Experimental Studies Concerning the Meteoroid Hazard to Aerospace Materials and Structures

J. W. Gehring,* D. R. Christman,† and A. R. McMillan‡
General Motors Corporation, Santa Barbara, Calif.

The expected meteoroid hazard to satellites and spacecraft is reviewed, and the hazard is defined from the available references. Damage mechanisms include sputtering, cratering, perforation, and spalling. The requirements for simulating the meteoroid hazard in the laboratory and the capabilities of some available projection techniques, such as light-gas guns and explosive charges, are discussed, and the application of special experimental techniques to hypervelocity impact studies is described (including high-speed framing camera, flash x ray, high-temperature furnace, and evacuated test chamber). Published empirical relationships for describing the damage resulting from hypervelocity impact are reviewed and compared with recent experimental data. Detailed test data are presented, including photographs of typical test materials and structures and graphs giving quantitative test results.

Introduction

THERE is considerable interest in, and concern over, the problems of hypervelocity projectile impact, especially in relation to the meteoroid hazard and anti-intercontinental ballistic missile (AICBM) or antisatellite fragments. Meteoritic particles may damage satellites and spacecraft, and fragments are of interest because of the obvious offensive and defensive military applications. (Fragments, as considered here, are meant to include both "true" fragments, i.e., particles of essentially random size and shape, as well as "unusual" projectile configurations, i.e., rods, disks, etc.) The study of the damage that would be inflicted by meteoroid or fragment impacts requires the simulation of these impacts in the laboratory.

Meteoroid Hazard

Investigators have extracted data on meteoroids from numerous sources; among these are astronomical observations,[1] studies of the Zodiacal light and the Solar corona,[2,3] luminous intensity measurements of meteors,[4] satellite and space-vehicle data,[2,5,6] radar measurements,[7] studies of meteoroids and meteoroid craters found on the earth,[8,9] and visual observations.[10]§ Large meteoroids and asteroids are an improbable hazard because of their rarity; and micron-sized meteoroids, though abundant, do not cause extensive damage because of their relatively low impact energy. The meteoroids of intermediate size (10^{-3} to 1 cm) are the ones that present the greatest hazard. Meteoroid shapes vary from highly irregular to nearly spherical. However, at the velocities involved in meteoroid encounters, the shape of the meteoroid should not be a significant factor in the resulting damage.

Meteoritic particles that have been collected and analyzed are divided into two general classes: metallic and stony. The metallics are primarily iron and nickel, but include manganese, chromium, and the precious metals. Stony particles are found to include such minerals as ferropigeonite, anorthite, and ferrougite.[11] In reducing material data to determine the gross properties of the meteor's mass and size (or density), the kinematic data are found to be insufficient for a direct determination; and the measurement of luminous intensity τ must be used to determine the mass and thus complete the determination of size or density. Unfortunately, τ is not well established, and there has been considerable uncertainty in the determination of the density of meteoroids. Estimates of density have ranged from 0.05 to 8 g/cm^3. The latest estimate is Whipple's value of $\rho = 0.44$ g/cm^3 for cometary meteoroids.[12] Since most meteoroids are thought to be of cometary origin and of composition similar to stone, the densities of meteoroids of intermediate size (10^{-3} to 1 cm) should range from 0.4 to 3 g/cm^3, giving a range in mass of about 10^{-9} to 3 g.

Velocity and distribution of meteoroids in space is another area in which some quantitative estimates can be made. Figure 1 is a summary of mass frequency distribution data.[3,12,38–40] Unfortunately, the bulk of this data is not applicable to space in general, for observations and measurements have shown

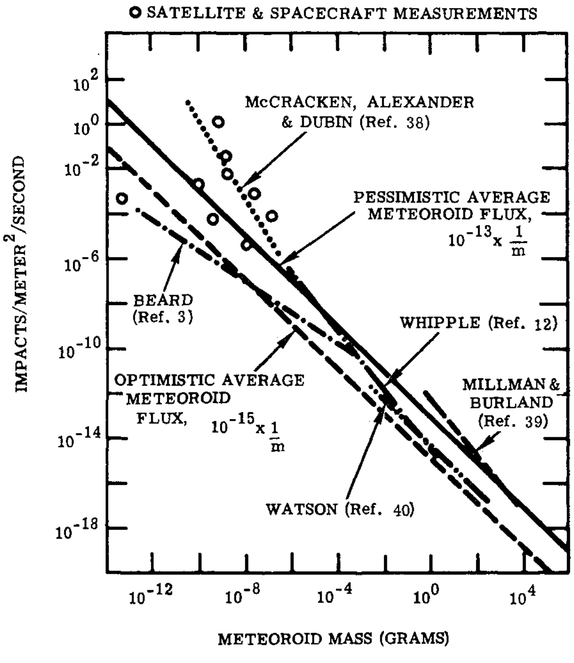

Fig. 1 Meteoroid frequency vs meteoroid mass.

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* Head, High Velocity Impact Group, GM Defense Research Laboratories. Member AIAA.

† Research Engineer, GM Defense Research Laboratories. Member AIAA.

‡ Research Physicist, GM Defense Research Laboratories. Associate Member AIAA.

§ For additional references on meteoroids, see Ref. 41.

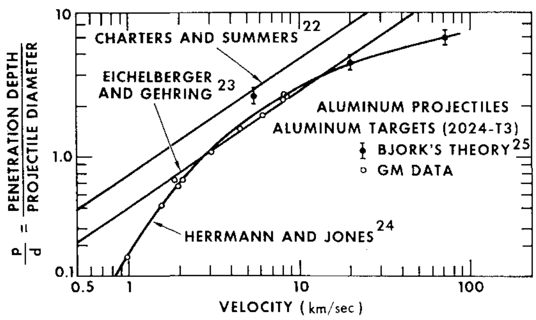

Fig. 2 Depth of penetration in semi-infinite aluminum targets.

that the meteoroid flux distribution in space is not uniform,[13] varying with solar latitude[14] and with distance from the plane of the ecliptic,[1] the plane of revolution of the earth about the sun. In general, the meteoroid flux density, at least of dust-like particles less than 10^{-4} g, decreases, the greater the distance from the earth and the ecliptic plane, although it increases in the vicinity of the sun and the planets.[3,15]

Also shown in Fig. 1 are the "optimistic average meteoroid flux" and the "pessimistic average meteoroid flux."[16] These two flux curves are intended to bracket the average actual meteoroid distribution in space. This actual or true distribution is really a nebulous factor, since it is time-and-space-dependent; that is, it does not necessarily remain constant with time and, as noted, there will be some variation with location in the solar system. Both fluxes are represented by equations of the form $\phi = k/m$, where k is a constant and m is meteoroid mass. As more information on meteoroid flux is made available through the use of satellites and spacecraft, a change in the form of this equation may be justified. A more accurate relationship may be $\phi = k/m^a$, where a is greater than one, thereby reducing the frequency of the larger meteoroids. The expected range of velocities for meteoroids is generally agreed to be from 11 to 72 km/sec, relative to the earth. Meteoroid impact velocity, relative to interplanetary spacecraft, could be in the range of 0–83 km/sec.

Whipple[17] has indicated that the majority of meteoroids will be in the range of 15 to 28 km/sec. Although laboratory simulation techniques are presently available to only 21 km/sec,[18] it is felt that these techniques provide true hypervelocity impact, and that the cratering phenomenon observed is the same that occurs at higher velocities.

Targets

Impact damage to aerospace vehicles and structures can be broadly related to two classes of targets: simple and complex. Simple targets can be subdivided as follows: 1) semi-infinite—a homogeneous material of thickness such that free-surface effects will have negligible effect on impact damage for a given set of impact conditions; 2) thick—a homogeneous material of thickness such that free-surface effects will influence impact damage, yet the target will not be perforated; and 3) thin—a homogeneous target that is perforated. Complex targets can be subdivided as follows: a) laminated—adjacent layers of the same or different materials, with or without a bonding agent between the layers; b) composite—two or more materials compounded in such a way that any given volume of the structure, of adequate size, has the same composition as any other volume of equal size (e.g., an array of particles in a plastic matrix); and c) pressure vessels.

As indicated by the previous definitions, simple targets are usually distinguished on the basis of results of impacts, which are related to impact conditions (e.g., projectile mass and velocity), whereas complex targets are usually distinguished on the basis of structure, material or application. Most military and space vehicle configurations can be classified according to these definitions. For example, the ablative shield or heat sink of a re-entry body might be classed as a semi-infinite or thick target for most projectiles; satellites and spacecraft with thin aluminum hulls surrounding control gas tanks, electronic modules, or recoverable instrumentation packages could be considered bumper-protected complex targets; and rocket nozzles could be classed as laminated targets or pressure vessels. Impact damage assessment and the use of test data in establishing critical damage criteria must be related to the mission requirements of the vehicle system or subsystem that is being evaluated.

Laboratory Simulation Techniques

Light-gas guns[19] are usually used in accelerating well-defined projectiles such as spheres and rods, whereas explosive techniques are usually used in accelerating less well-defined projectiles such as microparticles[20] and fast-jets.[21] Three accelerated-reservoir light-gas guns (0.22, 0.30, and 0.79 caliber) were used in the present work. The impact ranges were evacuated to pressures as low as 1 μ, and the velocity and condition of the projectile before impact were obtained from spark-shadowgraph stations. Impacts were photographed using a high-speed framing camera at framing rates up to 1.4×10^6 frames/sec, a three-channel, 0.07-μ sec x-ray unit, and a spectrograph-photomultiplier tube system.

The explosive accelerating devices used for impact experiments include air-cavity charges, shaped charges, and microparticle charges. Charges of solid cast explosives (such as Pentolite, Composition B, and Baratol) have been used. Discrete projectiles with a mass from 0.1 to 5 g can be launched at velocities from 2 to 21 km/sec,[18] whereas small clusters of microparticles with a mass distribution of 10^{-3} to 10^{-9} g can be launched at velocities as high as 15 km/sec.[20] The velocity and condition of the microparticles and jets, and the actual impact, were observed with the three-channel flash x-ray unit and laser shadowgraphs (pulse duration 0.02 μsec).

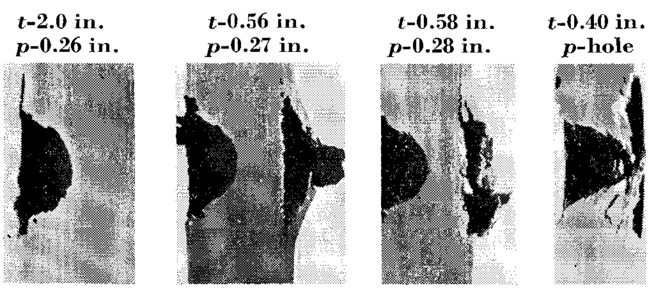

Fig. 3 Depth of penetration in flat targets of various thicknesses. Projectile: 0.125-in aluminum sphere, 0.047g; velocity: 7.4 km/sec; target: 2024-T3 aluminum.

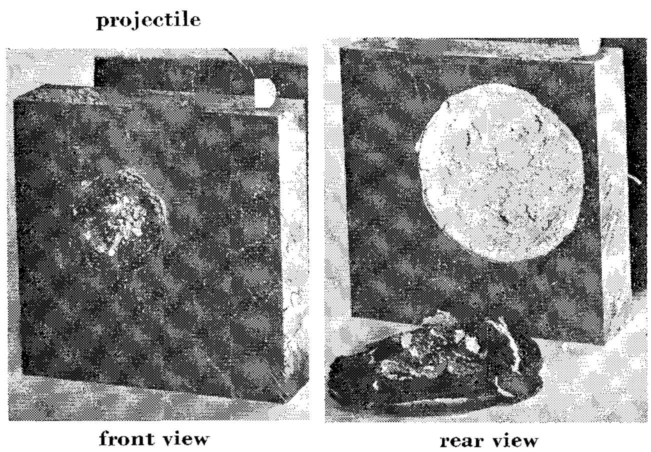

Fig. 4 Back spall from thick target. Target: 2.0-in. 2024-T3 aluminum; projectile: 4.14g polyethylene; velocity: 7.9 km/sec.

Experimental Observations

Simple Targets

The mechanisms of crater formation in semi-infinite metallic targets have been studied in considerable detail by many investigators, and a number of empirical relationships have been derived for predicting impact damage in terms of crater size and shape. Four of the more commonly used penetration laws[22–25] are plotted in Fig. 2, which shows depth of penetration/projectile diameter (p/d) as a function of impact velocity. Also shown on this graph are the results of recent experimental work. Especially good correlation is shown between the work of Eichelberger and Gehring[23] and the work of Herrmann and Jones[24] in the range of 1 to 10 km/sec. The theoretical points of Bjork[25] show penetration to be proportional to impact velocity to the one-third power. The empirical equation of Herrmann and Jones[24] also shows this dependence at high velocity, but these authors specifically caution against extrapolation of their equation to high velocities. The experimental data shown can be represented as being proportional to velocity to the two-thirds power. Theoretical calculations by Walsh et al.,[26] show penetration proportional to velocity to the 0.58 power.

The data shown in Fig. 2 are applicable only to semi-infinite targets. The importance of this is demonstrated in Fig. 3, which shows the increase in depth of penetration as target thickness is decreased. It can be seen that perforation of the target occurs at a thickness significantly greater than the crater depth in a semi-infinite target, and also that fracturing of the rear surface of the target contributes to the total damage. This fracturing is known as "spalling" or "scabbing"[27,28] and is significant in the transition from semi-infinite to thin targets. Spalling can be defined as fracture resulting from reflection of a shock wave from a free surface; it is illustrated in the right three targets in Fig. 3 and in more detail in Fig. 4. Note that spalling can occur even though the target is not perforated. The use of laminated structures as a means of reducing or eliminating spall is discussed later in this section under "Complex Targets."

Plots of depth of penetration vs target thickness, normalized with respect to penetration in a semi-infinite target, are given in Fig. 5 for two materials impacted under similar conditions. For this particular set of impact conditions, a target of 316 stainless steel must be at least 1.4 times thicker than penetration in a semi-infinite target to prevent perforation and must be at least 1.88 times thicker to prevent spall. For a target of 2024-T6 aluminum under similar impact conditions, the target must be at least 1.66 times thicker to prevent perforation and at least 2.4 times thicker to prevent spall. Several investigators have indicated that a ratio of 1.5 would be sufficient to prevent perforation, a value that is somewhat optimistic. These ratios depend on material properties, as shown previously, and impact velocity; however, the value to prevent perforation will be in the range 1.4 to 2.0, and the value to prevent spall will be in the range 1.8 to 2.6, for most impact conditions.

Selection of armor materials designed to function under particular environmental conditions poses a complex problem.

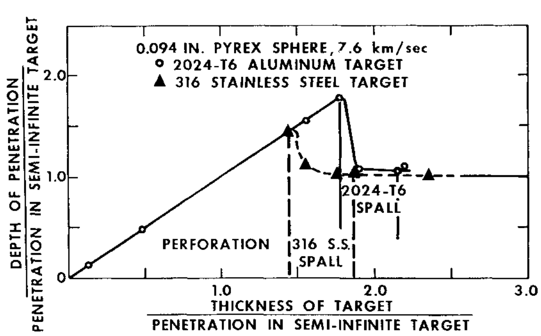

Fig. 5 Depth of penetration vs target thickness.

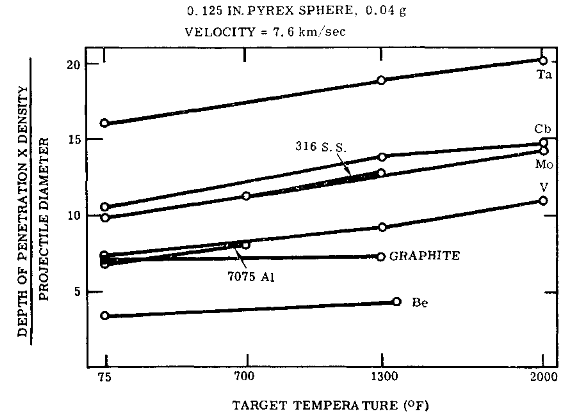

Fig. 6 Depth of penetration vs temperature.

Operation at elevated temperatures is an example. Using the crater-depth predictions,[22,29] beryllium appears to be a promising armor material on the basis of weight of material penetrated. Experiments evaluated on this basis (Fig. 6) support that conclusion. However, a more detailed examination of experimental results shows (Fig. 7) that reduction of penetration is not a sufficient criterion for damage evaluation, since cracking, spall, or delamination may also be serious modes of damage. The evaluation of damage must be based on the applications of the structure in question. For a fuel tank, spall or delamination may not be serious damage. For a liquid-filled radiator system, perforation, spall, cracking or delamination may present serious problems.

One of the most important aspects of hypervelocity impact is that of perforation or penetration of thin targets. Numerous investigators[17,30–32] have analyzed the use of a thin shield, separated from the main structure, to provide protection to a missile, spacecraft, or satellite from meteoroids or fragments. Experiments conducted at velocities up to 8.5 km/sec support the conclusions that both the target and projectile flow upon impact, material is ejected from both sides of thin targets, and the thin shield is effective because it causes the projectile to break up, spreading the fragments over a large area on the backup plate.[31] These facts are demonstrated by a framing-camera sequence in Fig. 8 and by damage photographs in Fig. 9. Of particular interest here is the spall that has come off the rear of the backup plates at the higher velocities. This spall, caused by the shock wave resulting from the high momentum of the debris that impacts the backup plate,

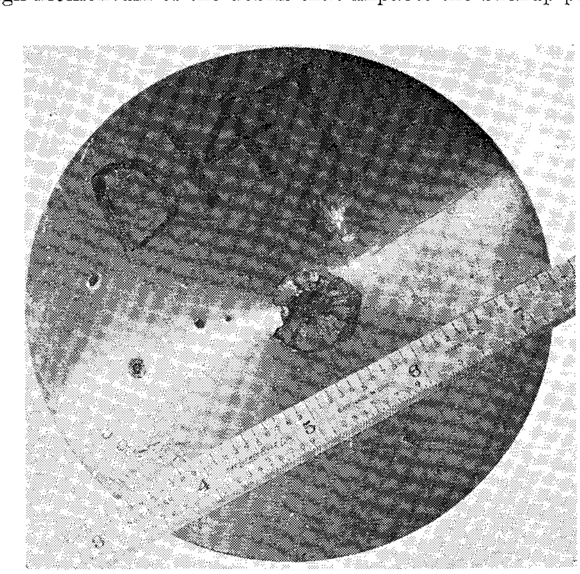

Fig. 7 Impact damage to heated beryllium target. Target: 1.063-in. beryllium, 700°F; projectile: 0.094-in. pyrex sphere, 0.018g; velocity: 7.5 km/sec.

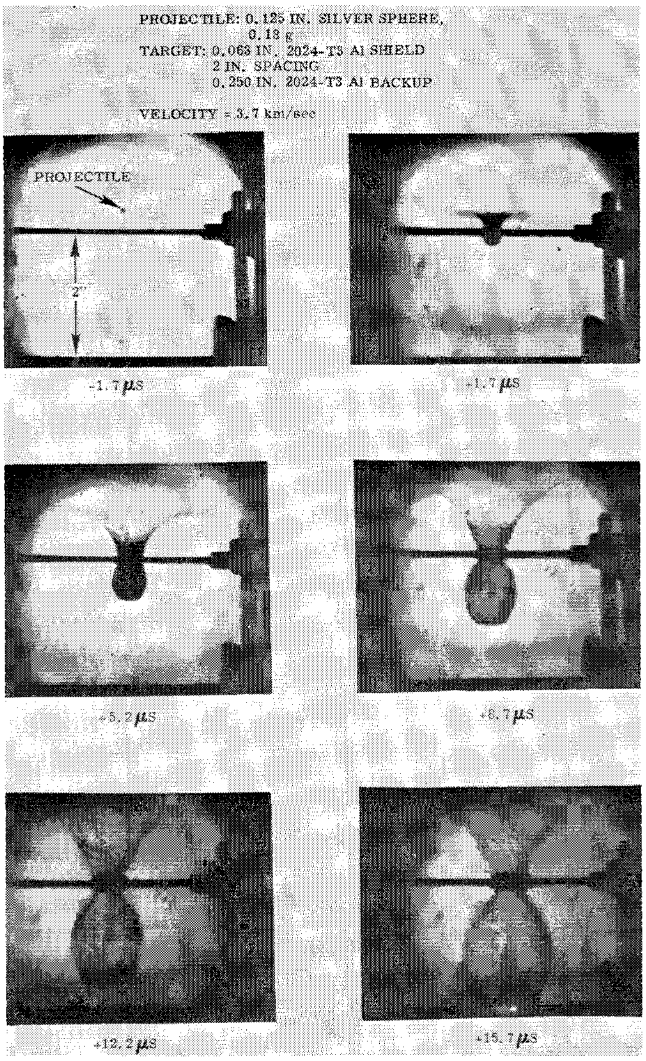

Fig. 8 Framing camera sequence of solid sphere impacting a multiple-sheet target.

indicates that the shield concept may not be of advantage under all conditions, i.e., the damage capacity of the debris behind a thin plate might, in some cases, be more severe than when no bumper is used.

The effectiveness of a thin shield in reducing total penetration of semi-infinite targets is demonstrated in Fig. 10. At impact velocities below 4 km/sec, the shield does not reduce total penetration, and there is some evidence that the penetration is greater with a shield at these low velocities. The damage to the bumper-protected target reaches a maximum at about 4.5 km/sec, decreases, and then levels off at 8 km/sec. It is believed that heating of the projectile debris and initial shield debris through the shock-release mechanism plays an

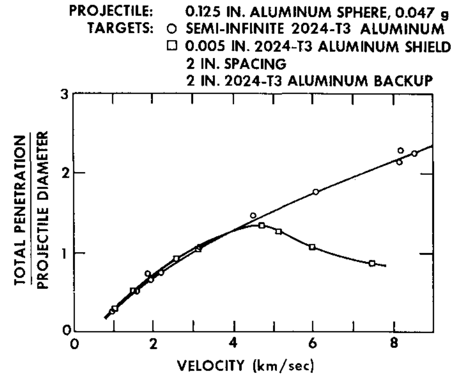

Fig. 10 Penetration in a bumper-protected target and semi-infinite target vs velocity.

important role in this behavior. Theoretical treatment and experiments indicate that, with sufficiently high impact pressures, melting and even vaporization of the debris can occur.[31] Treatment of the damage that results from the impact of this debris upon the backup structure has been initiated. These studies indicate that even though the penetration in a bumper-protected target may be slight, the momentum loading can be severe, resulting in damage through spall, delamination, or bending. The effect of bumper thickness is shown in Fig. 11. It is seen that the optimum bumper thickness for minimum penetration is a function of velocity, which means that a bumper that must operate over a range of velocities cannot give maximum protection at all velocities.

Complex Targets

Although complex targets have not been analyzed to the same extent simple targets have, they are of greater interest to the design engineer because they represent functional vehicle structures, as well as practical meteoroid-protection systems. The use of laminates can result in significant changes in the nature of the damage to a structure as a result of hypervelocity impact,[33] as demonstrated in Fig. 12, in which all of the four targets are of equal weight per unit area. The plain aluminum target was not perforated but was severely spalled. The addition of a polyethylene laminate behind the aluminum resulted in perforation of the aluminum, but no spall was ejected from the back of the structure. A copper laminate behind the aluminum prevented perforation and spalling of the aluminum, although the copper was severely deformed. The copper/aluminum laminate at the bottom is shown for comparison only, since this combination does not offer any advantages with regard to penetration or spalling. The main point illustrated in Fig. 12 is that the type of protection required (minimum penetration, no perforation, or no spall) will determine the combination of materials and thicknesses.

A more complicated application of laminates is shown in Fig. 13, namely, tubular structures that have been considered for use as space radiators for nuclear auxiliary-power sys-

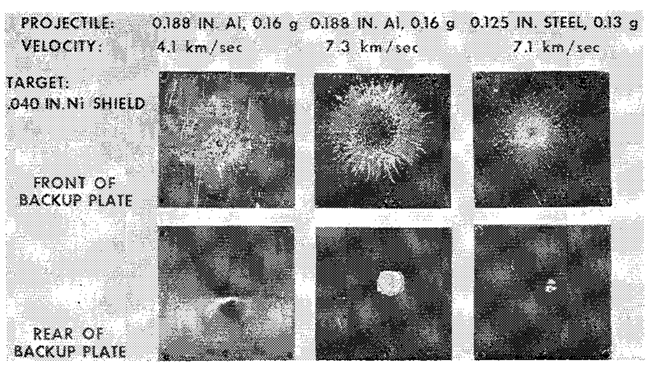

Fig. 9 Multiple sheet target: backup plate damage.

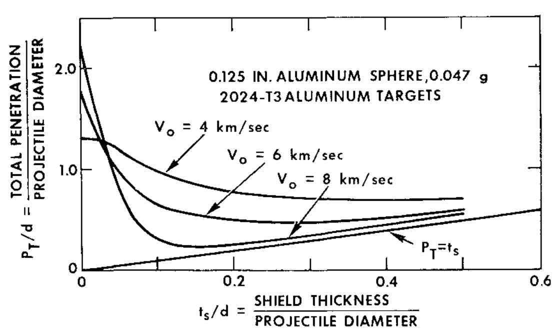

Fig. 11 Penetration vs bumper thickness.

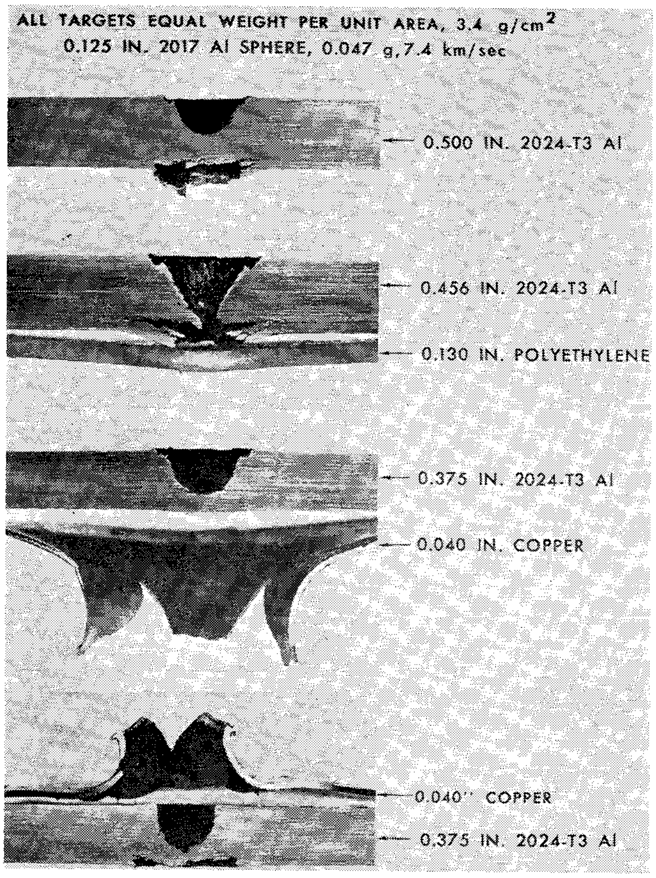

Fig. 12 Effects of laminates on spall and perforation-flat targets.

tems.[29] Without the laminate, or liner, the tube was perforated, and the shock wave generated by the impacting projectile caused a substantial piece of spall to be separated from the inside wall. A thin liner of a tough, ductile material actually reduced the weight per unit length and prevented both perforation and spalling.

Honeycomb structures with thin face sheets have high stiffness- and strength-to-weight ratios; however, under conditions of hypervelocity impact, the honeycomb cells serve to channel the debris from the projectile and face sheet. This results in substantially higher impulsive load per unit area and greater penetration, than would occur in the absence of the honeycomb cell structure.

Hypervelocity meteoroid impacts against windows can seriously affect guidance and control systems or docking maneuvers, especially in manned spacecraft, by impairing the transparency of the windows. Two examples of this are given in Fig. 14. The acrylic window has been severely damaged

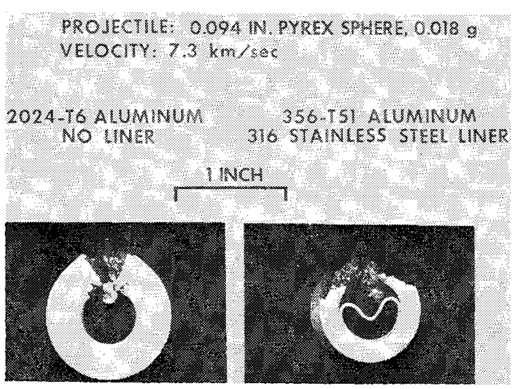

Fig. 13 Effect of liner on spall-cylindrical targets.

1.0-in. stressed acrylic-plastic window **0.50-in. thick laminated tempered safety glass, window**

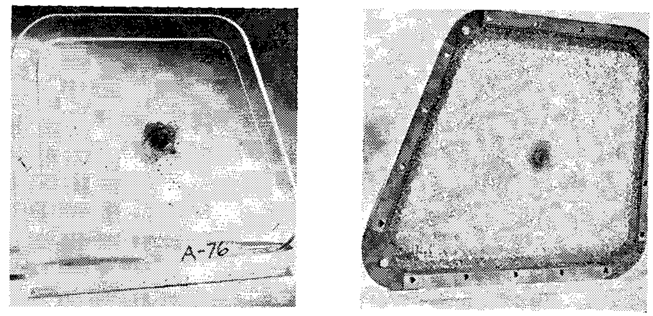

Fig. 14 Impact damage to windows. Projectile: 0.125-in. glass sphere, 0.04 g; velocity = 7.7 km/sec.

in the area of impact but still permits outside observation. The laminated glass window, however, has been rendered almost useless as a result of the impact. Also of concern, of course, would be any through-cracks in the windows that might result in loss of pressure inside the vehicle.

Another structure that warrants special attention under conditions of hypervelocity impact is a pressure vessel.[34-36] A projectile may perforate the vessel, spewing particle fragments and spall into the vessel and allowing leakage of its contents; or the projectile may not perforate but could generate a shock wave into the internal gas or liquid, resulting in excessive stresses in the walls of the vessel or otherwise damaging the vehicle. The impact damage to a relatively thick-walled, liquid-pressurized vessel is shown in Fig. 15. The damage has been confined to a clean puncture of the vessel wall that could be repaired. There are some cases, however, such as impact against relatively thin-walled, highly stressed structures, where the vessel fails catastrophically with no possibility of repair.

Projectile Effects

The results of a series of experiments conducted to assess the effects of projectile density at an impact velocity of 6.6 km/sec are given in Fig. 16. The penetration is proportional to $\rho_p^{0.19}$ whereas results of a similar series of tests at 2 km/sec[22] showed penetration to be proportional to $\rho_p^{0.33}$ Note the significant decrease in exponent for an increase in velocity from 2 to 6.6 km/sec. Extrapolating these results to meteoroid velocities (11 to 72 km/sec) indicates that the influence of projectile density on penetration would probably become small, and may even be negligible.[26]

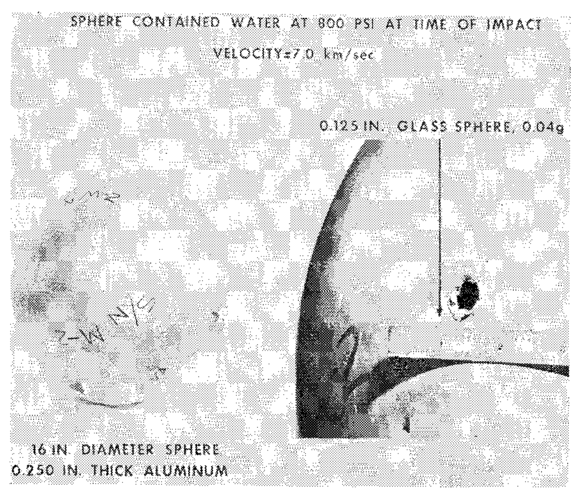

Fig. 15 Impact damage to liquid-pressurized vessel.

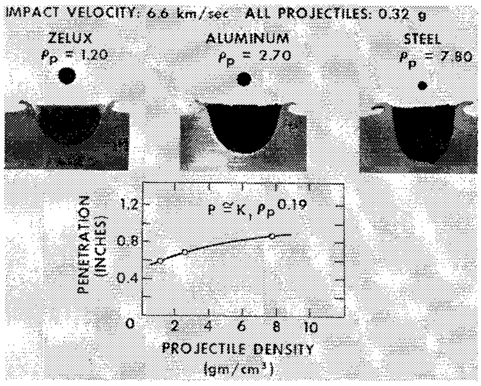

Fig. 16 Penetration from equal mass spheres of various densities.

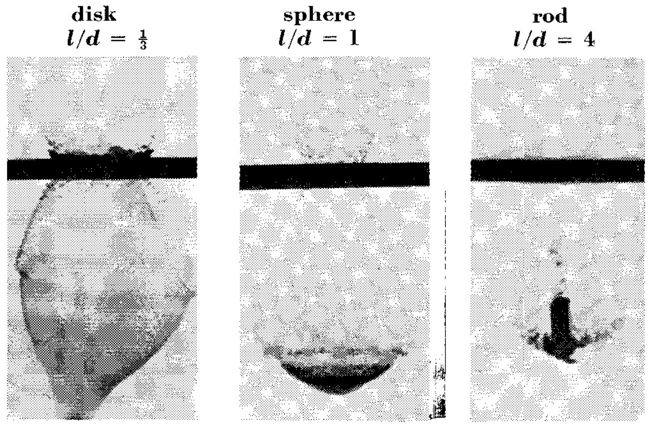

Fig. 17 Effect of projectile shape: thin bumpers.

Figure 17 shows x-ray photographs of three different projectile shapes after impacting a thin shield. The x-ray of the rod shows a significant portion of the projectile still intact. Projectile shape, then, can strongly influence the damage inflicted upon a structure. This result is significant in military applications where projectile shape can be controlled, providing that the projectile orientation at impact also can be controlled. However, for meteoroid impact, it is reasonable to assume that the particles are approximately spherical, and, consequently, that shape is not a governing factor in damage.

Impact Flash

One of the phenomena associated with the initial stages of impact at hypervelocities is the emission of electromagnetic radiation. The energy of this radiation is generally considered to be concentrated in the visible and near-visible regions of the spectrum; this enhances the use of this radiation as a potential source of information for determining the occurrence of a collision, the damage inflicted upon a target, and the identification of the target material. An impact flash is shown in the last frame of the sequence in Fig. 8. The duration is the flash is normally very short—on the order of several μ sec, although the peak luminosity and duration of the flash are functions of impact velocity and projectile and target materials.

An empirical relationship has been established which permits estimates to be made of the intensity of an impact flash.[37] The equation in its present form, however, can account for variations in the target and projectile materials only by use of a constant for each of the possible combinations. The equation now appears as follows:

$$L_p = Cav^n$$

where L_p is the peak luminosity (visible), a is the presented area of projectile on target surface, v is the projectile velocity, n is the velocity exponent, and C is a constant. The equation shows that: peak luminosity is proportional to projectile area, not to projectile mass (and, therefore, not to projectile momentum or kinetic energy); peak luminosity is strongly influenced by impact velocity (n varies from 3 to 9), depending on projectile and target properties; C is also a function of projectile and target properties (with target properties being more important than those of the projectile). Finally, it should be noted that there is no allowance for either the pressure or the composition of the surrounding gas. Tests conducted with air at pressures ranging from 0.0014 to 760 mm Hg, and with helium at pressures of 0.004 to 760 mm Hg, have shown that the peak intensity of the impact flash is independent of ambient pressure in a helium atmosphere and that there is a measurable effect on the peak intensity in an air atmosphere only at pressures above 0.20 mm Hg.

In the area of remote observation of impact radiation, calculations have shown that observation of the impact of a vehicle such as the Ranger spacecraft on the lunar surface is probable when the moon is at opposition (dark surface). Also, observation of a projectile's impact on a missile or satellite at altitudes of 200–300 km is possible.

Summary and Conclusions

Detailed experimental studies of hypervelocity impact phenomena and their effects on aerospace materials and structures can be carried out with available particle-projection techniques. Empirical data are available concerning simple targets, but it is apparent that, although there is a general understanding of basic target behavior, there is a decided lack of detailed knowledge concerning such specific areas as: 1) the influence of variables such as strengths, density, wave velocity, crystal structure and anisotropy on cratering in semi-infinite targets and perforation of thin targets; 2) projectile behavior after perforating a thin target, including the fragmentation of the projectile and the distribution of fragments in terms of mass, velocity, and direction; and 3) high-strain-rate properties of materials, including shock-wave propagation and attenuation.

The behavior of complex targets is even less well defined than simple targets, although some experimental information pertaining to particular structures is available, and some qualitative conclusions regarding the behavior of targets such as laminated structures and pressure vessels can be drawn. The study of complex targets usually requires specific experimental programs before meaningful results are obtained.

Both projectile density and shape have been shown to influence target damage below about 10 km/sec, but the exact role of projectile properties and configurations in cratering and perforation is not fully understood and requires further experimental and theoretical analysis.

Impact flash has potential application in the areas of hit detection and target discrimination. Such an application would require a detailed study of the spectral characteristics of the radiation and determination of the quantitative effects of projectile and target materials and structure.

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