Effects of Bumper Material Properties on the Operation of Spaced Meteoroid Shields

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An experimental study has been conducted to investigate the importance of bumper materials upon the performance of two-component hypervelocity impact shields. Sixteen different bumper materials were investigated ranging in densities from 0.85 to 16.6 g/cm³. Several bumper materials were found that were equally effective on a mass per unit area basis. Bumper material effectiveness dropped rapidly with bumper material density when this density was below 2 g/cm³. An optimum bumper thickness exists for minimizing total shield weight for each bumper material investigated. The results in this study can be explained by an analysis of the states of the impacting pellet and bumper material within the debris cloud projected behind impacted bumpers. One-dimensional plate impact theory is used to predict the physical state of the cloud material. No other parameters but those controlling cloud material state had discernible effects upon two-component shield operation.

Introduction

LARGE space vehicles committed to long duration missions are subject to potentially disastrous encounters with meteoroids. Protection against this hazard must be provided to assure adequate mission reliability.

The "bumper shield" concept originally proposed by Whipple[1] remains, after extensive investigation, the most promising technique for providing the required protection against particle impacts. The protected component (such as the vehicle hull) is shielded from a direct impact by placing a relatively thin continuous sheet of material (bumper) some distance in front of the component. The incident particle is disintegrated by impact with the bumper, creating a relatively diffuse debris cloud. The protected component must only withstand an encounter with this cloud instead of with the incoming pellet. The resultant reduction of spatial impact intensity on the protected component allows it to be lightened enough to more than offset the weight of the bumper and its support structure without sacrificing over-all impact resistance. Equivalent impact resistance has been demonstrated for bumper structures weighing as little as 20% of corresponding single plate shields.[2]

Many studies of both general bumper shield structures and specific structures proposed for particular vehicles have been carried out.[2-4] In all cases, the impact velocities used for the studies are significantly below those anticipated for encounters with macroparticles in space due to limitations of currently available pellet accelerators. The velocity extrapolations that are required to extend laboratory test data to cover meteoric encounters are hazardous unless the phenomena controlling particle shield operation are well understood.

Background

Upon impact of a pellet with a thin plate, strong compressive shock waves propagate forward into the plate and rearward into the pellet. These waves establish a material flowfield that controls the subsequent directions and velocities of both plate and pellet materials. Shortly after initial contact, the bulk of the affected material is projected at high velocities behind the plate in an expanding bubble which becomes the high-energy component of the debris cloud. A significant amount of plate material adjacent to the initial hole is detached at late times and forms the low-energy component of the debris cloud.

The directions, speeds, spatial densities, and physical states of the materials projected behind an impacted plate establish the debris cloud damage potential. Two approaches have been available to vehicle designers for predicting this damage potential for some time. Rolsten et al.[5] noted that, over a wide range of material properties, equal bumper areal densities produced debris clouds with approximately equal damage potentials (i.e., thick bumpers of low-density material behave in a similar manner to proportionately thinner bumpers made from higher density material). Rolsten examined materials whose densities ranged from 1.35 g/cm³ (magnesium-lithium alloy) to 7.8 g/cm³ (steel). Riney and Heyda came to similar conclusions based on a theoretical study of impacts between cylindrical aluminum projectiles and thin composite plates at 15 km/sec.[6] They computed the ratio between the debris cloud impulse directed along the original pellet trajectory and the outward directed impulse perpendicular to the trajectory for several composite bumpers subjected to identical hypervelocity impacts. These ratios correlated with the total areal density of the bumper configurations only. Riney and Heyda reasoned that these impulse ratios determined the effectiveness of bumpers for diffusing the pellet impulse and, hence, the over-all effectiveness of the plates for reducing secondary damage.

Maiden[7] reported significant differences in bumper effectiveness that were correlated with the fusion and sublimation energies of the pellet and bumper materials. He reported that debris clouds of solid particles are considerably more destructive than those made up from liquid droplets and both are more destructive than gaseous debris clouds. These results have been verified experimentally by Zwarts[4] and Carey.[8] The states of debris cloud materials can be pre-

Presented as Paper 69-379 at the AIAA Hypervelocity Impact Conference, Cincinnati, Ohio, April 30–May 2, 1969; submitted May 2, 1969; revision received October 3, 1969.

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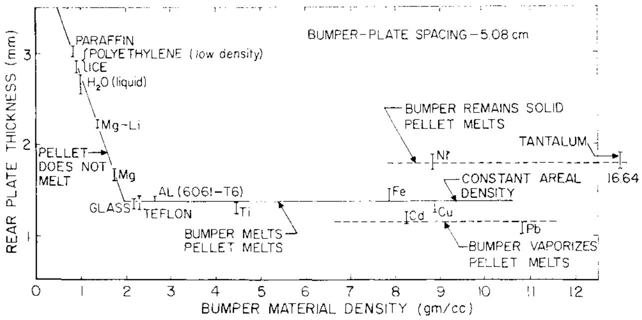

Fig. 1 Data plot for constant bumper areal density study, showing states of bumper and pellet materials in the debris clouds.

dicted using arguments presented by Bjork et al.[9] The primary compression waves generated by a hypervelocity impact are sufficiently intense to significantly increase the entropy of the material through which they propagate. The unloading waves that return the material to zero pressure are nearly isentropic regardless of their pressure span. Thus entropy is trapped in material subjected to intense shock compression; the entropy increase appears as increased internal energy of the material after shock-induced pressures have returned to zero. The specific heat of the material as a function of temperature, plus the material fusion and sublimation energy, can be used to compute the residual state and temperature of the shock-loaded material after it returns to zero pressure. If the increase in internal energy is greater than the fusion energy, the material returns to zero pressure in a liquid state. Similarly, the material is vaporized if the residual internal energy exceeds its sublimation energy.

This thermodynamic line of argument leads to the prediction that bumpers with equal areal densities will not be equally effective if they create debris clouds whose materials are in different physical states. This is a direct contradiction to the constant areal density rule cited earlier. The ranges of applicability of these two approaches and their apparent contradictions must be resolved in order to design reliable space vehicle shields. Furthermore, little is presently known of the relative importance of bumper and pellet materials in determining debris cloud destructiveness, since investigations considering the thermodynamic states of the cloud material have utilized identical pellet and bumper materials.[1,8,9]

Current laboratory accelerators can achieve pellet velocities required for generating solid or liquid debris clouds when realistic pellet and bumper structural materials are employed. Materials with exceptionally low sublimation energies such as plastics, cadmium, tin, lead, etc. must be employed to generate vaporous clouds.

Experimental Design and Results

The over-all purpose of this study was to compare the relative effectiveness of bumpers made from a wide variety of materials. This effectiveness was established by impacting the bumpers with 3.18-mm-diam. aluminum spheres and determining the thickness of 6061-T6 rolled aluminum rear plates required to just prevent perforations by debris clouds. Alternate ballistic limit definitions involving production of spall debris behind the rear plates, rear plate dimpling, or catastrophic rupture of prestressed rear plates have been used in other studies. The simple perforation definition of ballistic limit was chosen for this study to facilitate comparison of the reported data with the largest amount of other data that is currently available. The bumper-plate spacing of 5.08 cm chosen for this study is a widely-accepted compromise between optimal shield performance and engineering effectiveness. Bumper materials were chosen specifically for their sublimation and fusion energies such that clouds of solid particles, liquid droplets, and vapor would be produced when impacted by aluminum pellets. The bumper thicknesses were adjusted to achieve a predetermined bumper mass per unit of presented area. The areal density chosen for this series was 0.22 g/cm³, equivalent to a 0.079-cm-thick 6061-T6 aluminum bumper whose optimum characteristics were established during a previous study.[2] The other experimental parameters and results are presented in Table 1. Note that pellet velocities vary over a relatively extended range. Earlier studies showed (and this study has verified) that rear plate ballistic limit thicknesses are quite insensitive to pellet velocities in the velocity range of these experiments.[2] No anomalous results caused by pellet velocity variations have been found to date.

The double values presented in the "rear plate" and "total" columns represent the ballistic limit resolution achieved for each case considered (i.e., the minimum rear plate thickness that did not fail, together with the maximum thickness that did).

A plot of limit rear plate areal densities vs bumper material densities presented in Fig. 1 illustrates that several bumper

Table 1 Thicknesses of 6061-T6 Al rear plates required to prevent perforation by 0.318-cm-diam 2017 Al sphere impacting from 6.2 to 7.4 km/sec for various bumpers with $\rho_b t_b \simeq 6.22$ g/cm² areal density and 5.08-cm spacing

Bumper					Cloud state	
Material[a]	ρ_b, g/cm²	t_b, cm	Rear plate t_p, cm	Total shield $\rho_s t_s$, g/cm²	Bumper	Pellet
Paraffin (A)	0.84	0.254	0.295–0.307	0.996–1.030	g[b]	s
Polyethylene (P)	0.92	0.236	0.279–0.292	0.963–0.997	g[b]	s
Ice (C)	0.92	0.246	0.279–0.292	0.972–1.006	g[b]	s
Water (A)	1.00	0.234	0.257–0.279	0.920–0.979	g[b]	s
Mg-Li (HCP)	1.37	0.157	0.218–0.229	0.797–0.826	1[b]	s
Magnesium (HCP)	1.76	0.127	0.160–0.203	0.650–0.766	1	s
Glass, crown (A)	2.19	0.104	0.130–0.142	0.575–0.607	1[b]	
Teflon (P)	2.31	0.099	0.130–0.145	0.575–0.616	1	1
Al 6061 (FCC)	2.67	0.084	0.140–0.145	0.596–0.609	1	1
Titanium (HCP)	4.46	0.051	0.127–0.140	0.566–0.601	1	1
Steel 1020 (BCC)	7.65	0.030	0.140–0.152	0.609–0.643	1	1
Cadmium (HCP)	8.26	0.028	0.114–0.127	0.535–0.568	g	1
Nickel (FCC)	8.73	0.028	0.173–0.191	0.710–0.758	s	1
Copper (FCC)	8.78	0.028	0.127–0.140	0.588–0.623	1	1
Lead (FCC)	10.82	0.020	0.102–0.114	0.498–0.520	g	1
Tantalum (BCC)	16.64	0.013	0.173–0.191	0.670–0.718	s[b]	1

[a] (Microstructure): A = amorphous, C = crystalline, P = polymer, FCC = face-centered cubic, BCC = body-centered cubic, HCP = hexagonal close-packed.
[b] Postulated from character of debris on rear plate.

Table 2 Shock heating data for metallic materials; P = pressure, Mb; V = Al impact velocity, km/sec

		Melting				Vaporization			
		Incipient		Complete		Incipient		Complete	
Material	Ref.	P	V	P	V	P	V	P	V
Mg	10	0.48	5.4						
Al	10	0.7	5.6	1.00	7.0				
	12	0.67	5.5	0.88	6.6	1.67	10.2	4.7	
	13	0.61	5.1	0.85	6.5				
Ti	10	1.3	7.6						
Steel	10	1.8	7.9	2.10	8.8				
Cd	10	0.33	2.5	0.46	3.20				
	12	0.4	3.0	0.59	3.9	0.88	5.2	1.8	8.1
	13	0.33	2.5	0.43	3.15	0.70	4.4	5.3	
Cu	10	1.4	6.6	1.84	8.0				
	13	1.4	6.6	1.84	8.0	3.40	12.6	34.0	
Ni	10	2.3	9.0						
Pb	10	0.25	2.0	0.35	2.6				
	12	0.27	2.1	0.34	2.5	0.84	4.8	2.3	9.1

materials whose material densities are greater than 2 g/cm^3 adhere to the constant-areal-density rule. Data from some bumper materials fall below the constant-areal-density line (Cd, Pb) and some fall above it (Ni, Ta), however. The most striking feature of Fig. 1 is the extreme excursion from the constant-areal-density rule that occurs when bumpers whose material density is below 2 g/cm^3 are employed. A rapidly rising linear function appears to fit the rear plate areal density vs bumper material density plot in this material density regime. This sharp reduction in bumper effectiveness with decreasing material density is of considerable importance to the design of particle shields for space vehicles, since several candidate bumper materials fall in this density regime.

Table 2 presents shock heating data for the metallic materials used in the investigation, as determined from the entropy trapping arguments discussed above. The peak pressures generated in bumper materials by the impacts of aluminum pellets at 7 km/sec are shown in Fig. 2. These shock pressures were computed using procedures and results developed to treat one-dimensional impact situations.[10] The one-dimensional approximations are valid only during the early phases of an impact between a sphere and a flat plate, but this is the time when maximum pressures are produced. The average pressure produced throughout the pellet and plate material which forms the energetic debris cloud, is always less than the maximum pressure and is determined by geometric and material factors as well as maximum pressure.

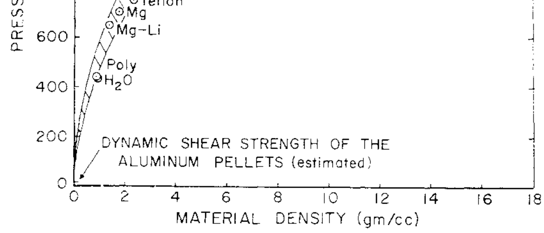

Fig. 2 Peak shock impact pressure generated by aluminum pellet impact vs bumper material density.

Relationships Between Materials Properties and Bumper Effectiveness

Material properties other than density and thermodynamic quantities may affect the operation of meteoroid bumpers. The microscopic forms of the materials largely control their behavior under impulsive loading. Therefore, strength and strain rate effects should be manifest during a hypervelocity impact against thin plates, since the hydrodynamic phase of the impact process terminates long before the hole formation is completed. Bumper materials which were both crystalline and amorphous were utilized in this study. As can be seen from Fig. 1 and Table 1, the effects of these properties upon bumper performance cannot be discerned within the resolution of the data.

Several investigations of spaced particle shields have indicated that optimum bumper thicknesses exist for specific impact situations.[2,3,5] Basically, very thin bumpers do not completely fragment the pellet and large pieces with high residual momentum are projected intact behind the bumper plate. Conversely, excessive bumper thickness is detrimental to shield operation, since it leads to large reductions of average impact pressures in the bumper material below the maximum pressures presented in Table 2. The reduced average pressure caused large fragments of bumper material to be projected behind the bumper. Optimum bumper thicknesses exist between these two extremes. The optimum thicknesses for several bumper materials used in this investigation were evaluated to determine whether deviations from optimum bumper thicknesses were responsible for any of the results.

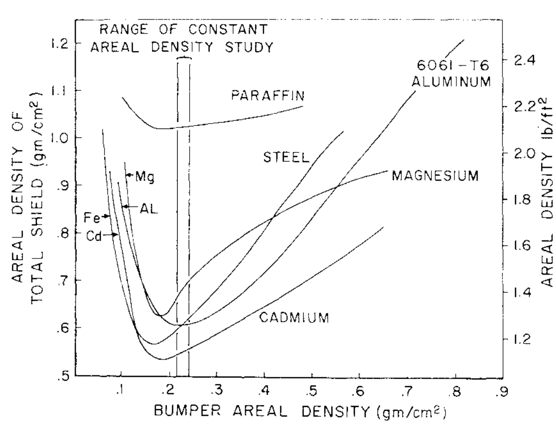

Fig. 3 Total shield areal density vs bumper areal density for five representative bumper materials.

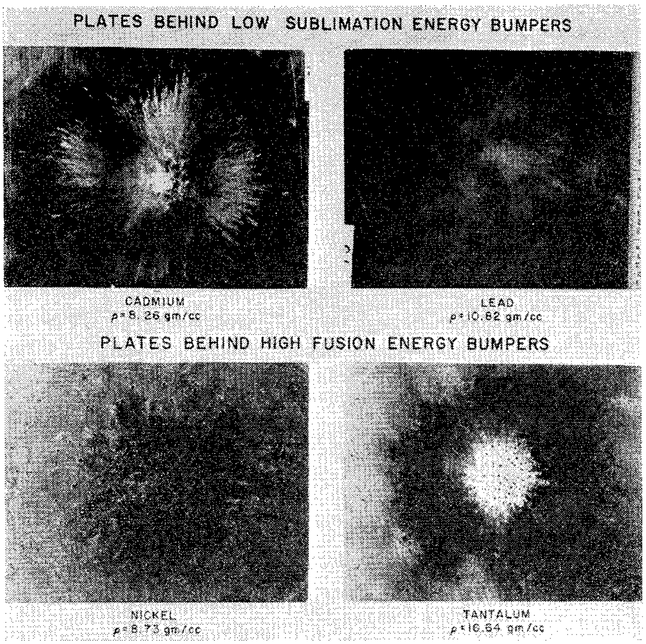

Fig. 4 Rear plates behind bumpers that were vaporized (Cd, Pb) and bumpers that were shattered by pellet impacts (Ni, Ta).

The over-all results of the bumper thickness investigation appear in Fig. 3. The plot of total shield areal density vs bumper areal density shows that none of the materials examined have the same optimum bumper areal density as 6061-T6 aluminum (the bumper material used as standard for the constant areal density investigation), but that all the optimum densities are quite close to that of aluminum. In the most extreme case, steel, a 5% reduction in total shield areal density would have resulted if the optimum bumper thickness had been employed. Thus no indication exists that the use of nonoptimum bumper thicknesses is responsible for either the qualitative or quantitative results of the bumper areal density study.

Discussion

The following explanation of the experimental results discussed previously had been adopted as a working hypothesis.

The rate of debris cloud divergence from the original pellet trajectory, and the physical state of the debris cloud material, are the most crucial parameters controlling debris-cloud damage potential. When both the pellet and bumper materials are liquefied by impact-induced shock waves, the constant-areal-density rule describes bumper performance. Similar areal density rules employing different values for bumper effectiveness may describe the behavior of bumper-pellet systems where the bumper materials remain solid or vaporize, but where the pellet material is melted. Bumper materials with high sublimation energies used for this study (Ni, Ta) were not melted by the impact-induced shock waves. The rear plates behind these bumpers exhibited deep craters indicating impact by relatively large fragments which are almost certainly bumper material (see Fig. 4). The bumper materials with low-sublimation energies (Cd and Pb) were vaporized by the impact-induced shock waves while the pellet material was melted (see Fig. 4). The resulting debris clouds made up of liquefied pellet material and vaporized bumper materials were correspondingly less destructive (see Fig. 1).

Both of these effects arising from bumper material states are relatively minor. The maximum deviations observed from the constant-areal-density behavior were 25% in the region of the plot (Fig. 1) where bumper density was greater than 2 g/cm.[3] The relative insensitivity of the debris cloud destructiveness to changes of state of bumper material arises from the fact that the energetic bumper material makes up a relatively minor fraction of the total debris clouds. Almost all the energetic bumper material in the debris cloud comes from a cylinder within the bumper whose diameter approximates that of the pellet. Since all bumpers considered have equal areal densities, the masses of all these cylinders are approximately equal and contribute somewhat more than one quarter of the total masses of the debris clouds. Thus, the major portion of the debris clouds consists of pellet material which is in the same state (molten) for all cases where bumper densities exceed 2 g/cm.[3]

Rosenblatt et al.,[11] in an analytical study of the impacts of 3.18-mm-diam aluminum spheres against 0.79-mm 6061-T6 aluminum bumpers at 7.5 km/sec, have demonstrated that the peak pressure experienced by the sphere and plate is approximately 1.1 Mbar which corresponds to pressures calculated using one-dimensional approximations. Their calculations also show that this pressure is achieved very early in the impact process and rapidly decays, to the extent that the maximum pressure the rearmost portion of the projectile experiences is only 200 kbar. Thus the peak pressure at the rear of the pellet is less than that required for incipient melting of aluminum as shown in Table 2. Therefore, shock heating cannot be the sole factor in determining the residual state of the projectile and bumper material.

Two other energy sources besides shock heating are available for heating materials during hypervelocity impacts. Incoming pellets and the target material immediately under the impacts are massively deformed. The bulk of the energy involved in this deformation process appears as material heating. A closely-related phenomenon is the energy expended in overcoming friction between elements within the projectile and target during the deformation process. This energy also appears as material heating. Crude calculations based on quasi-static deformation models indicate that the

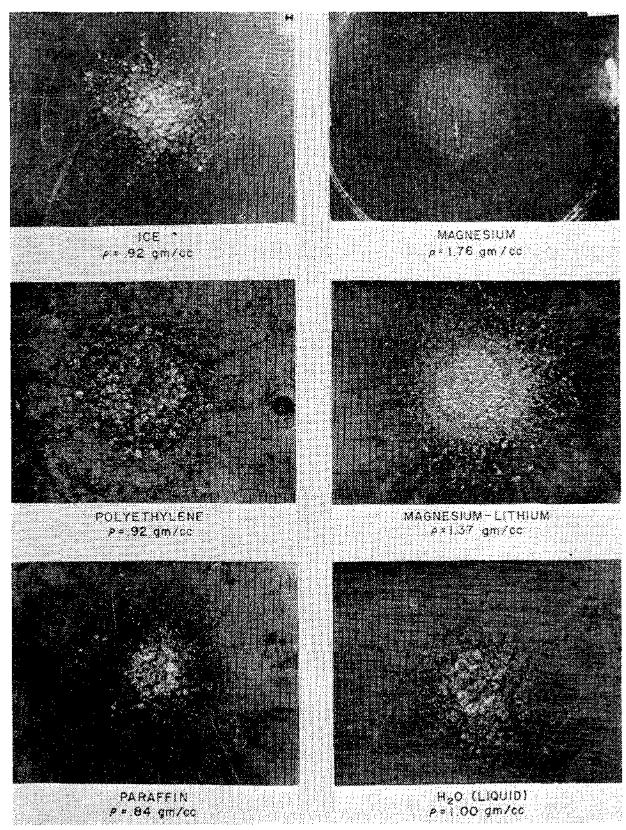

Fig. 5 Rear plates behind bumpers whose material densities are below 2 g/cm^3.

temperature of aluminum can be raised several hundred degrees centigrade by extreme deformation. Too little is yet known of the dynamic response of materials at very high pressures to make accurate estimates of deformation and friction heating during hypervelocity impacts. Over the range of the experiments carried out in this study, it appears that non-shock-wave heating is sufficient to cause complete pellet melting or vaporization when the peak pressure generated by the impact caused localized shock melting or vaporization.

Pellet impacts with bumper materials whose density is less than 2 g/cm^3 do not produce sufficiently intense shock waves to melt the pellet material. Thus, progressively larger chunks of pellet material pass through the bumper and impact the rear plate with progressively greater destructive power as bumper densities are reduced, since these reductions lead to corresponding reductions in peak shock wave pressures. The resulting progressive increase in mean crater size on the rear plates protected by bumpers with progressively lower densities can be observed in Fig. 5.

The only bumper material parameters that were found to affect particle shield operation were the material density, fusion energy, sublimation energy, and possibly fracture energy. In particular, wide variations of material static strengths, low-strain rate ductility, and high-strain rate behavior had no discernible effect upon shield performance. Material strength parameters affect the components of the debris cloud launched during the later stages of the hole growth processes, but have virtually no effect upon early-time processes where typical pressures are far in excess of materials strengths. Since bumper operation is not affected by bumper material strength and high strain rate parameters, the high energy components of the debris cloud must determine cloud lethality almost exclusively.

Conclusions

The conclusions of this study must be considered in the light of currently available information pertaining to the operation of bumpered particle shields.

The shock and deformation heating description appears to be valid for describing many of the phenomena controlling particle-shield response to hypervelocity impact. The constant-areal-density rule for predicting bumper performance has been validated at least for the cases where both pellet and bumper materials making up the debris clouds are liquid. Absolute shifts occur in bumper effectiveness between bumpers whose debris cloud material remains solid, is melted, or is vaporized. Therefore, indications are strong that other constant-areal-density rules with different values for bumper effectiveness can be established to describe shield operation for cases where the shocked bumper material remains solid or vaporizes.

The state of pellet material in debris clouds is the strongest factor influencing the performance of bumper particle shields. Bumper effectiveness drops rapidly with decreasing peak shock wave pressure once these pressures are reduced to values below those required to melt the incoming pellet.

Many lower-velocity meteoroids and man-made pellets will be melted by encounters with space vehicle bumpers, whereas the higher velocity pellets will be vaporized. Practical two-plate meteoroid shields must be capable of withstanding impacts from pellets that will be either melted or vaporized by impact-induced shock waves. This study has shown conclusively that high sublimation energy bumper materials such as beryllium or refractory materials should be avoided because lower-velocity meteoroids would not melt them upon impact and would thus create relatively more lethal debris clouds containing solid debris. The material and thickness of bumpers should be selected to assure that incoming pellets are either melted or vaporized. Solid pellet material increases debris cloud lethality more than any other factor observed.

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