Phenomena Resulting from Hypervelocity Impact

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Crater damage to a thick plate via hypervelocity impact can be predicted from the tensile strength established by standard metallurgical techniques. Some of the results indicate that the frequently quoted empirical rule that the thickness of a plate that will just prevent penetration by a high-velocity particle is approximately 1.5 times the depth of the crater that it would make in a very thick plate is rather questionable; factors from 1.4 to more than 2 have been observed. In order to acquire reliable data relevant to the impact behavior of bumpered structures, impact spray cones of fragmented particles were studied. Low-density material placed in the bumpered structure significantly alters the impact spray cone; the data suggest that such hull systems might be either 15% lighter or as much as 75% thinner (due to reduced spacing between the skins) for given protection.

Introduction

METEOROID technology has grown in importance and urgency with the programing of missions involving greater exposure to meteoroid fluxes. In view of the potential meteoric particle damage to space systems, numerous investigations have been carried out during the past several years. These investigations have been concerned primarily with the theory of hypervelocity impact and the experimental assessment of the related phenomena. On the other hand, designers of space systems have proposed several schemes and configurations for protecting vehicles from meteoric particles, but these configurations are partly supported by very isolated and inconsistent experimental data.

The paucity of pertinent space vehicle design information has resulted from the concentration of most laboratory research programs on the impact phenomena occurring with targets of semi-infinite thickness rather than on thin sheet configurations or flight structures. Cratering is important for those impacts where the target responds in a manner identical to a plate of infinite thickness. This behavior will manifest itself in normal armament as well as with space radiators, but apparently has limited usefulness in the design of a thin hull and light-weight spacecraft.

There is a pronounced difference between the impact behavior of thin and thick plates. Materials initially behave as though they were fluids[1-4] with virtually zero shear strength when subjected to high-speed impact. The time for interaction between the impacting particle and the thin plate is of such short duration that the entire impact process, with complete penetration, predominately involves quasi-fluid or hydrodynamic behavior rather than material strengths. Part of the energy of the impacting particle will be utilized in the process of fragmenting the particle and forming a hole in the thin plate. The time for interaction between the impacting particle and the thick plate is of such comparatively long duration that the impact process will be quasi-hydrodynamic, with pressure exerted equally over the expanding crater surface, and the final form of the crater being dependent upon the strength of the material. Part of the energy of the impacting particle will be utilized in forming the crater. Because of the difference in impact mechanism, caution must be exercised in using data obtained with thick plates to predict the behavior of thin plates. The incorporation of such variables as 1) different materials, 2) different number of plates, 3) different spacing between plates, and 4) filler material placed between the plates adds complexity to the experimental observations and hinders the elucidation and definition of the parameters important in the impact process.

It is impossible to establish experimentally impact data for all structural combinations to be exposed to the space environment. This impossibility can be attributed to the unjustified expense as well as the lack of time to study all materials systems. Not to be overlooked is the sobering fact that well-defined experiments with very low particle mass and meteoric impact velocities cannot be achieved in the laboratory. Consequently, it is imperative that the pertinent fundamental relationships are established so that reliable predictions can be made about response of materials subjected to impact.

There is no particular geometrical configuration associated with meteoric particles. Cylindrical and spherical projectiles are used to study the impact behavior of materials. The cylindrical projectile used in this experimental program is not the most desirable projectile geometry but was used because disks lend themselves to higher accelerations, without fragmentation, by explosive charges.

Impact on a Single Plate

High-velocity particles produce an inelastic collision. Thus, permanent deformation and changes will be produced in the colliding bodies with a corresponding decay or conversion of the energy of relative motion into radiation and heat. The projectile and target materials in the immediate region of the impact are melted, vaporized, compressed, and/or disrupted depending upon such parameters as the density, viscosity, physical and mechanical properties of both the projectile and target, particle mass, impact velocity, and angle of impingement on the target.

Hemispherical craters are usually formed[5] as a result of high-velocity impact of thick plates when 1) the projectile and target are of the same material, i.e., aluminum on aluminum; and 2) the projectile material has a moderately lower strength,

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Table 1 Tensile strength computed from impact force and crater area

Alloy	Force/area, dynes/cm^2	Accepted value, ultimate tensile strength, dynes/cm^2
6061-T6	3.2×10^9	3.0×10^9
2S-0	1.05×10^9	0.8×10^9

density, and viscosity than the target, i.e., glass and nylon on aluminum. Deep, nonhemispherical craters are usually formed[5] as a result of high-velocity impact on thick plates when the projectile has greater strength, density, and viscosity than the target. However, the influence of strength parameters on crater geometry diminishes with increasing impact velocity, and is believed[6] to vanish at ultra-high velocity. Thus, the physical and mechanical properties manifest themselves in the shape of the crater formed in the high velocity (10,000 to 20,000 fps) impact region. High-strength materials are more resistant to viscous flow than low-strength, whereas high-density materials (at the same impact velocity) require more work to change their state of motion than low-density. For this reason, experimental penetration equations derived to predict impact damage usually have a projectile-to-target density ratio as well as a velocity ratio raised to a suitable power,[5] e.g., in the general form

$$\frac{\text{penetration}}{\text{projectile diameter}} = \text{const}\left(\frac{\text{projectile density}}{\text{target density}}\right)^{1/3} \times \left(\frac{\text{impact velocity}}{\text{target sonic velocity}}\right)^{2/3}$$

When a hemispherical crater is produced in aluminum, the equations for uniformly accelerated rectilinear motion are applicable.[5] The plot of impact force vs crater-surface area (corrected for relaxation after the pressure release) results in a straight line, the slope being equal to the engineering tensile strength of the target material. This relationship can be ascertained from the data in Table 1 for two aluminum alloys.

The model of cratering proposed[5] can be expressed by the equation $d^3 = mv^2/4\pi S$, where

d = radius of hemispherical crater
m = mass of projectile
v = velocity of projectile
s = maximum stress

It can be concluded that a near-hemispherical crater formed from the impact of a hemispherical projectile of known mass and velocity on a target of known *true stress* to fracture strength will produce a crater whose dimensions can be predicted within the experimental accuracy of 10%. It is significant that crater damage via hypervelocity impact can be predicted from the tensile strength established by standard metallurgical techniques.

A frequently used empiricial rule [7–9] is that the thickness required for a high-velocity particle just to penetrate a thin plate is 1.5 times the depth of a crater formed in a plate of infinite thickness. This rule-of-thumb may not apply to all combinations of materials for projectiles and targets, and should not be used without experimental verification.

The following experimental evidence is cited to support the inaccuracy of the 1.5-times rule. The impact of a 0.57-g cylindrical 4130 steel projectile on a 1.5-in.-thick 6061-T6 aluminum plate at 16,400 fps formed a crater 0.625 in. deep. Under almost identical conditions it was observed that a 0.875-in.-thick plate was nearly penetrated since a large bulge was formed on the rear surface. Plates thinner than 0.875 in. were cracked or completely punctured.

These experimental results indicate a 1.4-times rule. In other experiments, a 0.299-g spherical nylon projectile with an impact velocity of 17,800 fps struck the semi-infinite plate of 6061-T6 aluminum and produced a nearly hemispherical crater. Under almost identical conditions it was observed that a 0.875-in.-thick aluminum plate, although not completely penetrated, suffered both crater and spall damage. The crater damage was not indicative of the total damage sustained by the plate. Thus, the 1.5-times rule would not be applicable under these experimental conditions, since it largely ignores the effect of material strength, which plays a far more important role in the spallation process than it does in crater formation. Mortensen et al.[10] observed that the impact of 1100-F aluminum on 2024-T4 aluminum targets in the velocity range of 26,000 to 32,800 fps resulted in a 1.75-times rule. Gehring et al.[11] observed that 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. Andriankin and Stepanov[12] observed a factor of 1.5 to 2.0.

The energy of an impacting projectile is delivered to a target in less time when the penetration is shallow than when the penetration is cylindrical. The intensity of the resulting shock waves with the short time-shallow crater are, therefore, presumably greater than the latter case and result in greater spall damage.

Impact on Two Plates That are Flush

A thin plate placed in contact with either a thick plate or dense material and subjected to high-velocity particle impact will undergo extensive damage with petal formation (star breaks or rips). There are three damage phenomena of interest in this system, and total damage can be compared to that displayed by a single thick plate (Fig. 1).

Petals in the thin (0.090-in.) plate

The diameter of the hole resulting from petal formation is usually larger than the diameter of the crater in the thick plate (Fig. 1b). In addition, the metal petals are typical of material that failed in shear, and this behavior should not be misconstrued as resulting directly from the high-velocity impact but are produced after the thin plate has been pierced. The petals in the thin, low-strength material, further weakened by the hole, are produced by the inertial effects of the material ejected from the crater in the thick plate.

Initial hole in the thin plate

In several experiments, the petals of metal were forced back into the original plane of the plate in order to ascertain the original size of the hole formed in the thin plate by the impacting particle. The diameter of the initial hole formed by the projectile in any given thin plate is less than the diameter of the crater in the thick plate and is always the same irrespective of whether the thin plate is impacted alone or when it is in contact with a thick plate. The edges of the initial hole in the thin plate are typical of hypervelocity impact in contrast to the metal petals.

Crater in the thick plate

The dimensions of the crater in the thick plate depend on the properties of the impacting projectile as well as the material and thickness of both plates. However, damage is typical of hypervelocity impact.

The observed phenomena indicate that when two plates (thin in contact with thick) are struck with a hypervelocity projectile, the projectile initially moves into both plates producing a hole slightly larger than the diameter of the projectile. Below the surface, penetration will be significantly diminished but the radial expansion of the cavity becomes more rapid. With the radial expansion resulting from the ejection of the fluid (not liquid) material from the crater, the quasi-fluid material can move only in the direction away from the surface. This ejecta moves at high velocity and forms a lip at the crater edge or rim, and petals are formed in the thin plate. Radial plastic flow is arrested more quickly in materials having high yield strength or a high true stress to fracture (e.g. steel) than in low-strength materials (e.g. lead). This proposed mechanism was verified (Fig. 1c) by placing a 0.1875-in. aluminum plate in contact with an aluminum plate that was 0.500 in. thick. Although the impact separated the two plates in a localized region, deformation of the thin plate was slight and there was no evidence of petal formation. Thus, the thicker (0.1875 in. in comparison to the 0.090 in.) plate consumed more energy from the projectile as well as provided more resistance to flow from the effects of the material ejected from the crater. Further proof of the influence of the strength of the thin plate was demonstrated with 0.025-in.-thick plates of 301 stainless steel (full hard) placed in contact with a 0.75-in.-thick plate of aluminum (6061-T6). The behavior of this combination was almost identical with that shown in Fig. 1c, i.e., penetration and deformation with no petal formation.

Meteoroid Bumper

From the standpoint of the meteoroid bumper concept, a space vehicle structure is composed of three components: 1) the void (or core material sandwiched) between; 2) the main hull of the vehicle; and 3) the meteoroid bumper. The term,

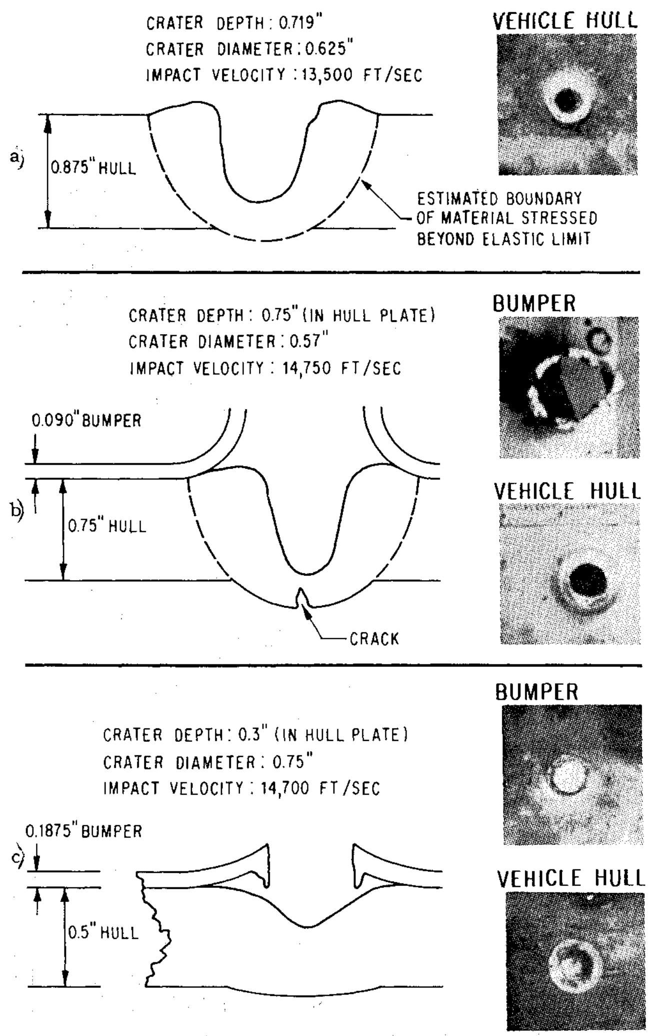


Fig. 1 Effect of bumper thickness on damage.

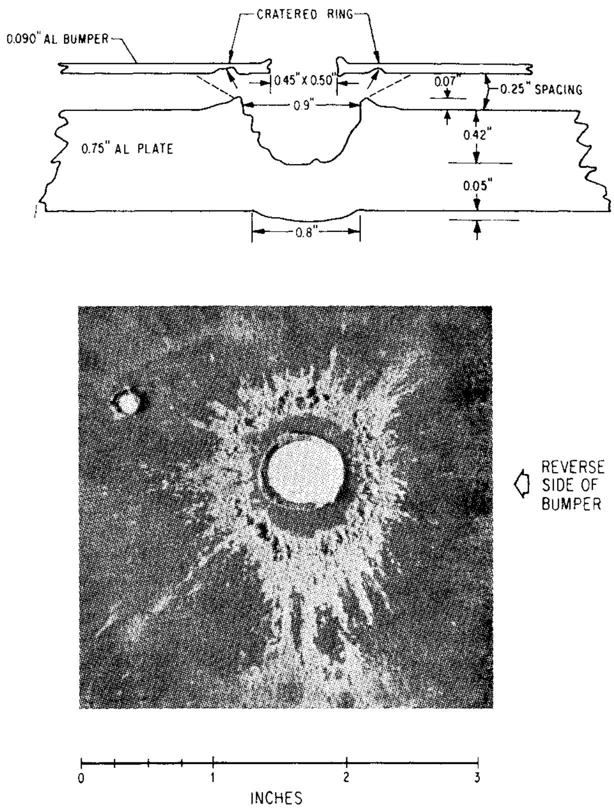


Fig. 2 Impact and splash-back damage to an aluminum (6061-T6) test structure (impact velocity = 15,200 fps).

"meteoroid bumper," includes any material that is used to protect the vehicle hull from impact damage. However, the term has been restricted to designate that part of the structure intended to change the condition of the impacting particle from a single compact solid to a cloud of dispersed particles (solid, liquid, and/or gas) before the particles impact the vehicle hull. The bumper must be capable of fragmenting the meteoric particle and dispersing its energy over a large area of the main hull; the core material (if used) may reduce the velocity of the particles, and the main hull must have sufficient strength to transfer the momentum of the impacting particles without being penetrated completely or producing spall fragments.

When a thin plate is struck with a high-velocity particle, the material in the plate is set into motion. Part of the target material is displaced in the forward direction of the projectile. This latter effect will produce a bulge on the rear surface of the plate. The bulge, with its curved surface, will increase in size because of the applied force of the impact. Thus, the material on the rear surface of the plate will be in motion, but not normal to the original plane of the surface. When the cohesive strength is exceeded, the material comprising the bulge will continue in the direction of its motion. This material from the bulge appears as a prolate spheroid of incandescent material when viewed photographically. Individual fragments travel in straight lines, and the term "spray cone" has been used to describe the locus of their collective paths.

Distance between the bumper and the vehicle hull will permit the cone of fragmented particles (meteoric) and shear plug material passing through the hole in the bumper to expand, so that energy per-particle contact area on the vehicle hull will be significantly diminished, thereby reducing the damage to the hull. A large distance cannot be tolerated, since this will impose severe volume difficulties on the vehicle system. On the other hand, the distance cannot be too small, since material splashed back from the main hull will cause extensive damage to a thin bumper.

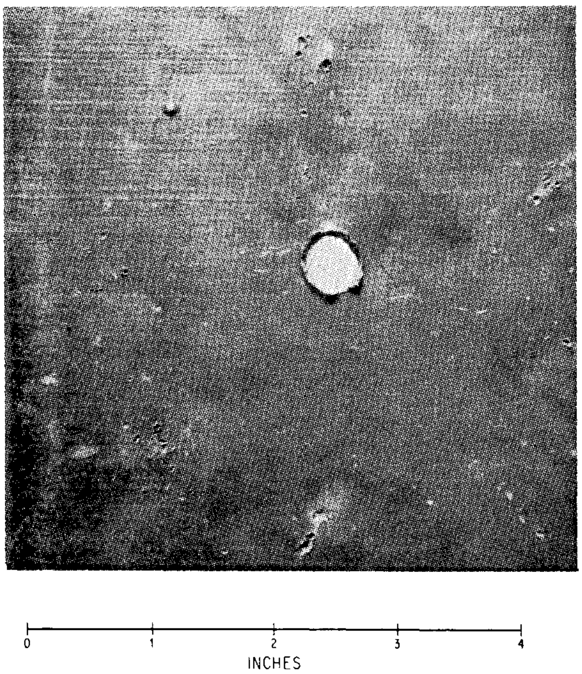


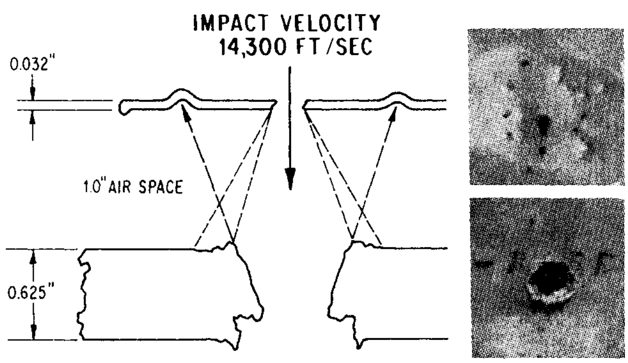
Fig. 3 Reverse side of 0.090-in-thick bumper (impact velocity = 21,700 fps).

The corporeity of the splash-back damage to 0.090-in.-thick aluminum bumpers can be seen from 1) the diagram in Fig. 2, in which the distance between the bumper and hull plate was 0.25 in. (note the coating of aluminum as well as the ring of small craters); and 2) the photograph in Fig. 3 where the separation distance was 2.57 in. (note the 4-in.-diam ring of small, deep craters).

Aluminum bumpers with a thickness of 0.040 in. or less were unable to withstand the force of the splashed-back material and were severely deformed when placed within 1 in. of the vehicle hull plate (Fig. 4).

The ejecta that moved from a 6061-T6 aluminum crater back toward the 301 stainless steel (full hard) bumper placed at a distance of 0.25 in. was composed of both the target and projectile material. This mixture of materials was ascertained by impacting a radioactive 4130 steel projectile on a nonradioactive target system. This well-established technique was used to determine the quantity of the projectile remaining in a hypervelocity crater.[13] It was observed with the 0.25-in. spacing that the annular ring (0.5 to 1.0 in.) surrounding the hole in the stainless-steel bumper was pitted deeply, coated with aluminum from the vehicle hull, and contained 2 to $2\frac{1}{4}$ times more radioactivity than any other section of the bumper. The annular ring (1.0 to 1.5 in.) surrounding the hole contained almost all the remainder of the radioactive projectile material splashed back onto the bumper. Inspection of the photograph of the back splash effects of all the aluminum systems given in Fig. 2 shows the excellent correlation between the visually observed physical damage and the measured radioactive data.

The most important aspect resulting from the contact of a high-velocity particle with the bumper is the extent of projectile break-up and the diminution of impact energy per unit area on the vehicle hull. Fragmentation has not been found to conform to a single type of behavior. However, there is an apparent tendency for the larger fragments to impact the vehicle hull near the center of the impact pattern. Occasionally, an impact pattern is found in which there is an even



NOTE:

WEIGHT OF TEST PANEL: 9.322 LB/FT^2

MATERIAL WAS EJECTED BACK FROM TAPERED PUNCTURE IN THE 0.625" ALUMINUM HULL WITH SUFFICIENT ENERGY TO DAMAGE BUMPER.

Fig. 4 Splash-back damage to a very thin meteoroid bumper.

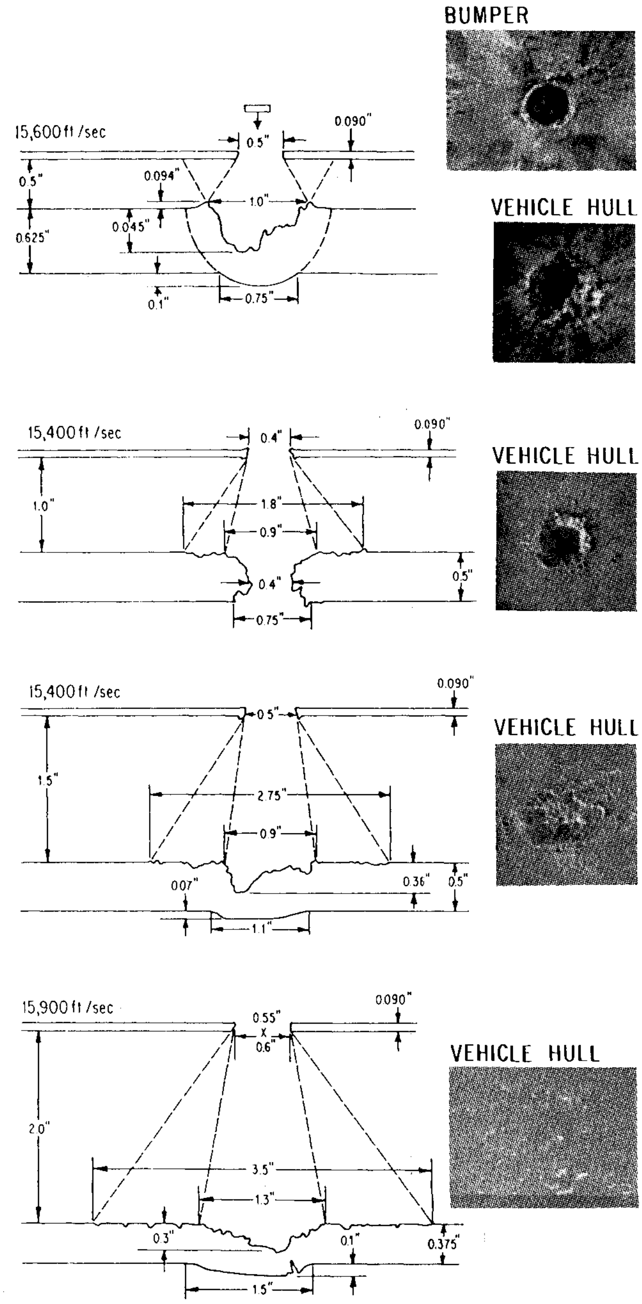


Fig. 5 Test panel composed of 0.090-in. aluminum (6061-T6) bumper separated from the aluminum (6061-T6) hull plate. Steel projectile weighed 0.57 g.

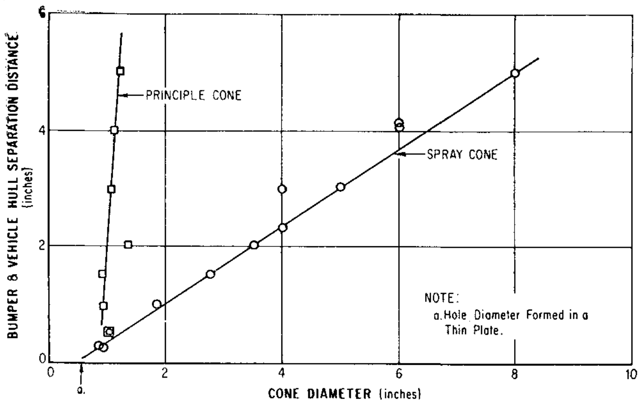


Fig. 6 Principle and spray-cone diameter dependence on separation distance (0.090-in. aluminum with 0.57-g projectile).

gradation of crater size, with the size diminishing uniformly with increasing distance from the impact pattern center. The nonreproducibility of this effect may be attributed to the tumbling action of the cylindrical projectile used in this experimental program.

In those experiments where the cylindrical base (flat face) of the projectile struck the bumper, there were always observed two distinct areas of impact patterns on the vehicle hull plate. The difference in cratering can be attributed to the expansion of the material as it leaves the rear surface of the bumper; i.e., a circular cone of material is formed with a right circular section of the cone at the rear face of the bumper, and the cone base at the front face of the vehicle hull. The particle concentration gradient was so pronounced that the surface damage to the vehicle hull plate appeared to be composed of an inner and outer segment (Fig. 5). There appeared

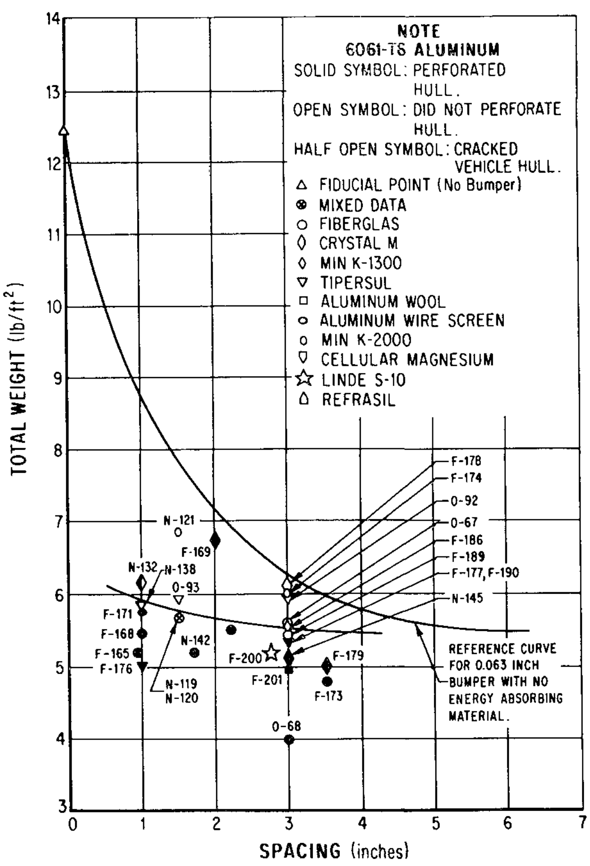


Fig. 7 Summary of energy-absorbing material test results.

to be an inner or concentrated cone (spray cone) of fragmented material that had a diameter of about 1.25 in. after it traveled about 8 in. beyond the bumper toward the vehicle hull. Pertinent data are summarized in Fig. 6.

The central or inner cone is probably composed of material from the projectile plus material from the bumper that was directly in the path of the projectile. The most heavily damaged section of the vehicle hull is in the inner cone, which conforms to the size of the cloud of fragmented particles which has been observed by high-speed photographs showing the ball or cloud of luminous particles emerging from the rear of the bumper. The size of this cone of material depends on the projectile impact velocity; the lower the velocity, the more compact the cone of material and the greater the damage inflicted to the vehicle hull. The outer part of the cone or spray pattern (principal cone) on the vehicle hull plate must be due to fragments removed from the bumper. The appearance of impact patterns on aluminum vehicle hulls obtained by projecting steel projectiles through glass bumpers supports this hypothesis.[14]

Energy-Absorbing Material

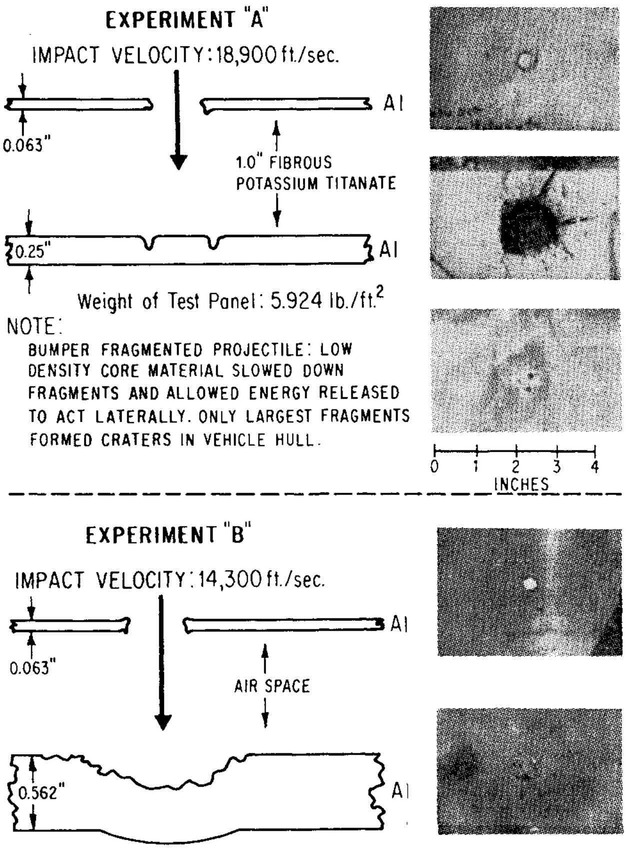
A functional distinction is made between the bumper, which permits some of the incident energy to be utilized in fragmenting the particle, and the energy-absorbing material, which dissipates some of the kinetic energy before particle fragments can cause damage to the vehicle hull. This distinction is justified by the different physical characteristics of the materials which are required to perform efficiently the two functions: the bumper apparently should be compact and thin with a moderately high density, and the energy absorber[14] should be porous and thick with a moderately low density.

The energy-absorbing material placed between the bumper and vehicle hull may insulate, support, stiffen, and hold the bumper and hull plates in their respective positions. From the standpoint of protection from meteoric particles, this energy-absorbing material is sacrifice material to save the vehicle hull. In this investigation refrasil, Min-K, Linde S-10, Tipersul, Crystal-M, metal wools, sponges, and foams were used as the energy-absorbing materials. Data from the preliminary experiments that were made with energy absorbers in conjuction with the 0.063-in. aluminum (6061-T6) bumper system are summarized in Fig. 7 and can be compared (reference curve of Fig. 7) with the total weight and spacing necessary for the 0.063-in. bumper without energy-absorbing material to prevent complete penetration of the vehicle hull. Systems that have a total weight-spacing on or above the curve will defeat a projectile system, whereas those total weight-spacing combinations below the curve will not defeat a pellet system. Thus, the smoothed curves provide a good representation of the dividing line for the experimental data observed between penetration and no penetration.

Cognizance should be taken of test panel F-169 where a 2-in. spacing was maintained between the bumper and vehicle hull. The entire 2-in. spacing was filled with core material (Min-K-1300). This test panel was completely penetrated, since too large a fraction (46.9%) of the total weight (6.65 psf) was contributed by the core material.

Differences in impact behavior for the same total weight of several tests panel configurations can be attributed to the mode of the cylindrical projectile impact, i.e., flat-face vs edge-on impact for the same projectile mass. It should be observed that edge-on impact leads to more extensive damage than flat-face, since the edge-on presents a greater effective length of projectile. Thus, it takes a longer period of time to consume the projectile, and with a longer reaction time, the sustained damage is greater. It was concluded that, for equal mass particles, rod-shaped projectiles would inflict the greatest damage to a structural system.

It can be seen that energy-absorbing material placed between the bumper and the main hull will significantly reduce



	"A"	"B"
SPACING (BUMPER TO PLATE)	1.0"	1.0"
CORE	TIPERSUL	NONE
TOTAL WEIGHT OF SYSTEM (LBS.)	5.924	8.918
HOLE DIAMETER, BUMPER (IN.)	0.35" X 0.44"	0.44"
CRATER DEPTH, HULL (IN.)	0.10"	0.25"
CRATERED AREA (DIAMETER)	0.55"	1.9"
PROJECTILE MASS (GM.)	0.568	0.583
PROJECTILE SIZE (IN.)	0.094" X 0.25"	0.094" X 0.25"

Fig. 8 Two experiments that show the relative advantage of energy-absorbing core material in certain configurations with aluminum plates.

the weight per unit area of the vehicle structural system with the same amount of protection. Substitution of energy-absorbing material must be less than half of the mass of the vehicle hull replaced. Under the described experimental conditions, fibrous core material could be substituted for 33 to 55% of the thickness of the vehicle hull, with either a 15% saving in total weight or a 75% saving in thickness.

The spray pattern, when a fibrous material was placed between the bumper and vehicle hull, was masked somewhat by material destroyed and by gases and fragments rebounding from the surface of the plate. However, there were usually three to ten closely grouped small craters or nicks in the vehicle hull. The impact pattern was usually very small in comparison with similar test panels in which energy-absorbing material was not used. The difference can be seen in Fig. 8.

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