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HANDLE WITH CARE

A STUDY OF HAIL IMPACT AT HIGH SPEED ON LIGHT ALLOY PLATES

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ABSTRACT

An experimental investigation was made to study the effects of impact velocity, impact angle, plate material properties and thickness on the damage to flat light alloy plates caused by the impact of one inch diameter hail at speeds up to 2500 ft/sec.

A description is given of the gas gun used for the firing of solid ice projectiles. Data are presented on indentation depth, dent profile and penetration for two aluminium alloys, L72 (25 ton/in², 15% elongation) and L73 (27 ton/in², 8% elongation) of thickness ranging from 0.028 inch to 0.064 inch. Photographic studies of the impact phase are shown.

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Introduction

In recent years the continued increases in aircraft climb and cruise speeds, traffic density and possibly the use of weather radar for storm penetration, have been accompanied by an increased number of in-flight encounters with hail resulting in severe damage to aircraft. Airworthiness Authorities on both sides of the Atlantic are now requiring some measure of hail impact resistance from aircraft structures.

In order to obtain basic data on the hail impact resistance of aircraft structure, an investigation (Ref. 3) was commenced at the RAE Farnborough, in late 1963, and is still in progress.

A brief description is given in this paper of the apparatus used for the study; some results are presented on hail impact damage to flat aluminium alloy plates and evidence is presented which indicates that hail impact tests must be made using ice projectiles of the correct size at the correct impact speed and correct impact angle.

Hail gun

The gun (Ref. 2), shown in Fig.1, was developed from one of the type used at the RAE by the late D. C. Jenkins for single impact studies of rain erosion by fitting a longer barrel (8 ft) and providing means for cooling the breech and barrel to sub-zero temperatures. The majority of studies have been made with 1 inch diameter ice projectiles but alternative barrels allow firing of $\frac{3}{4}$ inch, $\frac{1}{2}$ inch and $\frac{1}{4}$ inch projectiles. The gun is operated by compressed gas at pressures up to 1000 lb/in² and firing is by means of a gas driven servo-valve inside the firing chamber.

Using compressed air, ice projectiles can be fired successfully at discrete speeds in the range 250 ft/sec to 1400 ft/sec. By evacuating the barrel, the upper speed can be raised to 1600 ft/sec and when the internal valve is removed and the gun fired by bursting disc technique, speeds up to 1800 ft/sec can be obtained. A maximum speed of 2500 ft/sec can be achieved using helium as the operating gas.

Impact speed is derived from measurement of the time taken for the projectile to interrupt two light beams a known distance apart. This time is measured by means of photo-diodes and conventional electronics.

Hail

Two types of ice projectile have been used to represent hail: ice spheres and ice bullets which have an identical hemispherical nose with cylindrical after-body and mass equal to that of the sphere. The projectiles are formed in silicone rubber moulds from measured quantities of distilled water by freezing in a refrigerator at -15°C. Moulded ice spheres formed in this way frequently have internal faults and break up when fired at high speed. It is thought that, since the freezing process is from the outside inwards, the faults are due to stresses generated towards the end of the freezing process. The ice bullets, which are frozen in moulds with the hemisphere downwards and the upper surface, i.e. the rear face of the cylinder, unrestricted, are much less prone to internal faults and are generally used at speeds in excess of 1200 ft/sec. One inch diameter spheres and ice bullets of this type give identical damage results.

Specimens

Impact tests were made on flat plates of two typical aircraft light alloys L72 and L73; aluminium coated aluminium - copper - magnesium - silicon - manganese alloy more or less equivalent to 24 ST material. L72 alloy is solution treated, aged at room temperature and has an ultimate tensile strength of 25 tons/in² with 15% elongation. L73 alloy is solution treated, precipitation treated and has an ultimate tensile strength of 27 tons/in² with 8% elongation.

The specimens, 12 inch square plates, were secured with 3/16 inch screws at 2 inch pitch to a steel frame formed from 2 inch x 2 inch x 1/4 inch angle. The frame was rigidly attached to a support structure at the required impact angle. (Impact angle is the angle between the line of fire and the normal to the plate.) Impact was in the centre of the plate.

Normal impact indentation

When hail impacts on the plate at zero impact angle it makes a symmetrical smooth contoured dent which increases in size with impact speed as shown in Fig.2. Visually it is not possible to estimate the dent diameter.

Attempts were made to correlate dent volume (obtained by filling the dent with water plus a wetting agent), cross-sectional area of deformation at maximum indentation (obtained from measurements of dent profile) and maximum indentation with velocity. The only correlation obtained was that depth of indentation varies linearly with impact velocity. This is shown in Fig.3 for L73 alloy and Fig.4 for L72 alloy; the effect of elongation can be observed. Previous work by Kangas (Ref. 5) had suggested that indentation varied with the square of velocity but this is clearly incorrect for the two alloys tested.

Angled impact indentation

In the case of angled impact the dent is not symmetrical but it is again smooth contoured and it is impossible to estimate visually the dent diameter. Typical dent profiles are shown in Fig.5. Over the impact angle range 0° to 60° the depth of dent varies linearly with the component of impact velocity normal to the plate. Typical results are shown in Fig.6. A similar relationship was observed in tests of Concorde fuselage panel specimens (Ref. 1).

On this evidence it was suggested that high speed impact at large impact angles (e.g. highly swept surfaces) could be simulated by tests at zero impact angle with the same normal velocity component. This would avoid the need to develop high speed hail test facilities for supersonic aircraft testing. This $V \cos \alpha = \text{constant}$ relationship has been found to apply in a number of impact cases - e.g. bird impact tests on windscreens. It can be seen in Fig.6, that, for penetration, $V \cos \alpha$ is not constant.

Penetration speed

Fig.7 presents the true penetration speeds for both alloys over the range $\alpha = 0^\circ$ to 60° and thickness 0.028 inch to 0.064 inch. The curves are reasonably similar and show that resistance to penetration decreases with increase in impact angle to a minimum value at about 30° and then increases. (It was the discovery of this phenomenon with the thinnest plate specimens that resulted in our developing the gun performance to allow fuller investigation with the more representative thicker specimens.) It is interesting to

note that minimum resistance is about 30^3 which is typical of the wing sweep of modern subsonic aircraft.

Penetration damage

As hail impact velocity increases, the depth of indentation increases progressively until failure of the metal occurs. Initially this failure consists of a short split in the material at the base of the indentation. As the impact speed is increased beyond this splitting speed the split is opened up, the hailstone debris penetrates the plate and petals back the failure. Further speed increases result in increases in the number of petals.

The appearance of the initial metal failure has a resemblance to failure of a thin spherical shell under internal pressure, a case in which the internal pressure at failure, p , can be expressed as:-

$$p = 2tf/r$$

where f = ultimate tensile strength, t = shell thickness and r = shell radius. The pressure generated during impact will be some function of impact speed and of the projectile and specimen material properties under high rates of loading. For a given material, projectile and projectile size it is probable that the pressure will be related to the kinetic energy of the projectile and penetration speed would then be proportional to the square root of specimen thickness. The results in Fig.7 are in fair agreement with this relationship.

Photographic studies

Since no good explanation could be given for the decrease in penetration resistance with increase in impact angle from 0° to 30° , the hail impact phase was studied photographically to see if any evidence could be obtained to explain the phenomenon. Although the study did not achieve this aim the results are interesting.

A very high speed cine-camera was available and a number of impacts were photographed in silhouette at 500 000 to 600 000 frames per second. Fig.8 shows the impact of a 1 inch diameter hail bullet at a speed of $M = 1.0$ on a plate of L73 alloy 0.036 inch thick at zero impact angle. The following features can be seen.

- (a) The hail does not shatter completely on impact and there is no spalling from the rear face.
- (b) There is some sideways splash, similar to that observed in investigations of single impact rain drop erosion studies. The splash front speed is about four times the impact speed.
- (c) The indentation base shape is formed very rapidly and is maintained throughout the impact phase being progressively driven deeper through the plate. In the case of 1 inch hail impacting on L73 material the base shape is that of a 2 inch diameter sphere and on L72 material it is a 1.5 inch diameter sphere.

Figs.9 and 10 show indentation profiles constructed from a common base for various thicknesses of both materials and it can be seen that these base shape diameters apply over the full range tested. Additional tests of L73 alloy

with $\frac{3}{4}$ inch diameter hail gave a base shape equivalent to a 1.5 diameter sphere. This implies that the damage sustained by aircraft in flight, if measured by a fitting ball technique, will indicate encounter with hail some 1.5 to 2 times larger than that actually encountered. This large factor should be noted since the data from in-flight hail encounters have influenced Airworthiness Authorities in the formulation of hail resistance requirements.

Further studies made with short duration flash photography, using reflected light, provided evidence of change in the ice structure following impact. Fig.11 shows the ice projectile prior to impact with highlights as expected from a glaze ice surface. Immediately after impact the highlights disappear indicating a change in material crystal structure. This has been substantiated by examination of fragments of hail recovered after impact. The largest fragment recovered had a mass half that of the original projectile, a mushroom head shape which precisely fitted the indentation profile and a very fine grain crystal structure like a ceramic. It is thought that the impact shock transmitted through the ice causes this crystal structure change. The ice does not shatter completely into a mass of separate crystals: this is clear from the cine-photographs. The change is in the crystal structure itself.

Simulation studies

Earlier we showed that high speed impact of hail at large impact angles cannot be simulated by low speed impact at small impact angles on a $V \cos \alpha$ constant basis.

It has been suggested that high speed impact of small hail can be simulated by low speed impact of large hail on an equal kinetic energy basis. This has also been proved unacceptable. Typical results are shown in Table 1 for L73 material 0.036 inch thick. Using 1 inch diameter hail to simulate $\frac{1}{2}$ inch and $\frac{1}{4}$ inch hail on an equal kinetic energy basis gives penetration speeds of 1970 ft/sec for $\frac{1}{2}$ inch hail compared to a true value of 1355 ft/sec and 3330 ft/sec for $\frac{1}{4}$ inch hail compared to a true value of 1920 ft/sec.

Simulation of large hail by smaller diameter hail of equivalent mass (i.e. elongated bullet) is also unacceptable. Table 1 shows that a $\frac{3}{4}$ inch elongated bullet equal in mass to a 1 inch ice sphere caused penetration at 1090 ft/sec compared to 1230 ft/sec for 1 inch hail.

Simulation of ice projectiles with alternative materials can also give erroneous results. Fig.11 gives penetration results for 1 inch ice spheres a 1 inch poly (ethylene) spheres and the differences are clearly shown; they are attributed to the different behaviour of ice and poly (ethylene) during the impact phase. Poly (ethylene) pancakes out on impact but recovers rapidly to almost its original shape (Ref. 4) and rebounds if penetration has not been achieved. Before an alternative material to ice could be accepted it would be necessary to make comparative tests at representative speeds. This itself would require a high speed hail impact facility so there would be little reason to develop an ice-equivalent material.

Conclusions

From the results of this limited study of high speed hail impact on flat aluminium alloy plates it is concluded that:-

- (a) The maximum depth of indentation from hail impact varies linearly with the component of impact velocity normal to the plate.
- (b) Hail penetration speed is proportional to the square root of plate thickness.
- (c) The apparent diameter of the indentation, measured with the fitting ball technique, is larger than the impacted hail stone diameter by a factor of 2 for L73 material and 1.5 for L72 material in the case of normal impact.
- (d) Simulation of high speed hail impact is difficult since tests must be made at the correct speed, the correct impact angle and with the correct size of hail or hail equivalent material.

It would therefore appear that a matching set of high speed hail guns are necessary weapons in the armoury of the aircraft environmental test engineer.

REFERENCES

- (1) BAC Report SST/B76A-02/0089, Nov. 1964
- (2) Booker, J. D., Alum, Margaret C., "Development of a smooth bore gun for hail impact research", RAE Technical Report 68220, Aug. 1968
- (3) Chisman, S. W., "A proposed programme for research into hail impact damage", RAE Technical Report 68185, July 1968
- (4) Fyall, A. A., "Single impact studies with liquids and solids", Proc. 2nd Meersburg Conf. on rain erosion and allied phenomena, Aug. 1967
- (5) Kangas, Pell, "Hailstone impact tests on aircraft structure components", CAATDC Tech. Dev. Report 124, Sept. 1950

Table 1

Equivalent Kinetic Energy Simulation

Material: L73
Thickness: 0.036"
Impact angle: 0°
Hail: ½", ¾" and 1" diameter
but see Note 1

Note	Projectile type	Weight g	Penetration velocity ft/sec	Kinetic energy ft lb
2	Nominal 1" hail	7.4	1230	760
3	Simulated ¾" hail	7.4	1870	760
2	Nominal ¾" hail	3.2	1355	400
3	Simulated ½" hail	7.4	3330	760
2	Nominal ½" hail	1.0	1920	250
4	Simulated 1" hail	7.4	1090	600

Notes

1. Nominal 1" hail was made from 7.4g water, compared to 7.8g for 1" sphere of ice density 0.91, to minimise crack formation.
Nominal ¾" hail was made from 3.2g water compared to 3.3g for ¾" ice sphere.
Nominal ½" hail was made from 1.0g water compared to 0.975g for ½" ice sphere.
2. Experimental result.
3. Theoretical penetration speed derived from result with 1" hail assuming equivalent Kinetic Energy.
4. Experimental result using ¾" bullet of mass equal to 1" hail.

NEG.MD CMO-3



Fig.1

Fig.1. General view of hail impact test rig

Fig.2

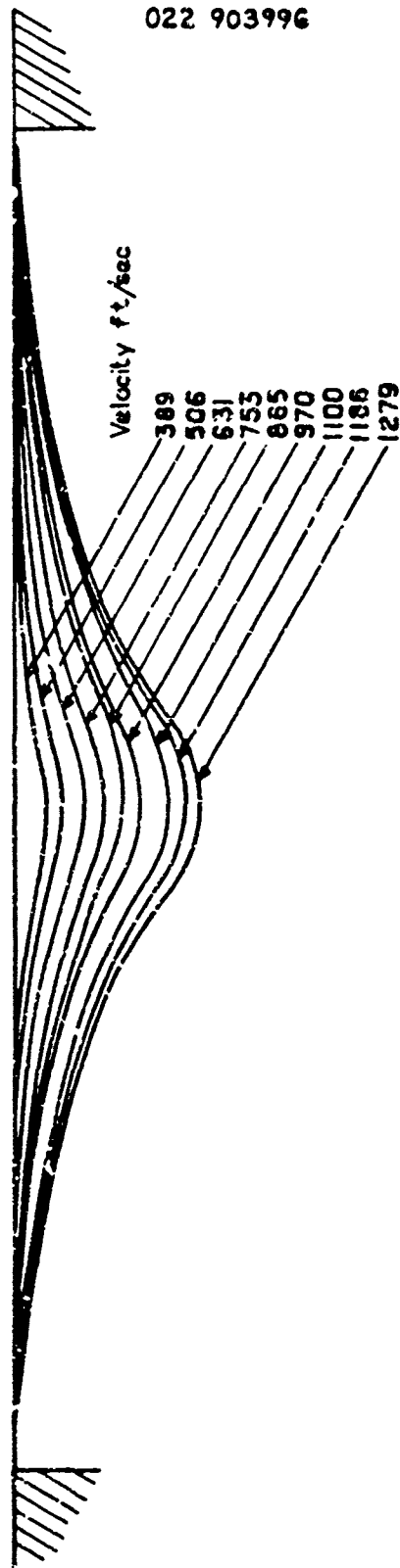


Fig.2 Indentation profile at maximum depth. Full size
(1 in dia hail - matl: L 72/20 swg)

Aluminium alloy L73

(swg) 16 ▽
 18 ○
 20 □
 22 ◇

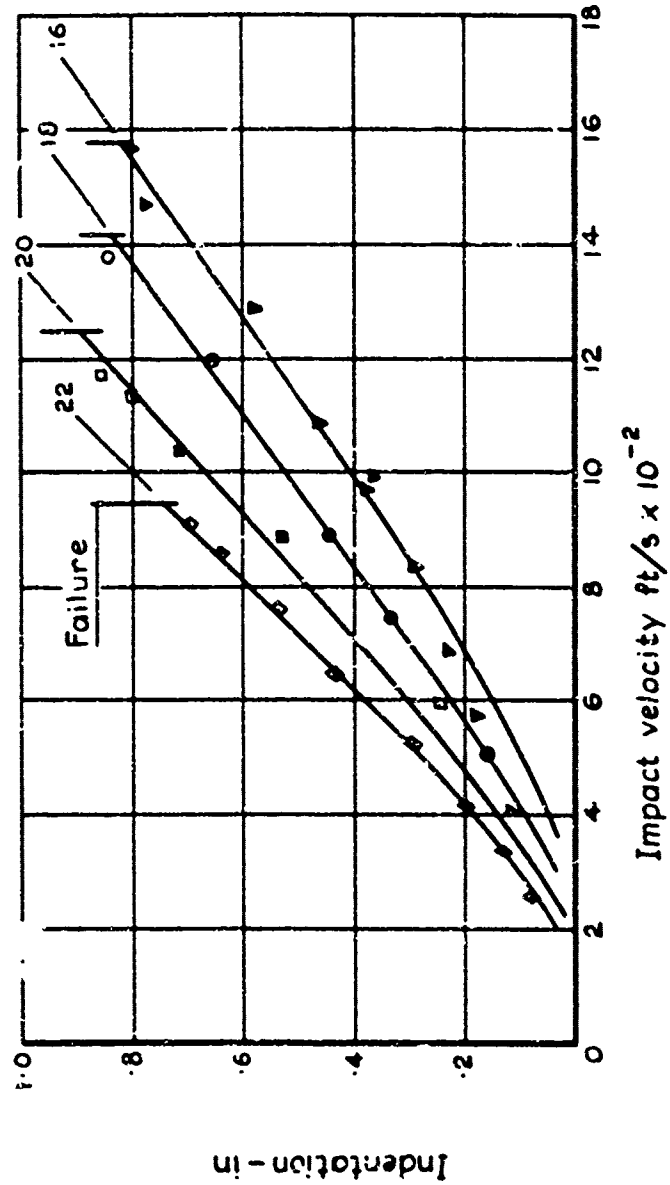


Fig. 3 Normal impact 1 in dia hail - aluminium alloy L73 flat plate

Fig.4

022 903995

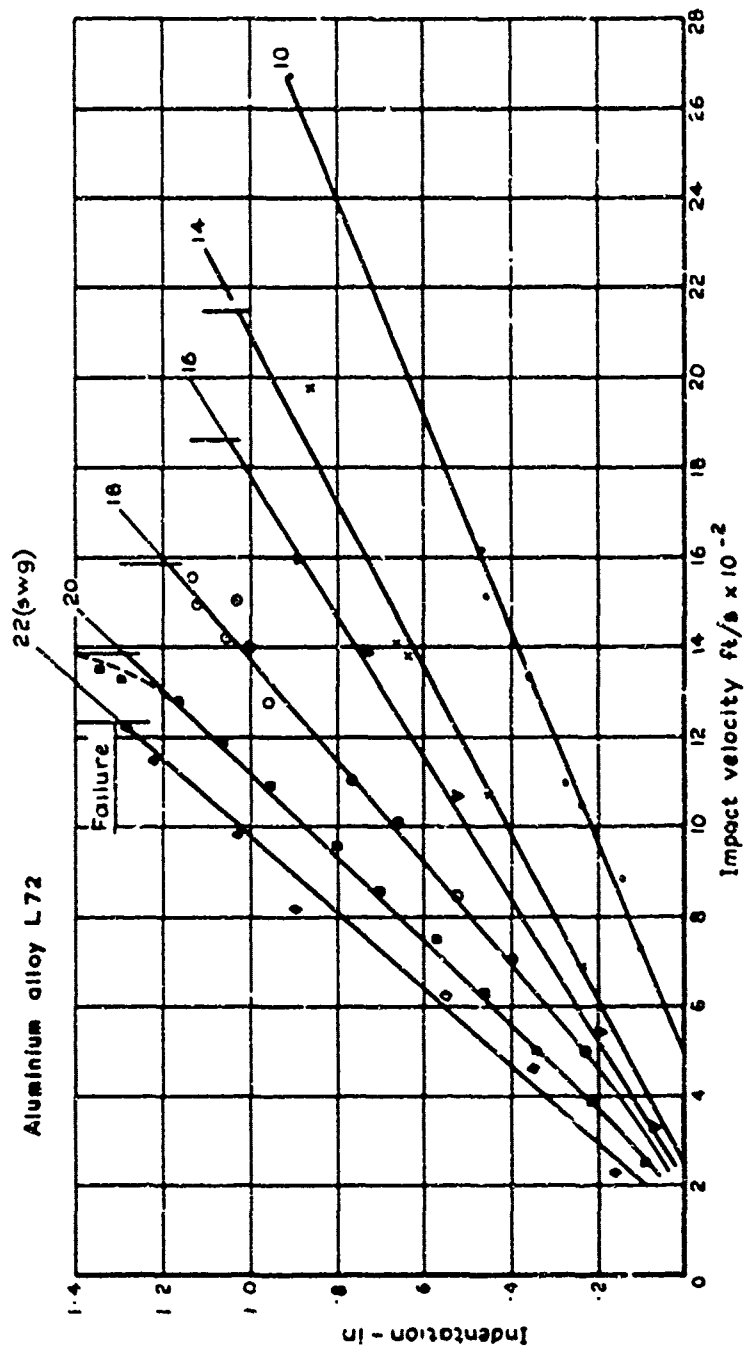
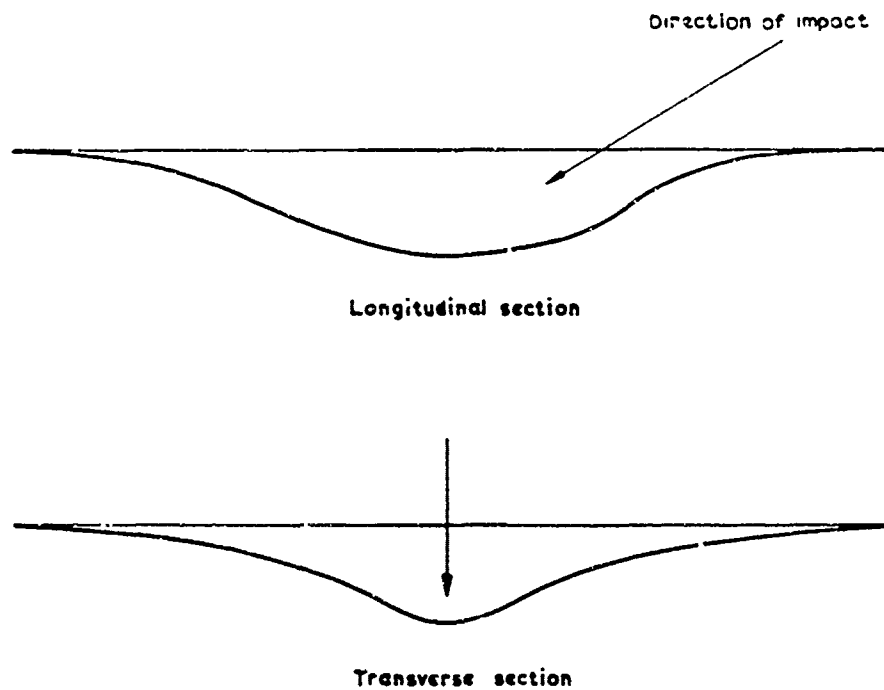


Fig.4 Normal impact 1in dia hail - aluminium alloy L72 - flat plate



Impact velocity	1560 ft/s
Hail	1 in. dia
Material	L72/20
α	60°

Fig.5 Indentation profile - angled impact

Fig.6

022 903998

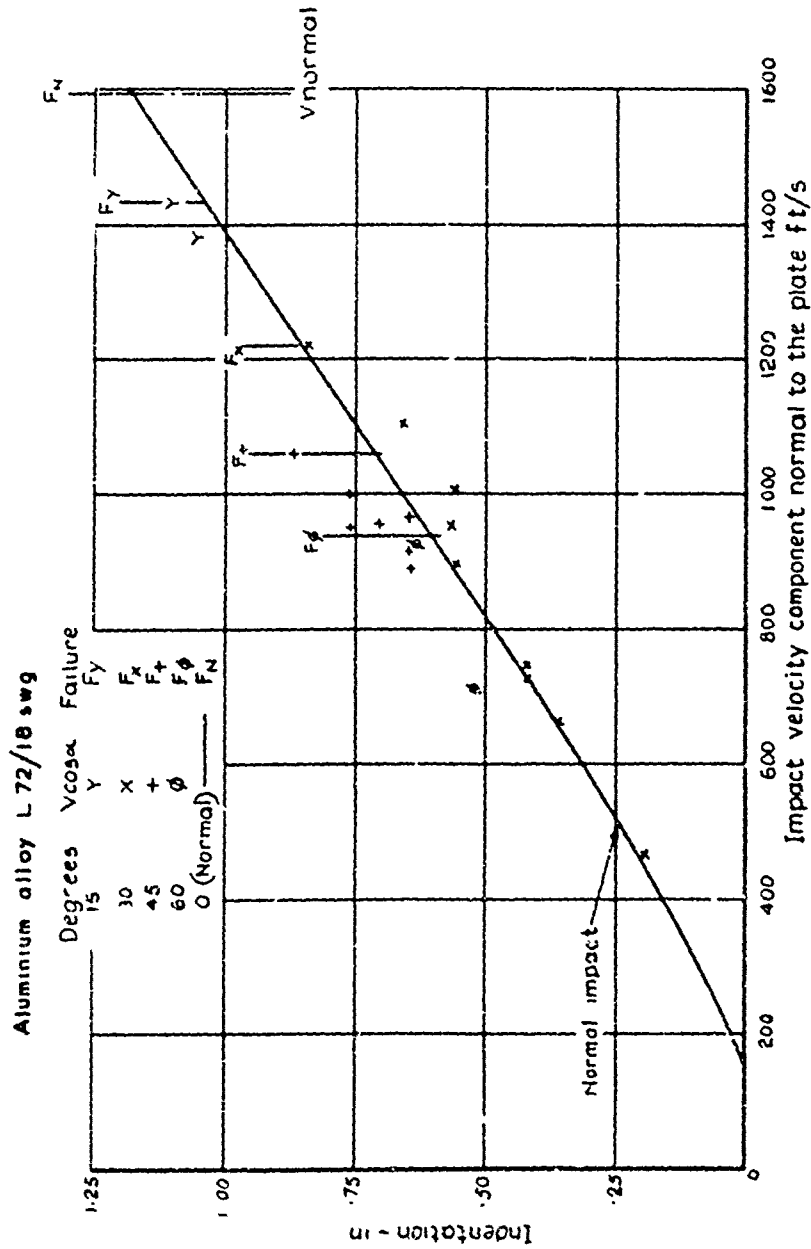


Fig.6 Comparison of normal & angular impact of 1 in dia hail on flat plates

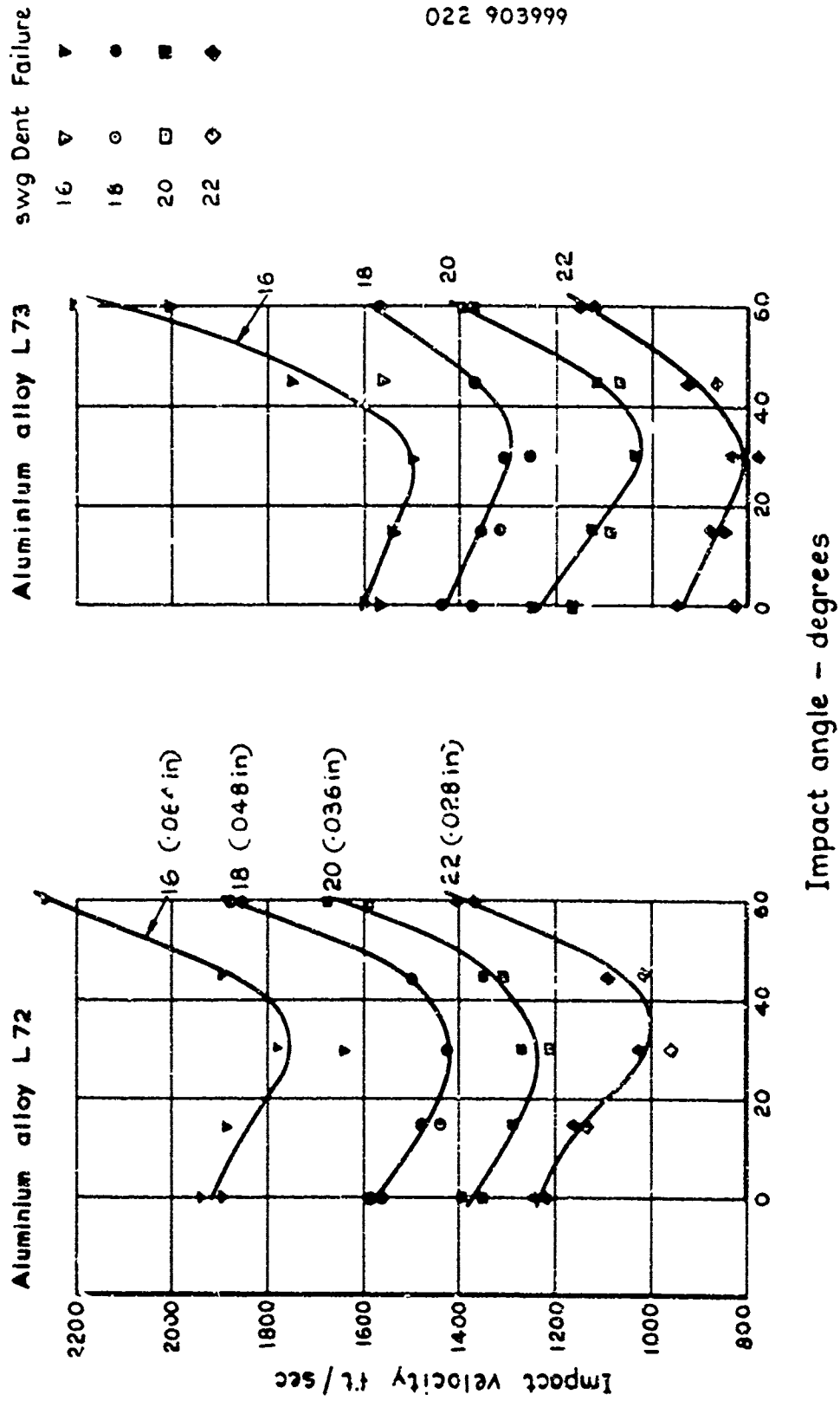


Fig.7 Effect of impact angle on panel failure by impact with 1in dia hail

Fig.8

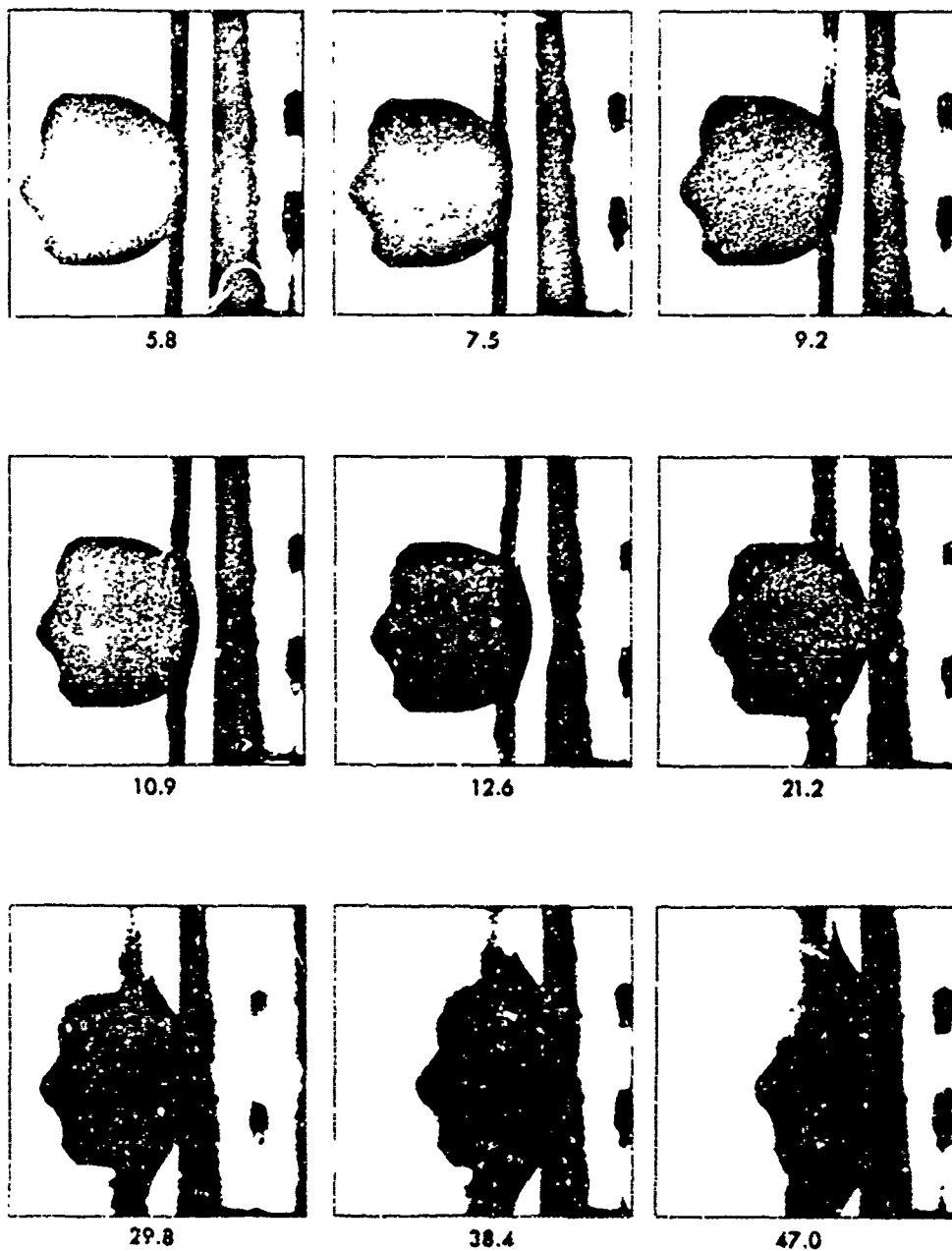


Fig.8 Impact of lin. dia hail bullet at 1100ft/sec:

L73/20 swg: $\alpha = 0^\circ$

Time after impact in μsec as indicated

MEG:HO C6044

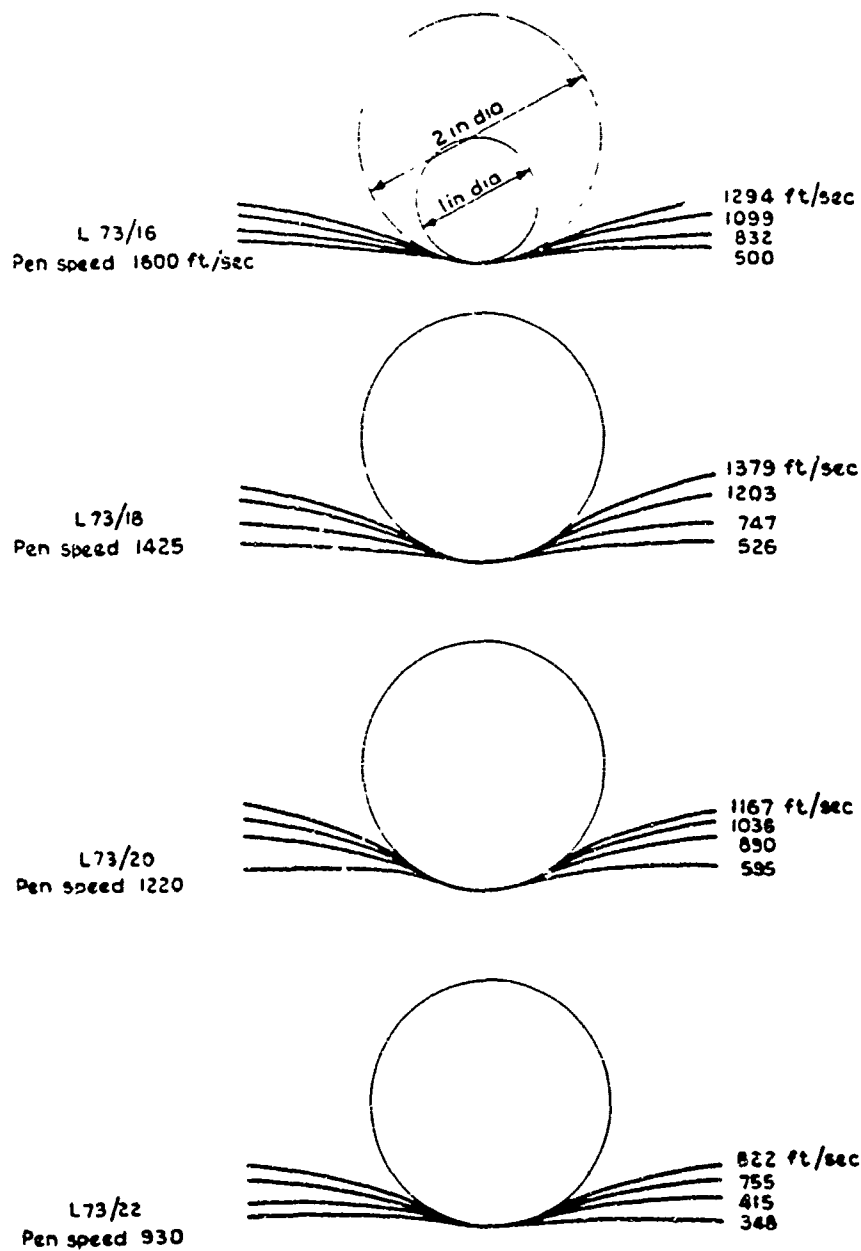


Fig.9 Dent profiles - normal impact

Fig.10

022 904474

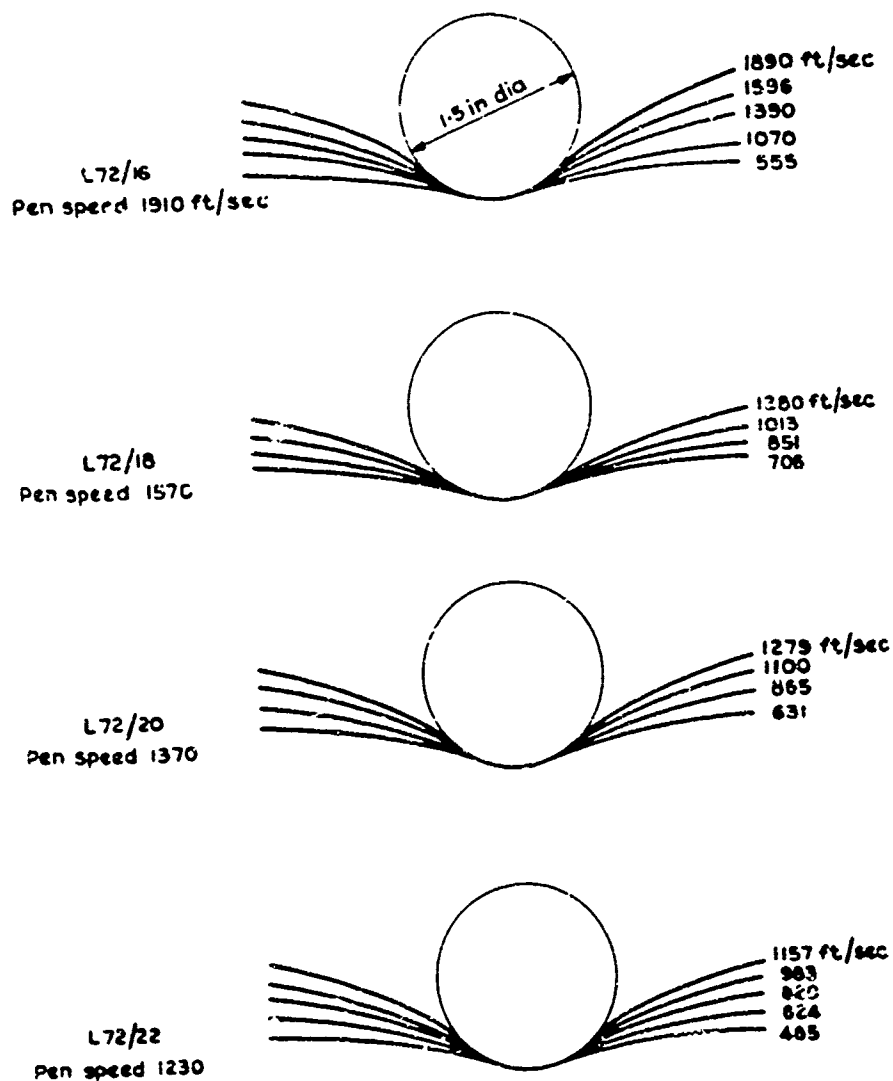


Fig.10 Dent profiles - normal impact

Fig.11

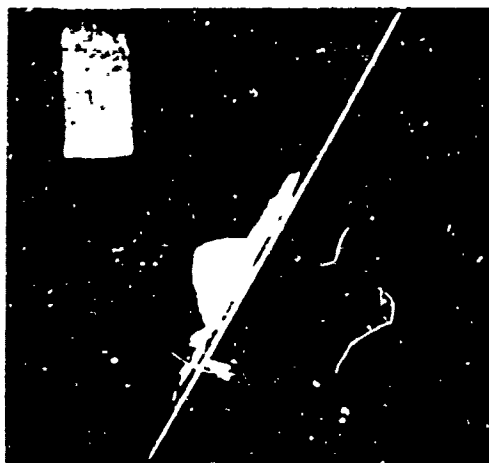
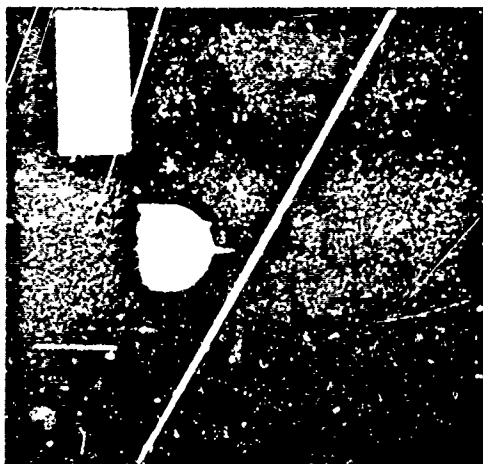


Fig.11 Impacts of lin. hail bullets at 1100ft/sec:
L73/20 swg: $\alpha = 30^\circ$

NEG NO C6045

Fig.12

022 904002

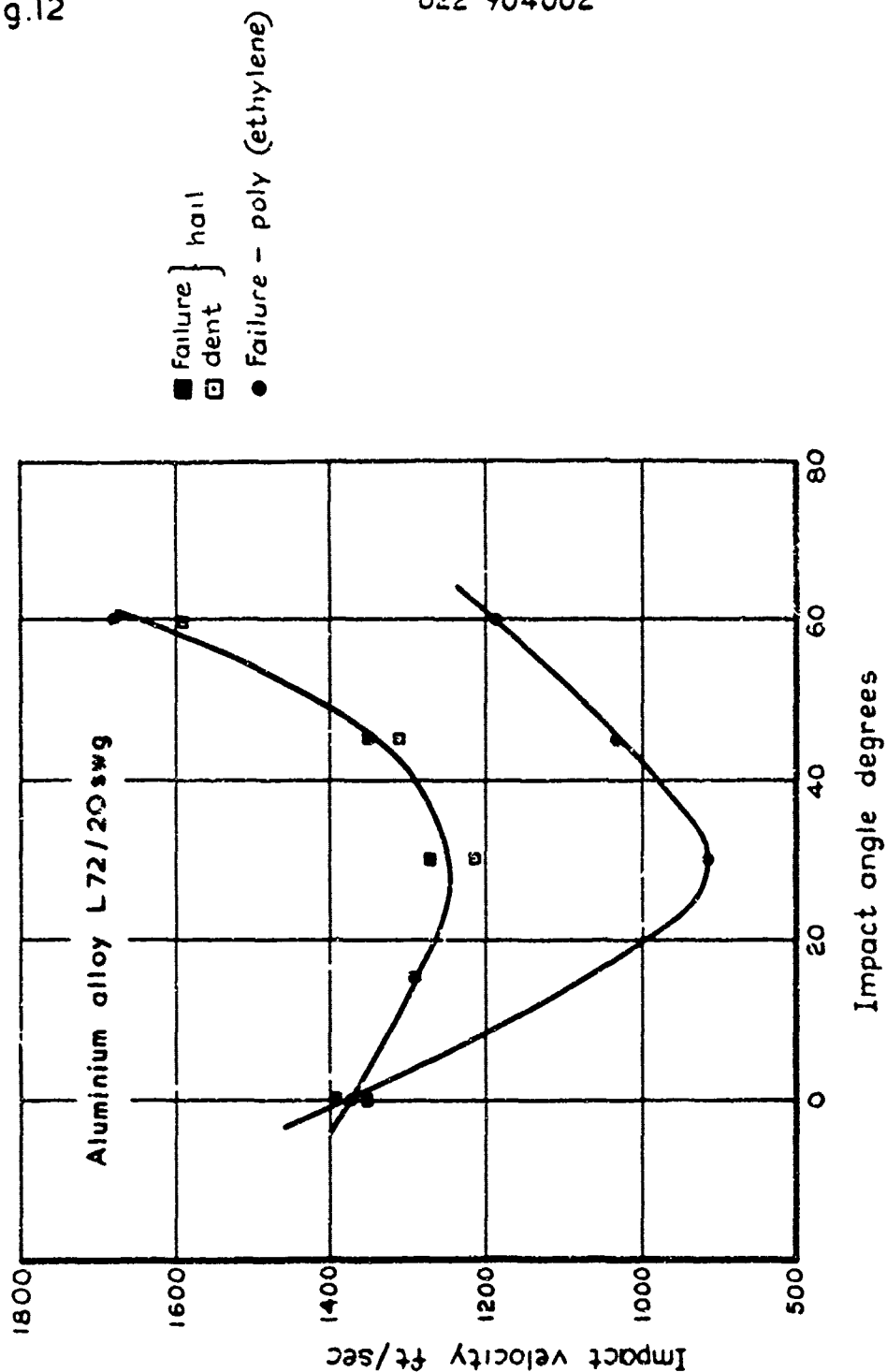


Fig.12 Comparison of panel failure by impact with 1 in dia hail and poly (ethylene)