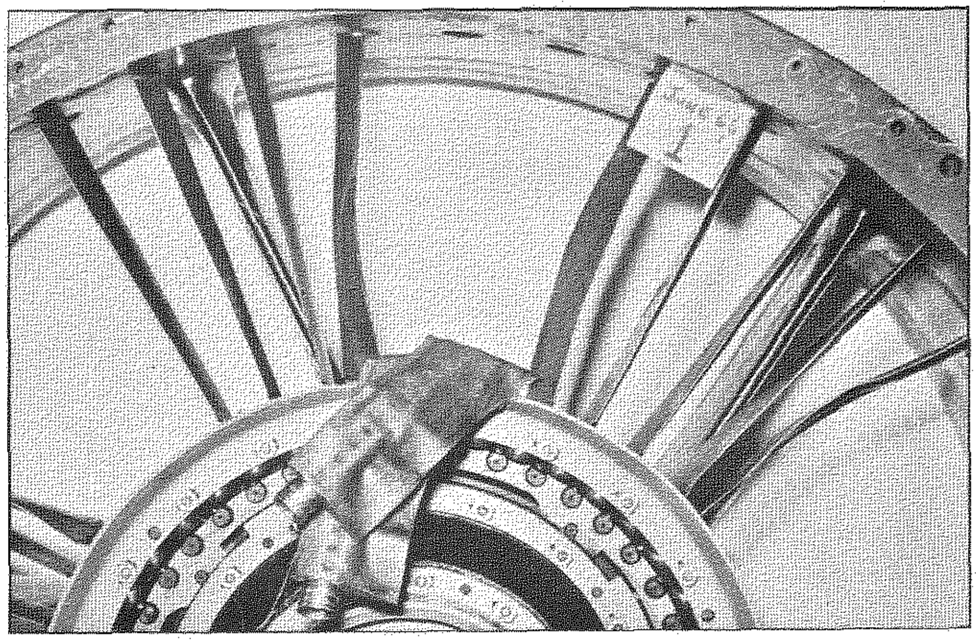
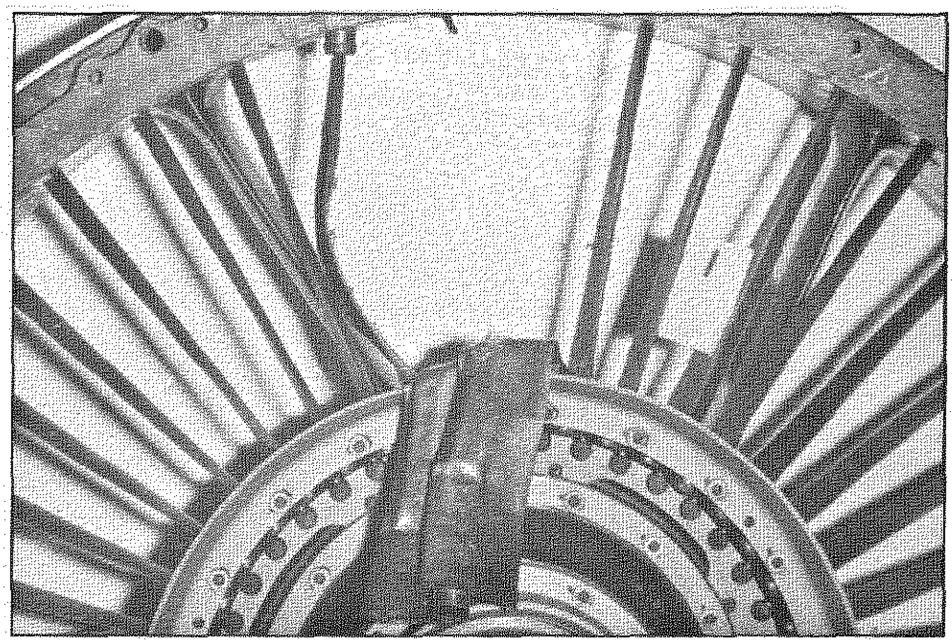


FIG. 30 STEEL I.G.V. DAMAGE: BLADES FULLY-OPEN



(a) 4·6 lb. CHICKEN CARCASE (+ 0·21 lb. DRIVING PLUG)

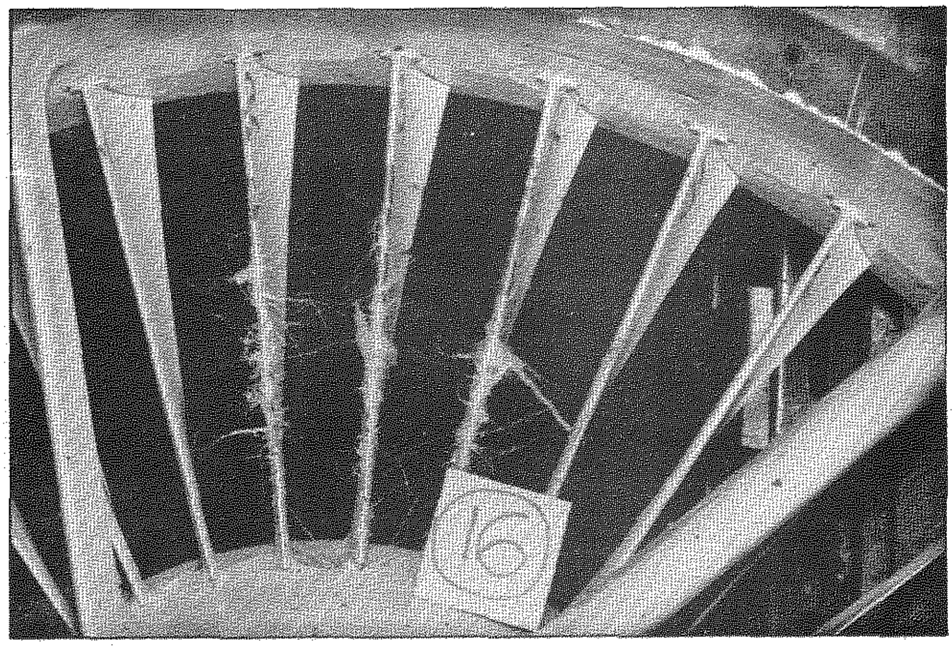
AT 599 ft/s



(b) 4·9 lb. GELATINE AT 560 ft/s

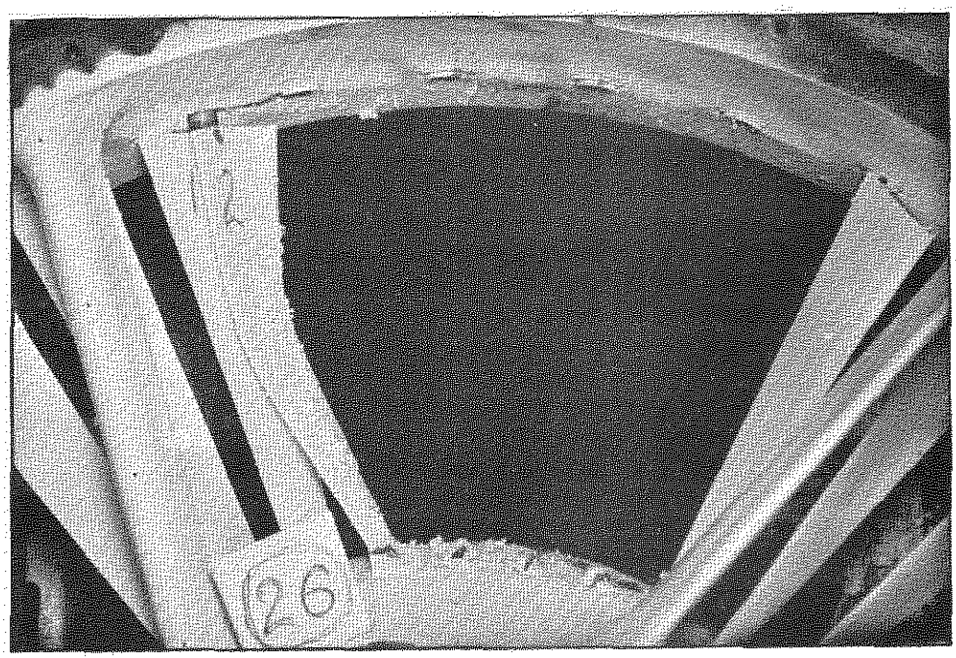
(BLADES FULLY - OPEN IN BOTH CASES : VIEW IS FROM REAR)

FIG. 31 DAMAGE COMPARISON WITH STEEL BLADES



(a) BLADES FULLY OPEN : DAMAGE RATING = 0

(3·77 lb GELATINE OIL EMULSION DUMMY AT 403 ft/s)



(b) BLADES CLOSED BY 5° : DAMAGE RATING = 11

(4·0 lb. GELATINE-OIL EMULSION DUMMY AT 373 ft/s)

FIG. 32 BLADE ANGLE EFFECT

A.P.C. C.P. No. 1071 598.2:621-757
June 1968
Allcock, A. W. R. and Collin, D. M.

THE DEVELOPMENT OF A DUMMY BIRD FOR
USE IN BIRD STRIKE RESEARCH

The problems of using bird carcases in bird strike testing are mentioned and the development of a dummy bird is described. Dummies of wax, wood, flexalkyd foam, emulsion and gelatine were tested, first by impacts on very simple basic target shapes, and then on engine inlet guide vane assemblies. Comparison of the results with those from chicken carcases showed that the foam, emulsion and gelatine dummies were all realistic simulators. The gelatine dummy is recommended because of its successful history of use as a flesh simulator in other types of impact study and because of its cheapness and ease of manufacture.

The deflections measured using the special targets agreed quite well with simple theoretical calculations, and approximate values of the friction

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DETACHABLE ABSTRACT CARDS

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