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ROYAL ARMAMENT RESEARCH AND DEVELOPMENT ESTABLISHMENT

R.A.R.D.E. MEMORANDUM 2/63

Basic processes in the disruption of box-like targets attacked by fast fragments or jets

W. M. Evans

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W. M. Evans

Summary

Some of the more likely basic mechanisms involved in the disruption of box-like targets such as aircraft wings or fuselages when attacked by very fast fragments and hollow charge jets are considered. The static pressures that might be evolved within such targets at various altitudes by transfer to the enclosed atmosphere of kinetic and exothermic processes consequent on attack by aluminium fragments are estimated. Facilitation of such transfer by fragment break-up during penetration into particulate and/or droplet form is discussed and associated processes of ablation and of jetting on impact are examined by analyses of simplified theoretical models. Factors in liner design that might lead to improved jet performance are briefly referred to and a programme of investigations is proposed.

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Approved for issue:

E. W. Chivers, Director.

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1. Introduction

Box-like targets when attacked by fast fragments may suffer violent disruption, as if a charge had exploded inside them. The effect has been well demonstrated, particularly in field trials in which the target is part of an aircraft such as a fuselage or wing or simulated structure and the attacking 'fragment' is a jet from a hollow charge. The term 'vaporific effect' was early coined in the U.S.A. to describe in a phrase what the mechanism of disruption was likely to be: following the processes of penetration of the relatively thin walls (or skin) of the target by the fast aluminium fragments of the jet, those fragments that were projected into the enclosure were imagined to be so heated as to be in vapour form, and in such a form they chemically reacted with the enclosed air in the manner of a vapour or dust explosion, the pressure evolved being sufficient to disrupt the structure.

Over the last five to ten years, a fair amount of field work has been carried out in the States on this phenomenon. Similar but somewhat less effort has been expended in the U.K. Trials have been mainly of an ad-hoc nature, designed towards obtaining information on the influence of some of the more important parameters thought to be involved in the process, and to obtaining direct evidence on the degree and extent of damage incurred under representative full-scale conditions. Targets and charges have differed in design and the degree of matching has varied considerably. There does not appear to have been a sustained and consistent effort towards planned programmes of research. In consequence, the basic mechanisms involved in what is clearly a very complex process are still far from being understood. Published information on the more quantitative influence of some of the more important parameters involved cannot be abstracted with much confidence; nevertheless, various deductions in trend and general behaviour can be made and can be used as a guide to developing a picture of the likely fundamental processes that occur in disruptive systems of this kind.

The following summary embraces the rough pattern of observed behaviour:

(a) A hollow charge jet composed of aluminium is more disruptive than a 'corresponding' hollow charge jet composed of steel or of copper. The jet formed from a hollow charge incorporating a conical liner of aluminium of small apex angle can produce somewhat greater disruption within a given range of standoff than that from a liner of large apex angle, and spread of jet consistent with easy penetration of the near skin of the target is conducive to such damage. There is an optimum distance from charge to target (called standoff) at which any hollow charge produces the maximum damage.

(b) Disruptive damage tends to decrease with altitude of attack and at very high altitude (from 80 to 100,000 feet) the reduction can be about 30% of that at sea level. Targets filled with inert gas, nitrogen, argon, etc., tend to be less disrupted than when filled with air.

(c) Relative motion between charge and target can lead to greater overall damage because of jet sweep across the target.

(d) The damage (tearing of rivets, bulging, disruptive motion, etc.) to a box-like target, the skin of which is made of steel, can be comparable to that when it is made of duralumin and there is an optimum skin thickness, depth and volume of target.

(e) A vented target exhibits less disruptive damage while the presence of an internal plate tends to increase it.

A number of mechanisms has been put forward to explain the effect:-

(i) Rapid heating of the enclosed atmosphere by transfer of the kinetic energy of the fragments or particles (from jet and target) projected in it.

(ii) Rapid heating of the enclosed atmosphere by its exothermic reaction with the particles projected in it.

(iii) Impulsive pressures induced mainly on the rear skin by the impact of projected particles.

(iv) Impulsive pressures produced by bow waves associated with projected particles.

(v) Pressures produced by purely physical explosion-like effects that may occur during high-speed impact and which are manifested in the enclosed atmosphere (analogous to the rapid expansion following the explosion of a small H.E. charge).

2. Specific Aspects

An indication of the magnitude of influence of some of the more important of the processes referred to under (i) to (v) can be obtained if at this stage the more basic mechanisms that may be involved are ignored. Aircraft and winged missiles consist largely of compartments or box-like structures that in detail obviously differ in dimensions and design. A typical compartment in an aircraft wing might measure roughly 6 ft. x 6 ft. x $2\frac{1}{2}$ ft., for example, and would consist of a duralumin skin about $\frac{1}{8}$ in. thick. For purposes of calculation such a box-like target of volume 100 cu. ft. is taken as representative and is assumed to be attacked by aluminium fragment(s) of velocities ranging from 5,000 to 25,000 ft. per second, under ambient pressures and temperatures corresponding to those at sea level and at altitude. Processes (i) and (ii) are first considered, the static pressure rise for a fragment, or composite fragment, of total weight 1 oz. that penetrates the near skin only and is stopped completely inside the box by the enclosed air being calculated.[1] The processes are assumed adiabatic at constant volume.

2.1 Kinetic Heating

Let T_0 P_0 be the ambient temperature and pressure, then the temperature of the enclosed mass of air following kinetic transfer is

$$T_1 = \frac{\text{kinetic energy of the particle(s)}}{\text{mass air x } k_1 + \text{mass particle(s) x } k_2}$$

where k_1 , k_2 are the appropriate specific heats at constant volume and the particle is assumed to be initially at temperature T_0 (abs.).

The corresponding pressure (atmospheres)

$$P_1 = \frac{P_0 T_1}{T_0}$$

2.2 Exothermic Heating

The aluminium is assumed to react completely with the oxygen available in the box according to the formulae $2\,Al + 3/2\,O_2 = Al_2O_3 + H$ (cals.). The amount of heat evolved depends on the mass of aluminium and on the oxygen available in the box at the altitude of attack. H is taken to be 390 kilo cals per gram mole.

Let T_0 P_0 be the ambient temperature and pressure, then the temperature of the enclosed mass of atmosphere following 'exothermic' reaction is

$$T_1 = \frac{\text{heat evolved by reaction}}{\text{mass atmosphere left} \times k_1 + \text{mass } Al_2O_3 \text{ formed} \times k_2 + \text{mass of any aluminium particle(s) left} \times k_2}$$

(Specific heat of the oxide is assumed the same as that of the metal.)

The corresponding pressure (atmospheres) is calculated as for kinetic heating.

Table I gives values of the pressure difference $\Delta P = P_1 - P_0$ developed at various altitudes when fragments of aluminium of various weights and velocity are completely absorbed by the atmosphere within the box. Table II gives similar values when the fragment reacts with the oxygen of the enclosed atmosphere.

Fig. I illustrates the relationship between the pressure difference and altitude when a one ounce aluminium fragment travelling at 5,000 ft. per second and at 20,000 ft. per second gives up its energy entirely to the atmosphere within the box by kinetic transfer and/or by exothermic reaction. The correction applied to the kinetic transfer term consequent on the reduction in the mass of enclosed atmosphere when reaction occurs is seen to be of little significance.

A plausible estimate of the excess static pressure required inside a representative target of the type considered for catastrophic disruption is about $1\frac{1}{2}$ atmospheres. Table I shows that excess pressure of this order can be achieved at all altitudes up to about 60,000 ft. by an ounce or so of fast fragments that can contribute also by combustion. At the highest altitudes, this pressure can never be achieved even by a total weight of 8 ounces of fragments, though it is closely approached. Reaction with nitrogen would, of course, increase the rise in pressure.

2.3 Particle Momentum Transfer

The extent and uniformity of impulsive pressure generated by particle impact clearly depend on a number of physical factors; but a rough appreciation of magnitude can be simply gained by considering, for example, a fragment of one ounce travelling at 5,000 ft. per second. Following penetration of the near skin, the fragment is assumed to break up into a large number of smaller ones, all of which are projected without much loss in velocity in a solid cone on to the rear skin and, on impact there, completely absorbed in a total time of the order 10^{-3} seconds. If the area of impact is taken to be about 2 sq. ft., then the average pressure rise over this area is about $2\frac{1}{2}$ atmospheres. This means that over this area an average pressure of $2\frac{1}{2}$ atmospheres is applied for a milli-second.

2.4 Bow Wave Effects

The bow-wave (shock wave) that accompanies a fragment moving at supersonic speed is, in the present context, the main means by which the loss in kinetic energy of the fragment is conveyed to and propagated through the atmosphere. The pressure rise inside the box by kinetic transfer, for instance, as calculated previously, is the final static pressure evolved when the fragment is completely stopped by the air inside the box. This pressure would probably be largely built up by bow-wave propagation from a number of fragments. A high-speed fragment that easily passes through the box target without appreciable loss in weight would lose energy by air drag as it traversed the air in the box. A fragment of aluminium of $\frac{1}{2}$ cm. in radius, travelling at about 25,000 ft. per second, would lose about a fifth of its velocity in traversing the metre or so of air in the box, at sea level, the resulting static rise in pressure being only about 1/20th of an atmosphere. Looked at in terms of wave propagation, the fragment in its passage through the enclosed air would be associated with a stagnation pressure of about 100 atmospheres, so that on the assumption of an inverse square law of pressure decay with distance, the peak pressure in the wave would drop to less than 1/10th of an atmosphere for one foot of travel. It would appear, therefore, that except for positions on the walls near to the line of motion of the fragment, significant impulsive stressing by bow-wave impingement is not likely if the fragment passes with ease completely through the structure. A large number of such fragments would be required to cause disruption.

2.5 Physical Explosion

A fragment travelling at 10,000 ft. per second has kinetic energy about equal to the detonative energy of the same mass of explosive. If, during impact, the energy of the fragment could be transformed and released in a time comparable to the time the mass of explosive takes to detonate, then ensuing processes analogous to explosive processes would appear to be likely. Some of the characteristics of craters formed in large targets by high-speed impact have been explained on this basis, particularly interesting examples being some of the craters on the moon formed by meteor impacts with approach velocities as high as 72 kilometers per second.[2] Such a process has also been put forward to explain the disruption of box-like targets when attacked by jets from hollow charges.[3] During penetration of the thin near-wall or skin of the target by a fragment of the jet, which is assumed to be of roughly the same linear dimensions as the thickness of the wall, the large stresses set up are postulated as being released in a time comparable to the time of detonation of the same mass of explosive, so that if release occurs within the enclosure, the effect on the box is similar to that exhibited when an explosive charge is detonated inside it.

The process can be visualized as the disintegration of a fragment(s) into a large number of very small fragments that are projected outwards at high velocity in the manner of the radial expansion of gases from an exploding charge. It could be implied that in the process of penetration that must precede radial or outward projection within the target, the fragment is heated, if not to the vapour state, at least to the molten state. Internal energy in excess of that required for its vapourisation might be thought of as being manifested in the manner of a charge detonating in flight while internal energy sufficient only to liquify it might be manifested more in the manner of a liquid jet breaking up in air. It is certain that reactive particles like aluminium, if only in molten form when in flight, would undergo some combustion. In vapour form they would be conducive to considerably greater and more rapid combustion.

Evans and Poole[4] considered such a problem, and they concluded that for high-speed impacts (around 20,000 ft. per second) whereas vapourisation involving low boiling point systems was possible, it was unlikely for those involving high boiling point systems. For aluminium, some vapourisation was likely, but since the aluminium would at least partly melt for much lower speeds of impact and would burn when molten (about 600°C.), the influence of combustion might be appreciable.

3. Ablation

There is ample evidence from field trials carried out by Forrest et al,[5] in which the jet is swept over the target, that catastrophic damage can occur when only a portion of the aluminium jet penetrates the target, for the skin shows penetration only in one place, caused by one fragment or by a number of well-aligned fragments or by an assembly of close-packed small fragments. An unswept jet, perfectly aligned, would normally pass with ease through box targets of the type considered and it could be safely assumed that only a portion of the tip of the jet would be expended in penetration of the thin walls, the remainder passing through largely unhindered, except by the drag of the enclosed atmosphere. In this case, as indicated previously, the bow wave propagated during passage of the jet whilst possibly possessing a high peak pressure would not lead to an appreciable static rise in pressure by kinetic transfer. The question arises, however, of what contribution combustion might make in that circumstance; this question raises in turn, what mechanism in jet flight and in the associated processes of penetration might be conducive to combustion. The field trials referred to show clear photographic evidence of the burning of aluminium jets as they traverse the long air path between charge and target. There is also some evidence of burning during the processes involved in target defeat (referred to later). In this long travel the jet is accompanied by a shroud of burning matter, a foot or so in diameter.

It would appear feasible that because of air drag, the very fast frontal portion, or tip of the jet, even when composed of high melting material of small reactivity is melted and possibly, at least partly vapourised, the melted material being swept radially outwards, dispersed in the manner of a water jet in air, causing a wide zone of luminosity and incandescence in the multitude of small burning particles and air shocks that are created. Lead jets exhibit such incandescence and so do steel jets. The work of Cannon, Partridge and Whited[6] clearly portrays the burning or flaring of cylindrical type pellets ranging from the reactive magnesium and aluminium to the lowly reactive lead and copper when projected from smooth bore guns or fired by explosive means at the comparatively low velocities of about 1,000 metres a second. At very high speeds of projection, some ablation of the projectile must occur, the extent clearly depending on the material and on the velocity with which it traverses the atmosphere. Considerable amounts of ablation of pellets are reported when the pellets are projected in air at sea level, but the main contribution to this is due to erosion by hot gases during propulsion in the propellant or high explosive gun. Maiden and C. St. Pierre[7] also observe, by spectroscopic means, ablative and reactive processes for projectiles travelling at hypersonic speeds in air at low pressure corresponding to very high altitudes (~ 300 miles). Savin et al[8] have recently reported large amounts of ablation for various thermoplastic materials projected at velocities in the region of 15,000 ft. per second.

A non-ablating, non-reactive fragment in its passage through air would lose energy simply by air drag. An ablating non-reactive fragment would also lose by drag but in a more complex manner, in that the ablated material, in the form of small particles, possibly vapour, with initially the same order of velocity as the main fragment, would be brought to rest by a similar mechanism, but in a comparatively short distance. An ablating reactive fragment can be pictured as contributing in a similar manner by drag but, in addition, the ablated material is in a physical condition of size and temperature much more conducive to reaction with the atmosphere than is the main fragment. The heat evolved by such reaction could, of course, contribute to the rate at which ablation and reaction occur, accelerating and increasing the magnitude of the process which can be visualized as possibly reaching a quasi-steady state condition.

3.1 <u>Non-ablative Conditions</u>

The equation of motion of a fragment travelling through air at speed is

$$\frac{dM}{dt} = - K M^2$$

M = Mach number

and $K = k \rho \frac{A}{m} c$

k = drag coefficient

c = velocity of sound in the atmosphere

ρ = density of the air

A = presented area of the fragment

m = mass of the fragment

It is useful to see how long a fragment of radius R takes to decay in velocity from say M = 20 to M = 1, and/or by means of the expression $\frac{dM}{dt} = \frac{dM}{dr} \cdot \frac{dr}{dt}$ in terms of r, the distance. This is given in Table III, the value of k at sea level being taken to be $\frac{3}{4}$, which is approximately valid for high Mach numbers.

The table indicates that non-ablating spherical fragments or particles of aluminium of about 10^{-2} cm. or less in radius, projected at high velocity into the interior of the representative target which is at sea-level conditions of pressure and temperature, will give up most of their energy by air drag within the target.

3.2 Ablative Conditions

When a fragment moves through air at hypersonic speed, the boundary layer associated with the general shock configuration set up has at any point within it a definite value of pressure, temperature and velocity. For a spherical fragment, the highest pressure and temperature is at its tip, where the velocity of the impinging stream of air is reduced to zero. At points radially outwards from this zone of stagnation, the velocity increases while the pressure and temperature fall, the extent depending on factors such as Mach number, size of sphere, etc. The sphere is therefore subjected to heating by conduction and by convection, and also by radiation as the Mach number of the motion increases, i.e., as the temperature increases. Depending on its thermal properties, the surface of the sphere may melt and even vaporise so that a complex heat transfer system is set up. Effectively, the sphere loses mass as it traverses the air, the ablated mass being swept radially outwards ultimately in the form of small 'molten' drops or as vapour.

In Appendix 1 a simple model of fragment ablation at very high speed is considered. An approximate relationship used to express the rate of ablation of a mass, m, moving in a still atmosphere is

$$-\frac{dm}{dt}(L_F + L_V) = \dot{q}_c + \dot{q}_r = \dot{Q}$$

where L_F and L_V are the latent heat of fusion and of vapourisation of the mass, and $\dot{q}_c$ and $\dot{q}_r$ the convective and radiative heat transfer rate terms, respectively.

For an idealised gas behaviour and for a spherical mass of radius, R, this takes the form:-

$$\frac{dR}{dt} = -\frac{\dot{Q}}{4\pi\rho_B R^2(L_F + L_V)} = -(K_1 M^3 R^{-\frac{1}{2}} + K_2 M^8) \qquad (1)$$

where K_1 and K_2 are dimensional constants contained in equations (4) and (5) in the appendix and M is the Mach number.

Application of this equation to a spherical fragment of aluminium of radius $\frac{1}{2}$ cm. travelling at a velocity of about 27,000 ft. per second (M = 25) over a distance of 1 metre at sea level and at 100,000 ft. altitude indicates very small amounts of ablated material, which material would lead to negligible heat evolution even if it reacted with oxygen. In the second simple model considered in the Appendix, chemical reaction by diffusion analogy is assumed to take place in the laminar boundary layer associated with the moving fragment. The amount of heat evolved is again deduced as very small.

The method outlined in the Appendix is exploratory only, meant to give some rough indication of amount of ablation and was actually written some eighteen months ago as part of a report for discussion by a S.A.C. Committee.[9]

Now as shown in Table III fragments of much smaller radius than $\frac{1}{2}$ cm. expend most of their kinetic energy in a distance of travel of about 1 metre; but in addition they must suffer greater ablation per unit mass. It was thought worth while, therefore, to consider in a more general way the kinetic and ablative aspects of small masses travelling at high speed, still using the heat transfer expression given by (1).

The kinematic relationship is as in (1)

$$\frac{dM}{dt} = - K_3 \frac{M^2}{R} \qquad (2)$$

or

$$\frac{dM}{dr} = - K_4 \frac{M}{R} \qquad (3)$$

where K_3 and K_4 are dimensional constants given by

$$K_3 = \frac{3k\rho_A c}{R\rho_B}$$

$$K_4 = \frac{3k\rho_A}{R\rho_B}$$

ρ_A = density of the atmosphere

ρ_B = density of the spherical fragment of mass m

c = velocity of sound in the atmosphere

k = drag coefficient

and r is the distance of travel

Equations (1), (2) and (3) cannot be solved directly. It was thought useful to obtain by numerical solution the quantitative relationships between the various parameters involved. Computations by AMOS enabled such relationships to be drawn for aluminium spheres of radii 0.5, 10^{-2} and 10^{-3} cm. respectively, projected in air under conditions corresponding to sea level and to 100,000 ft. altitude, at an initial Mach number of 20 that decayed to a value of 1; from which the ablation per unit mass was calculated. This was found to be small even for the smallest sphere.

Since as indicated the ablation or change in radius of the aluminium fragment if not much less than 10^{-3} cm. radius is very small during its motion from M = 20 to M = 1, it can be assumed as a first approximation that it remains constant in equation (2), which then becomes

$$-\frac{1}{M^2}\frac{dM}{dt} = \frac{K_3}{R_0}$$

and which on integration is

$$M = \frac{R_0 M_\infty}{K_3 M_\infty t + R_0}$$

or $$t = \frac{R_o}{K_3}\left\{\frac{1}{M} - \frac{1}{M_\infty}\right\} \tag{4}$$

(since for $R = R_o$, $M = M_\infty$ when $t = o$)

On substitution of the expression for M in equation (1), and on integration

$$R_o - R = \frac{K_1 R_o^{\frac{1}{2}}}{2 K_3} (M_\infty^2 - M^2) + \frac{K_2}{7K_3} R_o (M_\infty^7 - M^7) \tag{5}$$

Also from equations (3) and (4)

$$\frac{dr}{dt} = \frac{K_3}{K_4} \cdot M \approx \frac{K_3}{K_4} \frac{R_o M_\infty}{K_3 M_\infty t + R_o}$$

which integrated gives

$$r = \frac{R_o}{K_4} \ln \frac{M_\infty}{M} \tag{6}$$

These approximate but conveniently tractable equations give values that are in fact within a few per cent of those given by equations (1), (2) and (3) and as determined by AMOS.

A test of the physical validity of these equations revealed that for the same distance of travel of the spherical fragment, the ablated thickness $R_o - R$ was found to be significantly greater at altitude than at sea level. This is unlikely to be true and can be explained by the fact that the heat transfer conditions are more likely to obey real gas rather than the idealised gas conditions assumed in (1) (see Appendix I). Substitution of real gas stagnation temperatures for various Mach numbers in the idealised gas expression for $\dot{q}_r$ yields at once values many hundred times less. For real gas conditions where ionisation, dissociation and recombination processes can occur, radiation cannot be assumed to be black-body, so that the emissivity will be less, and the power to which the temperature is raised, appreciably lowered (for example, a fully ionised gas radiates proportionally to the power 1/2 according to Spitzer[10]).

Substitution of real gas stagnation temperatures in the expression for $\dot{q}_c$, for various Mach numbers indicates that its value is changed by a factor of two to three. In the present context, therefore, the contribution to heat transfer by radiation can be neglected by comparison with that by conduction, and the expression for $\dot{q}_c$ for an idealised gas, as given by (2) and (4) in the appendix can be taken as being roughly true for a real gas.

Equation (5) simplifies therefore to

$$R_o - R = \frac{K_1 R_o^{\frac{1}{2}}}{2K_3} (M_\infty^2 - M^2) \tag{7}$$

Using expressions (4), (6) and (7) values of the motion and of the ablation of various diameter spherical fragments of aluminium are shown in Table IV.

If the target is of average internal linear dimensions ~ 100 cm., (very roughly the representative target considered in section 1), it follows that under sea level conditions any fragments projected into the box at M = 20 must be $R_o < 3.34 \times 10^{-2}$ cm. to decay to M = 1 within it. Larger fragments suffer impacts with the rear wall at a Mach number $\geq$ 1. At 100,000 ft. altitude the corresponding value for R_o is 3.34×10^{-4} cm.

It would appear, therefore, that for ablation to play an important part in the process of target disruption by kinetic transfer and by reaction the impinging fragment would need to be broken up into very small fragments during penetration, which with those from the skin would be projected into the interior of the target. Reaction would tend to accelerate with rise in temperature within the target.

In the long distance of travel from charge to target, because of drag the jet must decay in average velocity and any ablative material would be projected radially ultimately in molten drops or possibly as vapour which might react with oxygen to form a burning shroud.

In general $R_0 - R$ is seen to be a small fraction of the original radius R_0 and the amount of ablation per unit mass of sphere is small except for the smallest spheres of about 10^{-1} cm. or less which are stopped within the postulated maximum allowable distance of travel of 100 cm. Clearly for the smallest spheres more accurate values would need to be obtained by numerical computation but this was not put in hand in view of the somewhat speculative nature of the heat transfer expression denoted by (1).

If, as is thought possible, ablative action is one mainly of melting, the vapourisation term, L_V, need not be included in expression (1), in which case the amount ablated is increased about 40 times. For the largest spheres considered the amount would still be small (see Appendix I) but in calculating the probably significant amounts for the smallest spheres recourse would need to be made to numerical computation since clearly $R_0 - R$ is not necessarily small with respect to R_0, provided expression (1) were considered accurate enough.

3.3 Ablation and Combustion

This concept is dealt with in the appendix. The influence of combustion on the ablative process is seen to be small. If the mass is in the form of minute particles, the contribution might become significant.

4. Discussion

If as is thought likely the more important processes involved in the disruption of box-like targets are in essence those outlined, it follows that for an attacking fragment to be highly efficient it should be in particulate or droplet form following penetration of the frontal skin and in such form with secondary particles from the penetrated skin itself be completely absorbed within the enclosure by air drag and by impact with the rear skin. The material of the fragment should be highly reactive with oxygen and if possible also with nitrogen yielding large amount of energy, ablation and reaction being a minimum over the long distances of travel from charge to target but a maximum during projection within the enclosure. The greater the break-up of the fragment on penetration the greater the amount of ablation and reaction per unit mass, and in turn the greater the useful transformation of energy in so far as that required for target disruption. Some appreciation of the degree of projection of particles beyond a defeated thin plate can be gained from the recent work of Becker, Vitali and Watson[11,27] in which small steel pellets are fired at fairly high velocity against thin aluminium type plates or skins, fragments of pellet and of plate being projected beyond at high mass and velocity, the amount increasing within limits with decreasing thickness of plate.

The amount of ablation of the attacking fragment depends to a great extent on whether melting only is a sufficient thermal criterion in the mechanism: if it is not sufficient, changes to the vapour state are implicit and ablation with combustion is considerably reduced as indicated in the model. Ablation would also tend to increase if the convective term in the heat transfer equation were based on the more complex but more likely condition of turbulent flow rather than on the assumed one of laminar flow.

In the present context attack is by hollow charge jet, that is by fragments strung out in depth with a gradation in mass and velocity, and, because of non-alignment, dispersed over a square foot or so in area after a fair distance of travel. Under low altitude conditions any small fragments in the continually changing frontal portions of the jet are absorbed by drag as are those generated and swept aside from the larger fragments by ablation. Only the larger fragments in the jet are able to attack the target and when there is relative motion between charge and target probably only those in a portion of its forward length. At high altitude, however, a proportion of the smaller fragments may reach the target to bombard the frontal skin, pushing it inwards, thus contributing to defeat.

For most systems of impact between metals only moderate velocities are required for the stresses set up to exceed the yield strengths of the materials involved. During impact between aluminium and aluminium and between steel and steel, for example at 1,000 m/sec., stresses are generated that are a few orders of magnitude greater than the yield strength of aluminium and more than an order of magnitude greater than the strength of steel. The processes of flow induced in such impact changes from a plastic to a fluid nature as the impact velocity increases.[12] The characteristics of flow of a lead projectile during impact with a steel plate can vary from the mushroom type flattening of the nose, which occurs at low velocities of impacts, to that of rapid radial flow at higher velocities with peripheral projection of material in particulate (or droplet) form. Impacts at high velocity of high strength metals such as steel exhibit deformation by plastic flow often accompanied by the projection of fast fragments. Such flow is also evident in steel when it is penetrated by the very fast jets from hollow charges, but a great deal of the mechanism of penetration is undoubtedly hydrodynamic in character[13] as it is in the mechanism of formation of the jet itself[14] which takes place on impact of the collapsing walls of the cone, along its axis, at velocities from 2 to 3,000 m/sec. The work of Summers and Niehaus[15] indicates, for example, that for impacts with steel fluid flow occurs at a velocity of about 1,000 m/sec. for lead and 2,000 m/sec. for copper.

Rapid radial flow is therefore likely in certain systems where the impact velocity is very high. The fast fragment of lead on impact with armour would exhibit a "splash" of projected material. Clearly the form and extent of splash in any system of high velocity impact must largely depend on the physical nature and geometry of the materials involved.

Where in the particular system of impact under consideration the hollow charge jet of aluminium impinges (usually at an angle) on the thin duralumin near skin of the box-like target, discrete portions of material are seen to be deflected or to be splashed at high velocity along its surface.[5] Ciné camera photographs record their luminous traces. Many traces spaced out in position and time are sometimes observed, which is not surprising when it is remembered that the jet is usually not well aligned in flight but wavers, particularly at long standoffs. Any particle or fragment of the jet that easily penetrates the near skin of the target may have a residual velocity high enough to make impact either wholly or in particulate form with the rear skin or any enclosed intervening object and if the velocities there are high enough 'splashing' may occur during the impact and process of penetration, the radially projected material, now inside the target, contributing to its defeat by the transfer mechanisms described.

Such 'splashing' bears some analogy with that which occurs when a drop of water impinges on a hard surface[16] and more faithfully, because penetration may be considerable, when a suspended mercury drop[17] makes impact with the face of a steel shot in flight or when a high speed, 'spherical' fragment such as lead makes impact with armour.

In Appendix II a simple analysis is attempted of some of the processes of spreading that occur when an idealised fluid drop impinges on a perfectly rigid plane. It is deduced that even for moderate speeds of impact very fast jets can be produced of high energy which travelling roughly parallel to the surface of the plane in the form of a rapidly expanding disk, must break up into droplet and/or vapour form. The practical model of relevant concern consists of aluminium fragments projected at high speed against a thin aluminium or duralumin skin. Provided the ratio of length to diameter of the fragments is not greatly different from one, they can be considered for simplicity as spherical. Penetration in this case takes place at a velocity roughly one half of the incident velocity. During the earliest stages of impact and of penetration, attendant radial flow is along the surface of the skin; but as penetration proceeds, is directed more and more along the sides of the expanding hole being formed. In this latter process, part of the radial flow is redirected upwards and out of the hole, ceasing obviously (for a skin) at that transitional stage in the process where stresses are relieved by reflections from the underside free surface.

If in the practical situation the high velocity sphere or fragment is too small to achieve through penetration of the skin of the target, defeat is still possible provided there is bombardment by a large number of such fragments spread over a fair area, aided by transient gas pressure effects following splash and exothermic reaction, and by spalling into the interior. Similar processes must apply when the sphere or fragment easily defeats the skin; but they occur also on the rear skin and are therefore amenable to produce disruption from within.

Hydrodynamic flow in impact processes is facilitated in the practical case under consideration by the fact that the jet fragments of aluminium are raised in temperature, even before impact with the target, by the impact process from which they are formed and projected[18,19] and by aerodynamic and reactive heating processes during flight. Such temperatures could well be several hundred degrees centigrade, so that effectively the fragments before impact might be reduced in yield strength to that appropriate if not to near-molten to plastic or semi-plastic conditions.[20] Impact with the near-wall would raise the temperature still further, and it is conceivable that even the lower velocity aluminium fragments of the jet just prior to and during impact with the rear wall are in a state conducive to kinetic transfer and to immediate exothermic reaction. The tendency to ablation by fragments already raised in temperature is increased particularly for those of relatively low velocity, since the temperature becomes more significant with respect to the stagnation temperature T_s (see Table V in Appendix I).

5. Practical Considerations

Much more is needed to be known before detailed thought can be profitably given to what might be the best weapon design characteristics for attack of targets of the kind considered; but if the foregoing basic processes are those of greatest dominance it would follow that the target should be attacked by a multiplicity of fair-sized fragments of high velocity spread over a few square feet. Spread is in fact partly achieved by natural waver in the jet and under operational conditions mainly by the influence of relative motion between charge and target on the velocity distribution in the jet. Thus stand-off and fuzing must largely determine for a specific type jet the number of fragments likely to hit a specific target. Preferably the fragments should be conducive to 'break-up' on impact so that with secondary fragments from the penetrated skin projection into the interior is in fine particulate and/or droplet form amenable for energy transfer to the interior by kinetic and exothermic means. The need for break-up decreases with increase in number of fragment hits, for a large number of fragments of high residual energy even if not broken up may result in bow wave effects sufficient to cause disruption. It is possible therefore that under operational conditions of attack jet configurations somewhat different from those currently exhibited might be found appreciably more efficient against specific targets, in which case the uniform aluminium conical liner might be replaced by one of different material, or by a tapered one or by one of different shape. It could well be that aluminium liners are in overall performance comparatively quite high. Nevertheless, it is worth while testing other reactive and/or pyrophoric liner substances in conjunction with that of liner design on the lines suggested by Evans and Poole.[21]

6. Conclusions

A few ounces of attacking fast fragments are indicated as being sufficient to cause disruption of box-like targets some 100 cu. ft. or so in volume, particularly if the pressure build-up by kinetic transfer from fragment to enclosed atmosphere is augmented by exothermic reaction.

The greater the fragment break-up into particulate and/or droplet form during penetration and projection into the interior of the target, the greater is likely to be the violence of disruption, since in such form kinetic transfer and reaction are facilitated. Examination of a simplified model consisting of very fast aluminium fragments moving through air at various pressures indicates that such contribution to break-up by ablation is small except for small fragments of the order of 10^{-1} cm. in radius or less, for which size almost complete absorption by drag is achieved in distances corresponding to those of the internal dimensions (a metre or so) of the box-like structures considered. A simple analysis of an idealised model of impact of a fluid drop impinging on a rigid plane indicates that aluminium fragments during high-speed impact with the skin of a metal target are likely to exhibit considerable radial projection or 'splash', the frontal portions of which are at very high velocity and possibly in droplet or vapour form. The contribution to break-up by splashing may be significant and if it occurs within the target, energy transfer is facilitated.

It is possible that a worth-while improvement in current operational performance of shaped charge warheads might be achieved by adopting somewhat different jet configurations in flight. This might be attained simply by modifying the design of the liner.

7. Recommendations

It is quite possible that the lethal capabilities of fast fragments and jets when used to attack aircraft and missiles are not fully exploited. Studies, both of a basic and applied nature, are considered necessary to test this. Existing techniques could be used to determine some of the mechanisms of penetration of thin skins, of projection beyond and of the more important processes involved in the disruption of box-like targets, emphasis being laid on the configuration of the attacking substance with that of its physico/chemical nature. Exploratory trials directed towards early practical application in shaped charge warheads should be guided by and carried out in conjunction with basic investigations.

8. Acknowledgements

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APPENDIX I

1. Jet Ablation

The influence and extent of the ablation of fragments or particles as they travel at high speed through the atmosphere have direct relevance to jet propagation and to the defeat of box-like targets by such jets. Ablative processes are complex and fairly elaborate treatments have recently been developed in explanation of some specific detailed aspects.[22,23] In the context of the present investigation a simple treatment suffices since the main purpose is to gain a rough appreciation of the mass ablated when a particle travels through the atmosphere at high speed.

The jet at any instant can be regarded as a long, thin pencil of discrete fragments of various sizes and of velocity decreasing almost linearly from front to rear. If it can be assumed that regions only around the front or tip suffer appreciable ablation and real gas effects are neglected, a rough order of the amount of such ablation may be gained by considering a single spherical particle travelling at constant high velocity through air at a certain temperature and pressure. The mass ablated over a fixed distance of travel at sea level and at 100,000 ft. altitude respectively is calculated for purely aerodynamic conditions of heat transfer and when such conditions are influenced by diffusive processes of chemical reaction between particle and atmosphere.

1.1 Heat Transfer

The heat transfer rate into a body at speed $\dot{q}$ is given by

$$\dot{q} = \dot{q}_r + \dot{q}_c \qquad (1)$$

where convective heat transfer based on laminar flow only is

$$\dot{q}_c \sim c_p \, (\mu_s)^{\frac{1}{2}} \, (p_s \, \rho_s)^{\frac{1}{4}} \, T_s \, R^{3/2} \qquad (2)$$

and radiative heat transfer (assuming the air radiates as a grey body with an emissivity of about 1/1000, which appears to be a not too unreasonable factor.)

$$\dot{q}_r \sim \frac{1}{10^3} \sigma \, T_s^4 \, \pi R^2 \qquad (3)$$

c_p = specific heat at constant pressure

μ = viscosity

p = pressure

ρ = density

σ = Stefan-Boltzmann constant

T = temperature

R = radius of sphere

subscript s denotes stagnation conditions, and

subscript ∞ free stream conditions.

For sufficiently high temperature $\mu_s/\mu_\infty = (T_s/T_\infty)^{\frac{1}{2}}$

For high Mach numbers M_∞

$$p_s/p_\infty \sim M_\infty^{\,2}$$

$$T_s/T_\infty \sim \frac{1}{5} M_\infty^{\,2}$$

$$\rho_s/\rho_\infty \sim 6$$

therefore $\dot{q}_c \sim \frac{1}{5} c_p \, \mu_\infty^{\frac{1}{2}} (p_\infty \rho_\infty)^{\frac{1}{4}} T_\infty M_\infty^{\,3} R^{3/2}$ (4)

and $\dot{q}_r \sim \frac{\pi}{6.25 \times 10^5} \; T_\infty^{\,4} M_\infty^{\,8} R^2 \sigma$ (5)

Typical approximate values at sea-level are

$$c_p = 10^7 \text{ ergs/gm/K}^0$$

$$\mu_\infty = 2 \times 10^{-5} \text{ gm./cm. sec.}$$

$$\rho_\infty = 10^{-3} \text{ gm./cm.}^3$$

$$p_\infty = 10^6 \text{ dynes/cm.}^2$$

$$T_\infty = 300^\circ\text{K.}$$

$$\sigma = 5 \times 10^{-5} \text{ ergs/cm.}^2 \text{ sec. deg.}^4$$

therefore $\dot{q}_c \sim 10^7 M_\infty^{\,3} R^{3/2}$ ergs/sec. (6)

and $\dot{q}_r \sim \frac{1}{5} \; M_\infty^{\,8} R^2$ ergs/sec. (7)

Table V gives approximate values of the heat transfer for various velocities of a spherical aluminium particle of $R = \frac{1}{2}$ cm.

1.2 Mass Loss

At a given speed, the rate of energy input is from (2) and (3) approximately

$\dot{q} = \beta R^2$ where β is a constant for a given speed.

In time ∂t if mass ∂m is ablated

then $- \partial m \, (L_V + L_F) = \beta R^2 \, \partial t$ (8)

$$= 4 \pi R^2 \rho \partial R \, (L_V + L_F) = \beta R^2 \, \partial t$$

since $\partial m = 4 \pi R^2 \rho_B \, \partial R$

Therefore $\frac{\partial R}{\partial t} = - \frac{\beta}{4 \pi \rho_B \, (L_V + L_F)}$

and $R_o - R = \frac{\beta t}{4 \pi \rho_B \, (L_V + L_F)}$

For a sphere $\frac{1}{2}$ cm. radius travelling over 1 metre at 27,500 ft. per second

$$\beta = 3.87 \times 10^{12} \text{ ergs/sec. cm.}^2$$

$$L_V + L_F = 8.5 \times 10^{10} \times 2.7 \text{ ergs/cm.}$$

and therefore $4\pi\rho_B (L_V + L_F) = 3 \times 10^{12}$ ergs/cm.^{3}

Since time of travel $\sim 10^{-4}$ sec., $R_0 - R$ is therefore $\sim 1.29 \times 10^{-4}$

Volume loss $= 4\pi R_0^{\,2}\, \partial R \sim 4 \times 10^{-4}$ cm.^{3}

Mass loss $\sim 3 \times 4 \times 10^{-4} = 1.2 \times 10^{-3}$ gm.

At lower velocities the mass loss is less.

If the "mass loss" can be regarded as reacting chemically with the atmosphere the ultimate increase in pressure within the box is clearly very small, even for a total weight of one or two ounces.

1.3 Deceleration of Fragment

Drag $\sim \frac{1}{2}\rho_\infty \pi R^2 U_\infty^{\,2}$ (drag coefficient $\sim \frac{1}{2}$)

Deceleration $\sim \frac{1}{2}\rho_\infty \pi R^2 U_\infty^{\,2} \Big/ \frac{4}{3}\pi R^3 \rho_B$

In a time t speed decreases by $\frac{1}{2}\rho_\infty \pi R^2 U_\infty^{\,2}\, t \Big/ \frac{4}{3}\pi R^3 \rho_B$

$$= \frac{3}{8}\,\frac{\rho_\infty}{\rho_B}\,\frac{1}{R}\,U_\infty^{\,2}\, t$$

If $\rho_\infty/\rho_B = \frac{10^{-3}}{3}$, $R = \frac{1}{60}$ ft., and $t \sim 10^{-4}$ sec.

The decrease in speed at the highest initial speed considered $M_\infty = 25$, is therefore about 500 ft. per second. The decrease is proportional to initial speed, so that for lower speeds the decrease is less.

1.4 The Effect of Altitude on Mass Loss

To obtain an indication of the effect of high altitude on the mass ablated, it suffices to consider 100,000 ft. altitude only. At this altitude

$T_\infty \sim 220^\circ$K $\quad T_{S.L.} \sim 280^\circ$K (S.L. = sea level)

$$\mu_\infty \sim \sqrt{\frac{220}{280}} \cdot \mu_{S.L.} = 1.5 \times 10^{-5} \text{ gm./cm. sec.}$$

$$p_\infty \sim 10^4 \text{ dynes/cm.}^2$$

$$\rho_\infty \sim 10^{-5} \text{ gm./cm.}^3$$

Thus from (4) and (5) $\dot{q}_c \sim 10^6 M_\infty^{\ 3}$ ergs/seo.

$$\text{and } \dot{q}_r \sim 5 \times 10\ M_\infty^{\ 8} \text{ ergs/sec.}$$

For a given speed, M_∞ at 100,000 ft. ~ 1.1 M_∞ at sea level

Therefore from (6) and (7), at the highest projectile speed of 27,500 ft. per seoond ($M_\infty = 25$)

$$\dot{q}_c \text{ (100,000 ft. alt.)} \sim \frac{1}{13}\ \dot{q}_c \text{ (sea level)} \qquad (9)$$

and $$\dot{q}_r \text{ (100,000 ft. alt.)} \sim \frac{1}{2} \times \dot{q}_r \text{ (sea level)} \qquad (10)$$

These ratios apply to the full range of projectile speeds considered.

The effect of altitude would appear therefore to influence heat transfer mainly by convection; and it must be borne in mind that at low densities the gas will not radiate as a grey body, so that the radiative term may be much over-estimated.

Since from (8) the mass loss is proportional to the rate of heat input, i.e., to $\dot{q}_c + \dot{q}_r$, it follows from (9) and (10) that the mass loss at 100,000 ft. is from a third to a tenth less than at sea level for the velocity and range considered.

2. Jet Ablation and Combustion

As soon as a thin layer is liquified and vapourised by aerodynamio heating, the problem arises as to how and to what extent the vapour contributes by its reaction with oxygen to further heat transfer into the metal. The process is obviously bound up with a complex mechanism of diffusion of aluminium vapour with oxygen molecules (and/or atoms), which is assumed to lead to a maximum concentration of vapour and oxygen in the middle regions of the boundary layer. The maximum heat evolution therefore occurs there. It is further assumed that one half of the heat evolved flows back into the metal, the other half flowing eventually into the surrounding atmosphere.

If oxygen molecules are considered first as flowing into the boundary layer, the rate at which they diffuse into the layer per unit area is

$$= \frac{1}{6} n_o v_s$$

where n_o is the number of molecules and v_s their average velocity.

If M = mass of an oxygen molecule, then mass transfer rate per unit area

$$= \frac{1}{6} n_o v_s M$$

If E denotes the energy per unit mass of oxygen, where

$$E \sim 3.5 \times 10^{11} \text{ ergs/gm. of oxygen (from } Al_2O_3 \text{ reaction)}$$

the rate of energy input per unit area of surface

$$= \frac{1}{6} n_o v_s ME \times \left\{ \frac{1}{2} \right\}$$

$$= \frac{1}{6} \rho_o v_s E \times \left\{ \frac{1}{2} \right\} \text{ where } n_o M = \rho_o \qquad (11)$$

Now $v_s \sim a_s$ where a_s = speed of sound $\sim 1.5 \times 10^5$ cm./sec. (for a real gas).

Density of oxygen $\rho_o \sim \frac{0.001}{5}$ gm./cc.

Therefore rate of input of energy is

$$\frac{7}{8} \times 10^{12} \text{ ergs/cm.}^2 \text{ sec.}$$

Area of the metal surface = $2\pi R^2 = \frac{3}{2}$ sq. cm. for $R = \frac{1}{2}$ cm.

Therefore rate of energy transfer $\sim 10^{12}$ ergs/sec.

2.1 The Effect of Altitude

The influence of altitude on the rate of transfer can be indicated by considering, for example, an altitude of 100,000 ft. where the atmospheric density

$$\rho_o \sim \frac{1}{100} (.001)$$

and the temperature is $\sim -50^\circ$C., so that v_s is ~ 0.98 that at sea level.

Substitution in equation (11) leads to

$$\text{rate of energy transfer} \sim 10^{10} \text{ ergs/cm.}^2 \text{ sec.}$$

Thus at 100,000 ft. the rate of energy transfer by combustion is about $\frac{1}{100}$ that at sea level. This ratio can be compared with that for purely aerodynamic heating, which is not far from 1.

2.2 The Effect of Nitrogen

Aluminium reacts also with nitrogen at $\sim 750^\circ$ compared with oxygen at $\sim 600^\circ$C. giving a heat evolution about $2\frac{1}{2}$ times less than that with oxygen. Therefore from (11)

rate of energy transfer by nitrogen reaction

at sea level $\sim 2 \times 10^{12}$ ergs/sec.

and at 100,000 ft. altitude $\sim \frac{2}{100} \times 10^{12}$ ergs/sec.

Total contribution to energy transfer that might be given by the reaction of both O_2 and N_2 with aluminium is

$\sim 3 \times 10^{12}$ ergs/sec. at sea level

and $\sim \frac{3}{100} \times 10^{12}$ ergs/sec. at 100,000 altitude

Thus in a travel of 1 metre (that is, in about 10^{-4} secs.), by the aluminium sphere of radius $\frac{1}{2}$ cm., its total contribution to pressure inside the box by exothermic reaction is again seen to be very small at any altitude of attack.

APPENDIX II

1. Jet Formation on Impact and Collapse of Fluid Drops

Some of the simpler characteristics of flow that occur when fluid drops 'splash' on impact with hard surfaces may be examined on the same basis as that used by Birkhoff et al[14] to explain the jet and slug that are formed during the high velocity collapse of a conical liner of metal when subjected to detonative forces. In this an analysis is made of asymmetrical two-dimensional model consisting of two incompressible, non-viscous fluid planes inclined to each other, which, making impact along the axis of symmetry result in two streams there, one of high velocity, the other of lower velocity but larger mass. High speed impact of two thin metal sheets similarly inclined to each other (thus forming a wedge) is assumed to exhibit like behaviour, the impact velocity being high enough for the metals to behave as fluids. The condition of steady state motion for the wedge cannot be imposed for the uniform cone unless its thickness is inversely proportional to the distance from the apex. Nevertheless as a first approximation the characteristics of formation and projection of jet and slug in the practical three-dimensional hollow charge becomes clear by analogy, being in close qualitative accord with observation and in some of the more important aspects in fair quantitative agreement.

2. Stream Formation on Impact of a Curved Fluid Sheet with a Rigid Surface

The plane wedge model considered by Birkhoff et al[14] is modified in the present context to that of two sheets, one of which is the idealised fluid, thin and curved in the form of a quadrant of a circle, the other plane and perfectly rigid. The essential features can be inferred from Fig. 2(a) which represents a vertical section through the centre of a sphere (or drop), the drop making impact with a perfectly rigid surface at a relative velocity $\bar{V}$ and an angle ϕ with the normal to the rigid surface.

In the region of the section to the right of the vertical line through the centre, O, Fig. 2(a), the point of impact, first at X, will move towards the right to X' and X'' as the centre of curvature moves from O to O' and O''. For a small interval of impact in which O' is near to O'' and X' near to X'' the velocity of the point moving from X' to X'' is from Fig. 2(b)

$$V_1 = \frac{\bar{V}}{\sin\theta} \cos(\phi - \theta)$$

where θ is the angle between the tangent to the curved surface at the point of impact X'' and the rigid surface X X' X'' ....

If in the process the mass per unit length of sheet with θ were constant, as it is in the wedge, an observer stationed at the moving junction X would be in a steady state system of flow, and Bernoulli's theorem relating velocity with pressure would apply. This condition can be approximated to by considering sufficiently short intervals X' X'', X'' X''' etc. in the process. During any such infinitesimal interval an observer at the moving junction would see a near element of the sheet streaming towards him with velocity

$$V_2 = \bar{V}\left[\cos(\phi - \theta)\cot\theta - \sin(\phi - \theta)\right]$$

This element separates into two streams moving away from him to the right and to the left along the rigid surface with the same velocity. In a stationary co-ordinate system the velocity of the fast stream (or jet) to the right is

$$V_j = V_1 + V_2 = \frac{\bar{V}}{\sin\theta}\left[\cos(\phi - \theta) + \cos(\phi - \theta)\cos\theta - \sin(\phi - \theta)\sin\theta\right] \qquad (1)$$

followed by the slower stream

$$V_s = V_1 - V_2 = \frac{\bar{V}}{\sin\theta}\left[\cos(\phi - \theta) - \cos(\phi - \theta)\cos(\theta) + \sin(\phi - \theta)\sin\theta\right] \quad (2)$$

Fig. 3 illustrates how the stream velocities associated with a small element of the sheet vary with θ for various values of ϕ between 0 and 90°.

Since mass and momentum are conserved it follows simply that

$$m_j = \frac{dM}{2}(1 - \cos\theta) \quad (3)$$

$$m_s = \frac{dM}{2}(1 + \cos\theta) \quad (4)$$

where dM is the mass of the material in any element of the sheet making impact at angle θ.

It suffices in the present context to consider only the simpler, symmetrical example of impact at normal ($\phi = 0$), for which the stream velocities given by (1) and (2) reduce to

$$V_j = \frac{\bar{V}}{\sin\theta}(1 + \cos\theta) \quad (5)$$

$$V_s = \frac{\bar{V}}{\sin\theta}(\cos\theta - 1) \quad (6)$$

Expressions (3) to (6) are clearly strictly valid only during the normal impact of an infinitesimal element of the curved sheet with the rigid surface (or during the entire impact of a corresponding plane sheet with the rigid surface). But since θ changes smoothly in value the process of impact and flow though not steady can be regarded as continuous. It follows therefore that during the motion the velocity of the jet V_j decreases while its mass m_j, increases and the velocity V_s of the slower stream increases while its mass m_s, decreases. It is of interest to note that the streams move in opposite directions.

The particular question arises of how much of the energy of impact is transformed into the faster stream or jet. Three progressive models are considered.

2.1 Mass and Energy of Jet

(a) Curved Sheet

If the curved sheet is of uniform small thickness and of mass m_o per unit length, the mass of an element subtending a small angle $d\theta$ is

$$dM = m_o R_o \, d\theta$$

where R_o is the radius of the circle (R_o >> thickness).

The mass of the jet generated from an element is therefore from (3)

$$dm_j = \frac{dM}{2}(1 - \cos\theta)$$

$$= \frac{m_o R_o}{2}(1 - \cos\theta)\, d\theta \quad (7)$$

and the mass of the jet generated during the entire motion is

$$m_j = \frac{m_o R_o}{2} \int_0^{\pi/2} (1 - \cos\theta)\ d\theta = \frac{m_o R_o}{2} (\pi/2 - 1)$$

The total mass of the sheet is

$$M_T = \frac{\pi m_o R_o}{2}$$

Therefore $\dfrac{m_j}{M_T} = \dfrac{\pi/2 - 1}{\pi} \approx 18\%$

For the corresponding plane sheet

$$0 \leq \frac{m_j}{M_T} \leq 50\%$$

The energy of the jet generated from an element is

$$dE_j = \frac{1}{2} dm_j V_j^2$$

and the energy of the jet generated during the entire motion is, using (5) and (7)

$$E_j = \frac{m_o R_o}{4} \bar{V}^2 \int_0^{\pi/2} (1 - \cos\theta) \frac{(1 + \cos\theta)^2}{\sin^2\theta} d\theta$$

$$= \frac{m_o R_o}{4} \bar{V}^2 (\pi/2 + 1)$$

The energy of the moving sheet before impact is

$$E_T = \frac{m_o \pi R_o}{4} \bar{V}^2$$

Therefore $\dfrac{E_j}{E_T} = \dfrac{\pi/2 + 1}{\pi} \approx 82\%$

For the corresponding plane sheet that makes impact at normal with the rigid surface (or for the explosive wedge that collapses normal to its surface), the corresponding ratio is

$$\frac{E_j}{E_T} = \frac{1 + \cos\theta}{2} \quad \text{i.e.,} \quad 50\% \leq \frac{E_j}{E_T} \leq 100\%$$

(b) Disk

The impact of a uniform disk with and normal to, a rigid plane can again be represented by inference from Fig. 2(a). During an infinitesimal stage in the collapse the mass of element involved is assumed to be proportional to the height above the point of contact. Therefore the mass of element at value θ is

$$dM = 2\,k\,R_0 \cos\theta \, dR$$

where $R = R_0 \sin\theta$

$k = \rho t$

t = thickness

and ρ = density

Thus if the same basic mechanism applies as for the curved sheet, the mass of an element of the jet is

$$dm_j = \frac{dM}{2}(1 - \cos\theta)$$

$$= k\,R_0 \cos\theta\,(1 - \cos\theta)\,dR$$

$$= k\,R_0^2 \cos^2\theta(1 - \cos\theta)\,d\theta \qquad (8)$$

on substituting the differential of the relationship

$$\cos\theta = \sqrt{\frac{R_0^2 - R^2}{R_0}}$$

The mass of the jet generated during the entire motion is

$$m_j = k\,R_0^2 \int_{-\pi/2}^{\pi/2} \cos^2\theta\,(1 - \cos\theta)\,d\theta$$

$$= k\,R_0^2 \left[\frac{\pi}{2} - \frac{4}{3}\right]$$

Total mass of the disk is

$$m_T = k\,\pi R_0^2$$

therefore $\dfrac{m_j}{m_T} = \dfrac{\pi/2 - 4/3}{\pi} \approx 8\%$

The energy of an element of jet is

$$dE_j = \frac{1}{2} dm_J V_j^2$$

and the energy of the jet generated during the entire motion is using (5) and (8)

$$E_j = \frac{k\,R_0^2}{2}\,\overline{V}^2 \int_{-\pi/2}^{\pi/2} \cos^2\theta(1 - \cos\theta)\,\frac{(1 + \cos\theta)^2}{\sin^2\theta}\,d\theta$$

$$= k\,R_0^2\,\overline{V}^2\,(\pi/4 + 2/3)$$

Total energy of the disk before impact is

$$E_T = \frac{k\,\pi R_0^2}{2}\,\overline{V}^2$$

Therefore ratio

$$\frac{E_j}{E_T} = \frac{\pi/2 + 4/3}{\pi} \approx 92\%$$

(c) Sphere

The streaming processes that occur on impact and collapse of a fluid sphere may be looked at in a similar manner. Since for impact at normal the processes of collapse are symmetrical, from Fig. 2(a) the elemental body undergoing impact at angle θ is in the form of a cylinder of radius R, thickness dR, and height $2\sqrt{(R_o^2 - R^2)}$

The mass of a cylindrical element is therefore

$$dM = 4\,k\,R\sqrt{(R_o^2 - R^2)}\,dR$$

where $k = \pi\rho_o$

The mass of an element of jet is

$$dm_j = 2\,k\,R\sqrt{(R_o^2 - R^2)}\left\{1 - \frac{\sqrt{(R_o^2 - R^2)}}{R_o}\right\}dR \qquad (9)$$

and the mass of the jet generated during the entire motion is

$$m_j = 2k\int_0^{R_o}\left[R\sqrt{(R_o^2 - R^2)}\left\{1 - \frac{\sqrt{(R_o^2 - R^2)}}{R_o}\right\}\right]dR = \frac{k_o R_o^3}{6}$$

In the more practical example of the sphere it is useful to note that in a similar manner

$$m_s = \frac{7}{6}\pi\rho_o R_o^3$$

(which also follows from $m_j + m_s = \frac{4}{3}\pi\rho_o R_o^3$ the mass of the sphere)

Thus a maximum total of $\frac{1}{8}$ of the mass of the sphere contributes to the fast outward radial jet motion and $\frac{7}{8}$ to the associated, slower motion.

The energy of an element of jet is

$$dE_j = \frac{1}{2}dm_j V_j^2$$

and the energy of the jet generated during the entire motion is, using (5) and (9)

$$E_j = k\bar{V}^2\int_0^{R_o}\left[R\sqrt{(R_o^2 - R^2)}\left\{1 + \frac{\sqrt{(R_o^2 - R^2)}}{R_o}\right\}\right]dR$$

$$= k\bar{V}^2\left[\frac{R_o^3}{3} + \frac{R_o^3}{2} - \frac{R_o^3}{4}\right]$$

$$= \frac{7}{12}k\bar{V}^2 R_o^3$$

(Similarly $E_s = \frac{1}{12}\pi\rho_o R_o^3\bar{V}^2$)

Since the total energy of the spherical particle

$$E_T = \frac{1}{2} \times \frac{4}{3}\pi R_o^3 \quad \rho_o \quad \overline{V}^2$$

E_j is about 88% of E_T and is clearly the maximum possible following impacts at normal of liquid spheres against rigid surfaces.

2.2 Axial Jets

The motion of the slower accompanying stream, denoted by subscript s, is worth brief mention. From equations (3) to (6), limiting values of the motion for impact at normal are:-

$$\theta \rightarrow 0 \quad \begin{cases} V_j \rightarrow \infty, & m_j \rightarrow 0 \\ V_s \rightarrow 0, & m_s \rightarrow M \end{cases}$$

$$\theta \rightarrow 90 \quad \begin{cases} V_j \rightarrow \overline{V}, & m_j \rightarrow \frac{M}{2} \\ V_s \rightarrow -\overline{V}, & m_s \rightarrow \frac{M}{2} \end{cases}$$

The faster jet-like stream moves outwards, the slower accompanying stream moves inwards, and from the sphere is in the early form of a cylindrically converging disk of thickness tapering to zero from the front to the back, but with a velocity gradient in the opposite sense. Such convergent motion must lead to a stream moving upwards along the perpendicular axis of the sphere, of maximum velocity $\overline{V}$ and of energy distribution that can be deduced as in the preceding treatment. If the target is not perfectly rigid two such axial streams might result moving in opposite direction, the one moving upwards, the other moving downwards into the target causing penetration. It is noteworthy that a jet-like stream, ad deduced above, is actually observed and beautifully photographed by Meloy and Mayfield[17], when the flat face of steel cylinders strike a stationary mercury drop at velocities of ~ 3,000 m/sec. The velocity of the jet is measured as approximately that of the velocity of impact, which corresponds with the value of $\overline{V}$ deduced above.

3. Comment

Since in the models of impact considered the physical requirement of steady-state conditions is not met but is assumed, the analysis must be regarded as an attempt at a first approximation to the problem. The neglect of compressibility and rigidity may well be regarded as small perturbations in the model. In general the results would indicate that for the more realistic example of a fluid sphere making impact with a very hard surface, two disk-like streams are generated and projected along the surface during the collapse, the one possessing jet-like properties in that the peripheral velocities are far higher than the incident velocity of impact. The angle of impact determines the spatial and kinetic characteristics of spread with that of the secondary axial streaming that appears possible on convergence of the associated slower stream. The energy available would appear to be mainly taken up by the faster stream. The numerical values derived above should be regarded only as indicative, being dependent on the assumed steady-state conditions with the elemental masses considered.

As the faster stream or jet spreads or fans out, it becomes thinner and breaks up. Break-up is bound to occur because of internal forces, of friction between the spreading fluid and the surface of impact, and of atmospheric drag. At high velocities of impact, at least the fast frontal or peripheral portions of the fluid jet are likely to suffer disruption and break-up into droplets, which are themselves rapidly attenuated in velocity by air drag.

Jenkins and Booker[16], in their investigations on the impact of solid shot with water drops, report measured radial velocities nearly four times the incident velooity of the shot and observe a transitional prooess of spread, break-up and mist formation. Bowden and Brunton[24] observe similar effects when water jets impinge on solid surfaces. Savic and Boult[25] calculate the pressure distribution and shape of a water drop during impingement with a solid, and they extend their photographic observations to molten drops of paraffin and to impacts with hot surfaces. High radial velocities are evident in all cases. Engel[26] maps the structure of flattening water drops during impact and observes that the part of the drop that strikes first is washed to the periphery of the radial flow; the part that strikes last possessing very little flow. Radial flow is channelled, probably because of viscous drag, between the solid surface and the flowing liquid, the number and extent of channelling seeming to depend on the energy of impact. The mechanism of such collisions is considered and the observation made that the characteristics of radial flow are dependent on the nature of the solid surface. Impact of the drop with a rubbery surface led to some spray in upward motion while impact of the drop with sand appeared like an "underground explosion in diminutive." Impact of solid shot with mercury drops results in violent radial projection of mercury[17], some of which appears to be in vapour form.

The mercury drop impact system bears analogy with the theoretical model examined though less closely than the water drop impact system, if only because of the significantly greater penetration by flow that occurs during the process of impact. Where there is penetration, less energy is available for radial flow which becomes directed along the surface and out of the crater being formed.

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TABLE I

PRESSURES DEVELOPED IN 100 CU. FT. BOX BY KINETIC TRANSFER OF ATTACKING ALUMINIUM FRAGMENTS

P_1 = Pressure Rise (atm.)

$\Delta P_1 = (P_1 - P_0)$ = Pressure Difference (atm.)

V (Ft./Sec.)	Alt. (Ft.)	1 oz.		2 oz.		4 oz.		8 oz.	
		P_1	ΔP_1	P_1	ΔP_1	P_1	ΔP_1	P_1	ΔP_1
5,000	0	1.05	0.05	1.09	0.09	1.18	0.18	1.34	0.34
	20,000	0.50	0.03	0.55	0.08	0.63	0.16	0.78	0.31
	40,000	0.23	0.05	0.27	0.09	0.34	0.16	0.46	0.28
	60,000	0.12	0.05	0.15	0.08	0.20	0.13	0.26	0.19
	80,000	0.06	0.03	0.09	0.07	0.12	0.09	0.12	0.10
	100,000	0.03	0.02	0.05	0.04	0.05	0.04	0.06	0.05
10,000	0	1.18	0.18	1.36	0.36	1.71	0.71	2.36	1.36
	20,000	0.65	0.18	0.82	0.35	1.15	0.68	1.73	1.26
	40,000	0.38	0.20	0.53	0.35	0.80	0.62	1.28	1.10
	60,000	0.25	0.18	0.38	0.31	0.59	0.52	0.80	0.73
	80,000	0.17	0.15	0.24	0.21	0.38	0.36	0.45	0.43
	100,000	0.11	0.10	0.16	0.15	0.20	0.19	0.20	0.19
15,000	0	1.41	0.41	1.82	0.82	2.60	1.60	4.05	3.05
	20,000	0.88	0.41	1.28	0.81	2.00	1.53	3.31	2.84
	40,000	0.60	0.42	0.95	0.77	1.58	1.40	2.58	2.40
	60,000	0.45	0.38	0.83	0.76	1.19	1.12	1.75	1.68
	80,000	0.32	0.30	0.51	0.48	0.75	0.73	0.99	0.97
	100,000	0.23	0.22	0.32	0.31	0.39	0.38	0.41	0.40
20,000	0	1.73	0.73	2.45	1.45	3.84	2.84	6.43	5.43
	20,000	1.19	0.72	1.89	1.42	3.20	2.73	5.50	5.03
	40,000	0.91	0.73	1.53	1.35	2.65	2.47	4.41	4.23
	60,000	0.72	0.65	1.23	1.16	2.03	1.96	3.05	2.98
	80,000	0.59	0.57	0.90	0.88	1.31	1.29	1.61	1.59
	100,000	0.43	0.42	0.55	0.54	0.69	0.68	0.75	0.74
25,000	0	2.15	1.15	3.27	2.27	5.43	4.43	9.48	8.48
	20,000	1.59	1.12	2.68	2.21	4.74	4.27	8.33	7.86
	40,000	1.29	1.11	2.29	2.11	4.05	3.87	6.83	6.64
	60,000	1.10	1.03	1.91	1.84	3.15	3.08	4.72	4.65
	80,000	0.92	0.89	1.39	1.37	2.01	1.99	2.62	2.59
	100,000	0.68	0.67	0.85	0.84	1.09	1.08	1.18	1.17

TABLE II

PRESSURES DEVELOPED IN 100 CU. FT. BOX BY COMBUSTION OF VARIOUS WEIGHTS OF ATTACKING ALUMINIUM FRAGMENTS

P_2 = Pressure Rise (atm.)

$\Delta P = P_2 - P_0$ = Pressure Difference (atm.)

Alt. (ft.)	1 oz.		2 oz.		4 oz.		8 oz.		Saturated Weight	
	P_2	ΔP	P_2	ΔP	P_2	ΔP	P_2	ΔP	P_2	ΔP
0	2.16	1.16	3.31	2.31	5.53	4.53	9.60	8.60	47.95	46.95
20,000	1.66	1.19	2.73	2.26	4.56	4.09	7.42	6.95	10.00	9.53
40,000	1.33	1.15	2.24	2.06	3.62	3.44	4.77	4.59	4.77	4.59
60,000	1.04	0.97	1.55	1.48	1.68	1.61	1.15	1.08	1.73	1.66
80,000	0.78	0.76	0.80	0.78	0.50	0.48	0.38	0.36	0.86	0.84
100,000	0.13	0.12	0.07	0.06	0.06	0.05	0.01	-	0.25	0.24

TABLE III

DECAY CHARACTERISTICS OF NON-ABLATIVE SPHERICAL FRAGMENTS (M = 20 TO M = 1)

ρ(gm/cc) / R (cm)	t (sec.)			r (cm.)		
	1	2.7	8	1	2.7	8
1	1.17×10^{-2}	3.16×10^{-2}	9.36×10^{-2}	1.11×10^{3}	3×10^{3}	8.88×10^{3}
10^{-1}	1.17×10^{-3}	3.16×10^{-3}	9.36×10^{-3}	1.11×10^{2}	3×10^{2}	8.88×10^{2}
10^{-2}	1.17×10^{-4}	3.16×10^{-4}	9.36×10^{-4}	1.11×10	3×10	8.88×10
10^{-3}	1.17×10^{-5}	3.16×16^{-5}	9.36×10^{-5}	1.11	3	8.88

TABLE IV

ABLATION OF SPHERICAL ALUMINIUM FRAGMENTS
($M = 20$ TO $M = 1$)

SEA LEVEL

R_o (cm.)	0	10^{-6}	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}
t (secs.)	0	2.88×10^{-8}	2.88×10^{-7}	2.88×10^{-6}	2.88×10^{-5}	2.88×10^{-4}	2.88×10^{-3}
r (cm.)	0	3.00×10^{-3}	3.00×10^{-2}	3.00×10^{-1}	3.00	3.00×10^{1}	3.00×10^{2}
$R_o - R$ (cm.)	0	2.88×10^{-8}	9.12×10^{-8}	2.88×10^{-7}	9.12×10^{-7}	2.88×10^{-6}	9.12×10^{-6}
dm/m %	0	8.65	2.74	0.86	0.27	0.09	0.03

Equations 4, 6, 7 with $K_1 = 4.77 \times 10^{-6}$ $K_3 = 33$ $K_4 = 10^{-3}$

ALTITUDE (100,000 FT.)

R_o (cm.)	0	10^{-6}	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}
t (secs.)	0	2.97×10^{-6}	2.97×10^{-5}	2.97×10^{-4}	2.97×10^{-3}	2.97×10^{-2}	2.97×10^{-1}
r (cm.)	0	3.00×10^{-1}	3.00	3.00×10^{1}	3.00×10^{2}	3.00×10^{3}	3.00×10^{4}
$R_o - R$ (cm.)	0	2.13×10^{-7}	6.74×10^{-7}	2.13×10^{-6}	6.74×10^{-6}	2.13×10^{-5}	6.74×10^{-5}
dm/m %	0	63.97	20.23	6.40	2.02	0.64	0.22

$K_1 = 3.42 \times 10^{-7}$ $K_3 = 0.32$ $K_4 = 10^{-5}$

TABLE V

(APPENDIX I)

HEAT TRANSFER VALUES FOR VARIOUS FRAGMENT VELOCITIES

Speed ft./sec.	M_∞	$\dot{q}_c$ ergs/sec.	$\dot{q}_r$ ergs/sec.	$\dot{q}_c + \dot{q}_r$ ergs/sec.	T_s °K
27,175	25	5.52×10^{10}	7.62×10^{10}	1.31×10^{11}	30,000
21,740	20	2.83×10^{10}	1.28×10^{10}	4.11×10^{10}	20,000
16,305	15	1.19×10^{10}	1.28×10^{9}	1.32×10^{10}	10,500
10,870	10	3.53×10^{9}	5.00×10^{7}	3.58×10^{9}	5,000
5,435	5	4.42×10^{8}	1.95×10^{5}	4.42×10^{8}	1,500

BOX TARGET (100 CU FT)

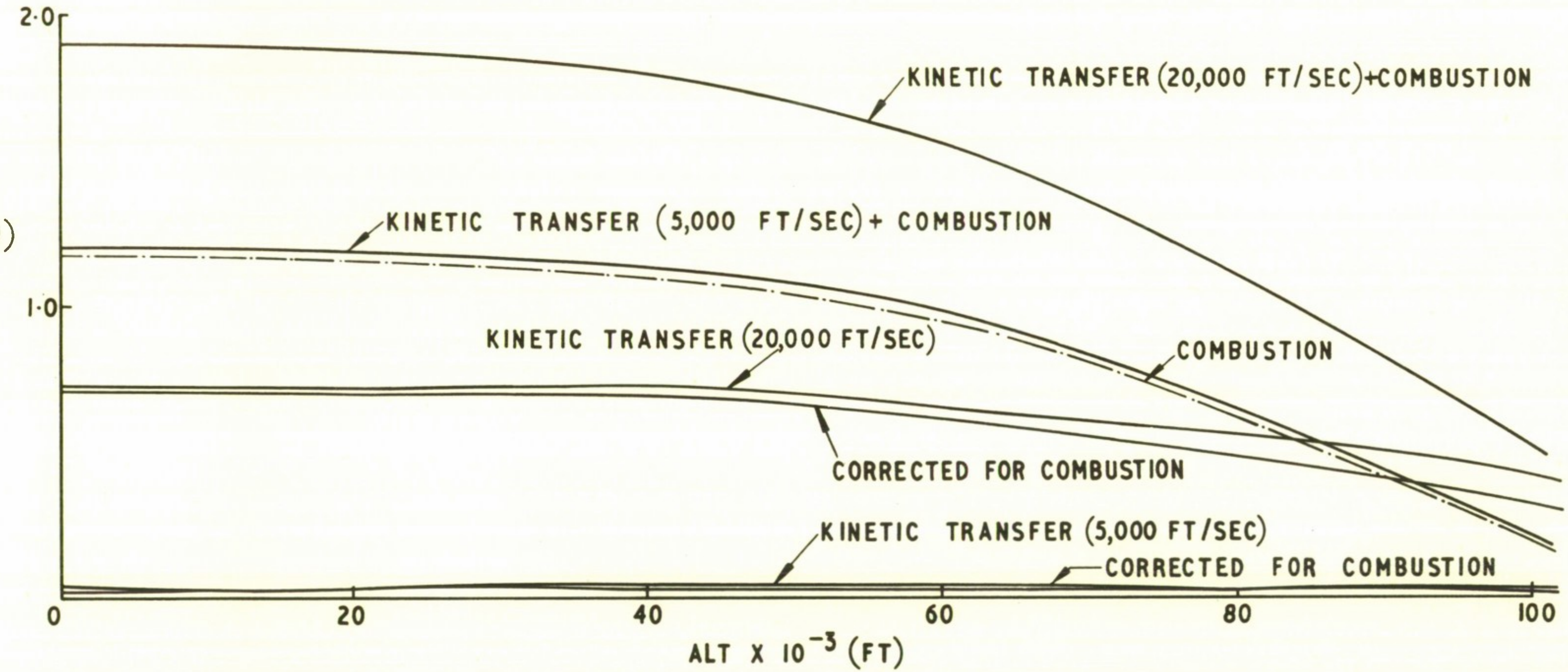

FIG.1 PRESSURE (DIFFERENCE) DEVELOPED IN THE TARGET BY KINETIC TRANSFER AND / OR COMBUSTION OF 1OZ OF ALUMINIUM TRAVELLING AT 5,000 AND 20,000 FT / SEC RESPECTIVELY AT VARIOUS ALTITUDES

FIG.1

FIG. 2

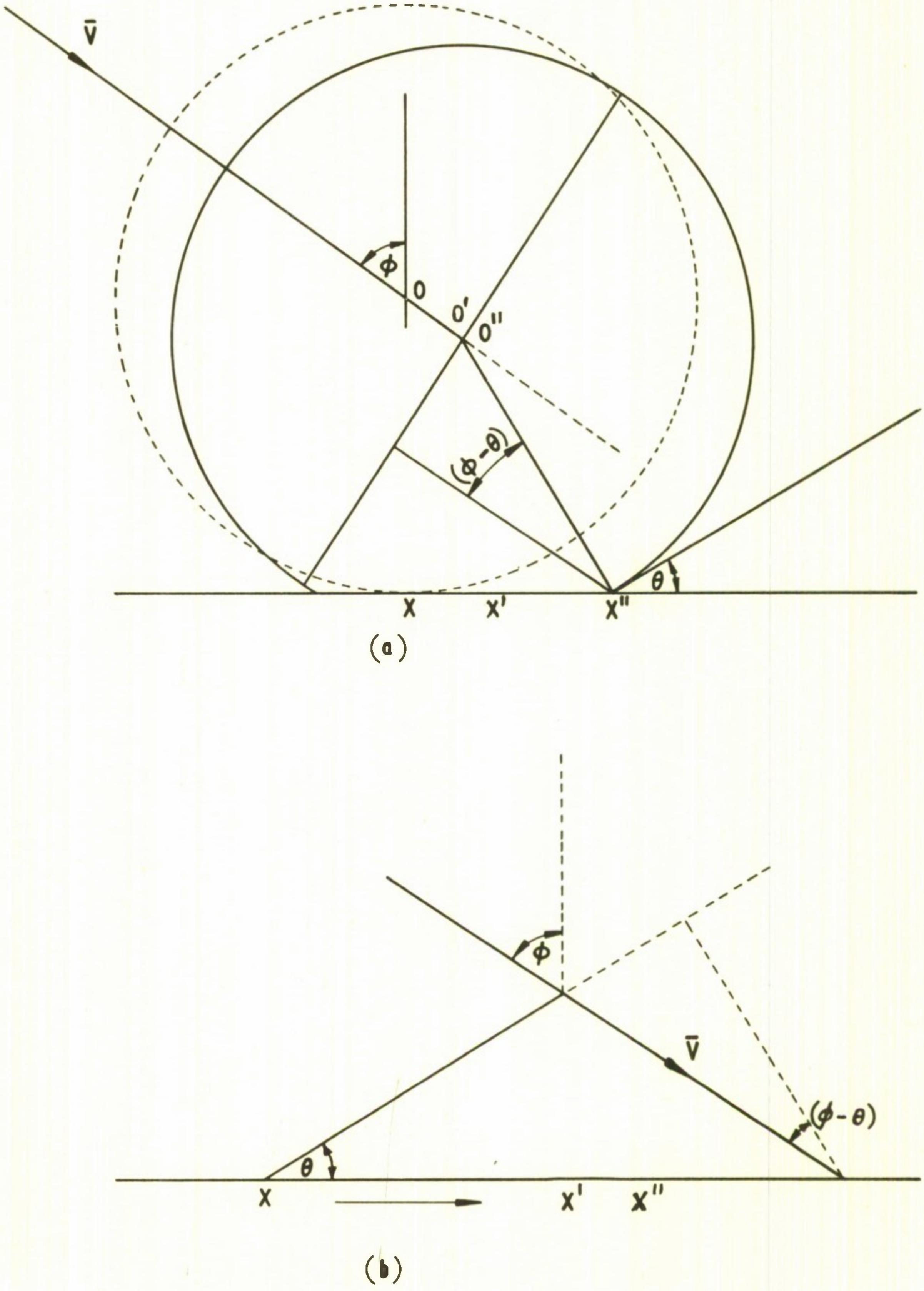

FIG. 2 TWO DIMENSIONAL MODEL OF IMPACT OF A CURVED IDEALISED FLUID SHEET WITH A RIGID SURFACE

FIG. 3

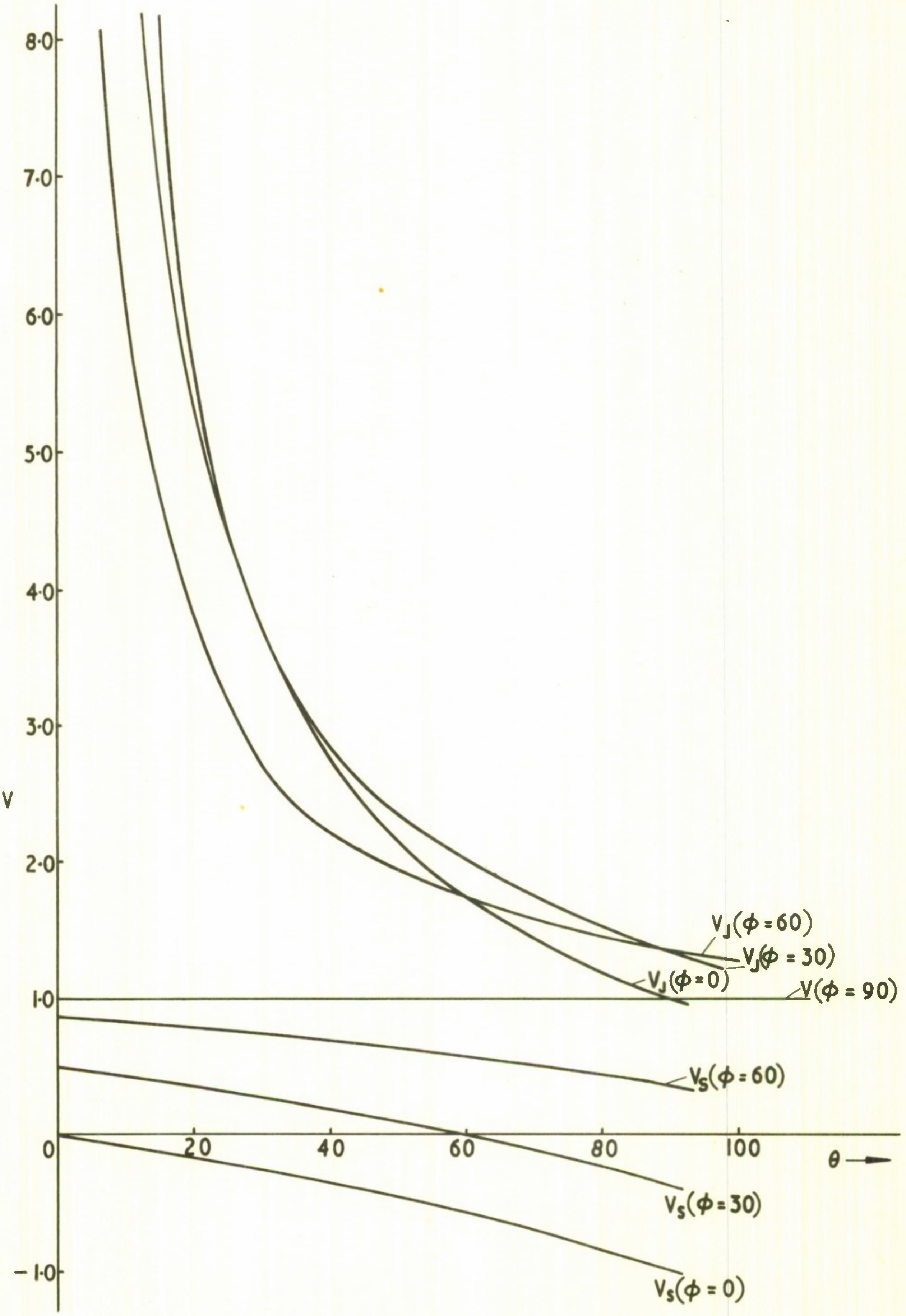

FIG. 3 IMPACT OF A PLANE IDEALISED FLUID SHEET WITH A RIGID SURFACE

RELATIONSHIP BETWEEN STREAM VELOCITIES V_J, V_S AND θ FOR VARIOUS ANGLES OF IMPACT ϕ

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R.A.R.D.E. Memorandum 2/63

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W.M.Evans. — February 1963

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30pp. 3 figs. 5 tabs. 27 refs.

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