A Combined System Concept for Control of the Meteoroid Hazard to Space Vehicles

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A space vehicle wall concept is presented in which a self-sealing feature is incorporated into a multisheet wall structure to give a configuration possessing both high penetration resistance and self-sealing capability. This latter capability minimizes fluid leakage from pressurized space vehicle compartments due to leak-provoking damage resulting from impacts by the more energetic meteoric particles. The self-sealing concepts have been experimentally verified by puncturing wall panel specimens with $\frac{1}{8}$-in.-diam steel spheres at impact velocities to 26,000 fps. The best configuration tested employed a foaming resin (activated by a catalyst on impact to produce a volume increase and seal the puncture). Preliminary weight estimates suggest that such a structure should produce a significant weight saving, relative to the bumper and thick-skin approaches, for mission durations exceeding a few months.

Introduction

VARIOUS conflicting opinions exist concerning the exact nature of the meteoroid environment and the magnitude of its hazard to space vehicles. However, it is generally agreed by most investigators that, due to their extremely high velocities (11 to 72 km/sec), meteoroids do present a real hazard to manned space vehicles, particularly those destined for long-duration missions. The potential hazards, other than punctures followed by irreplaceable fluid losses, include physical injury to the astronauts and damage to critical components or subsystems of a space vehicle caused by the resulting spray of impact induced particles. For limited space missions in the near vicinity of the earth, a certain number of punctures of the crew compartment may be tolerable with respect to air leakage rate, but the physical injury and damage effects may be of greater concern to the crew. However, as mission times are increased, the air leakage rates due to meteoroid induced damage or punctures may also be expected to increase. Some of these leaks may be located and sealed by the crew, but a number of undetectable or inaccessible punctures would probably remain. This would result in a critical leakage rate or point-of-no-return (with respect to the possibility of aborting the mission), which, if exceeded, would result in the loss of all life-supporting atmosphere before the crew could return safely to earth.

One structurally heavy solution would be to make the shell of the space vehicle sufficiently thick so as to be "puncture-proof" to meteoroid impacts. However, due to the uncertainties surrounding the definition of the meteoroid environment and the true mechanisms of hypervelocity impact and penetration, good design criteria for building a reliable, lightweight, single-thickness, armor-plate structure are not currently available. Summers and Nysmith[1] have experimentally demonstrated that the addition of a bumper shield will improve the penetration resistance of a structure over that of a single sheet configuration of equivalent weight. However, as is illustrated in Fig. 1, when the ballistic limit of the wall configuration is exceeded, blowout of the inner pressurized shell may be expected. Systems consisting of automatic leak detection, location, and manual repair have also been considered, but their complexity, plus the fact that the burden of sealing the puncture is placed on the astronauts, has delayed their acceptance.

In view of the preceding, the self-sealing feature of the proposed *combined system* concept appears sufficiently attractive to warrant a critical evaluation of its feasibility. Evaluation of this concept under a NASA-sponsored program has resulted in the development of various wall-panel configurations in which the self-sealing feature has been experimentally verified by puncturing panel specimens with $\frac{1}{8}$-in.-diam steel spheres at impact velocities to 26,000 fps.

Experimental Program

During the early phases of this program, various mechanical and chemically activated self-sealing panel configurations were investigated. A few of the basic operating principles of these initial panel configurations are illustrated in Fig. 2. Briefly, the principle of operation of the mechanically activated concepts depends upon either the mechanical response of elastomer materials in rebounding upon being punctured and sealing the hole (Fig. 2a), or on the forces generated by the pressure differential across a puncture in a pressurized compartment in drawing a rubber sphere or other sealing element into the hole and effecting a seal (Fig. 2b). The working principle of the chemically activated concepts depends upon the dynamic action of a penetrating particle causing the inter-

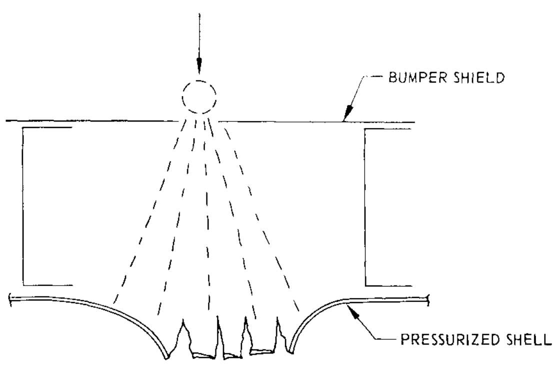

Fig. 1 Impact damage of particle velocities exceeding the ballistic limit.

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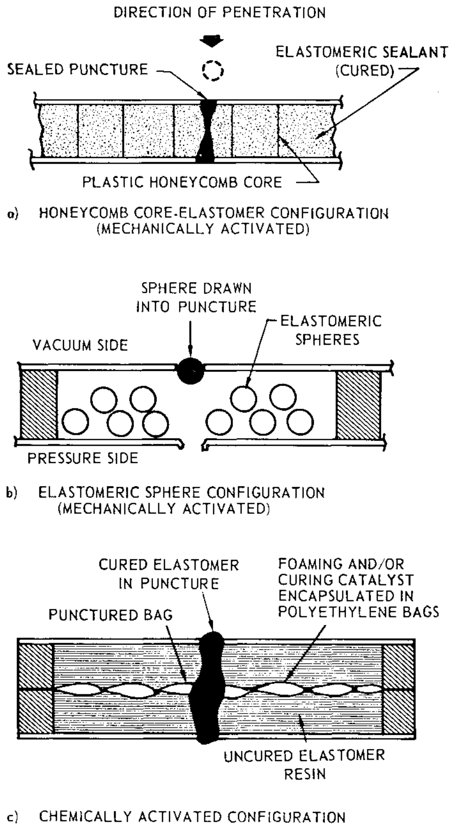


Fig. 2 Self-sealing structure concepts.

mixing of two initially separated chemical constituents (Fig. 2c). The ensuing chemical reactions will cause one of the constituents (an easy flowing elastomer) to cure, or foam and then cure, so as to form a solid mass along the pellet entry path and effect a seal. Further details on these basic self-sealing concepts may be found in Refs. 2 and 3.

Initial panel testing was conducted in a powder charge gun range by which $\frac{1}{8}$-in.-diam steel and glass spheres could be accelerated to velocities up to 7000 fps and leakage rates across punctured panels could be measured.[3] The impact faces of the test panels were attached to the test chamber of the gun range, which was then evacuated to approximately 200 μ. The pellet exit face was exposed to atmospheric pressure. Following puncture of the panel, under room temperature conditions, air leakage rates (for $\Delta P \simeq 14.7$ psi) through the puncture were recorded.

Some limited testing with $\frac{1}{8}$-in.-diam glass spheres at impact velocities to 23,000 fps was conducted at NASA's Light Gas Gun Facility, Ames Research Center, in an attempt to verify initial results obtained at 7000 fps. Five panels were tested, of which two were completely perforated so that their self-sealing capability could be thoroughly evaluated. Examination of the impacted panels indicated that shock-wave effects at these higher velocities would increase panel face sheet damage and material removal along the pellet entry path, thereby making it more difficult to achieve self-sealing action.

Figure 3 compares the damage sustained by a honeycomb core-elastomer configuration (Fig. 2a) when impacted by a $\frac{1}{8}$-in.-diam steel sphere at 7000 fps and a $\frac{1}{8}$-in.-diam glass sphere at 20,950 fps. It should be noted that, at 7000 fps, the metallic face sheet and elastomer sustained little damage, with the result that the mechanical rebound of the elastomer sealed the hole. At 20,950 fps, petalling of the face sheet occurred while excessive removal of material along the pellet entry path negated any sealing action. Figure 4 illustrates similar damage sustained by the metallic face sheet of a chemically activated panel configuration (Fig. 2c) when impacted by a $\frac{1}{8}$-in.-diam glass sphere at 21,8000 fps. The neoprene sheet bonded to the front face of the panel minimized the hole size through which the sealing constituents could flow. The rear face sheet of this panel was not perforated, but excessive loss of chemicals from the pellet entry hole prevented the formation of an effective sealing plug.

The resultant impact damage incurred by the pellet entry face of the two preceding panel configurations may be explained as follows. When a high-velocity particle penetrates a compartment containing a nearly incompressible material (liquid or solid), the incident shock wave induces extremely high pressures (in the megabar range) at the compartment wall interface which exceed the dynamic rupture strength of the penetrated wall. If the penetrated wall material is metallic or prone to rapid crack propagation when loaded at high strain rates (e.g., hypervelocity impact conditions), then the consequence will be petalling and/or explosive rupturing of the penetrated face sheets as is depicted in Figs. 3 and 4.

On the basis of these initial high-velocity tests, it was concluded that those concepts in which sealing capability was dependent solely upon the mechanical response of elastomeric materials (e.g., Fig. 2a) would not seal at the higher puncturing velocities, whereas for the other concepts (Figs. 2b and 2c), shock-wave damage control would be a prime prerequisite for obtaining successful self-sealing action.

In view of this, modifications suggested by shock-wave theory were incorporated into subsequent panel configurations in order to minimize shock-wave damage to the panel faces and increase their potential for successful sealing at impact velocities above 20,000 fps. The most effective of these damage-control techniques was found to be the use of nonmetallic face sheets and the isolation of the chemical compartment of the chemically activated configuration from the face sheets by air gaps or the interposition of compressible low-density materials. In addition to the preceding, self-sealing capability at the higher impact velocities was enhanced

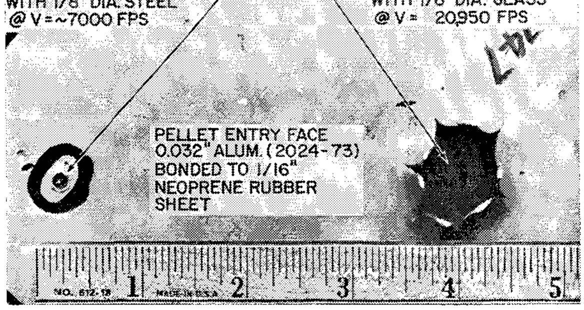


Fig. 3 Comparison of damage of two impact velocities for the honeycomb core-elastomer configuration.

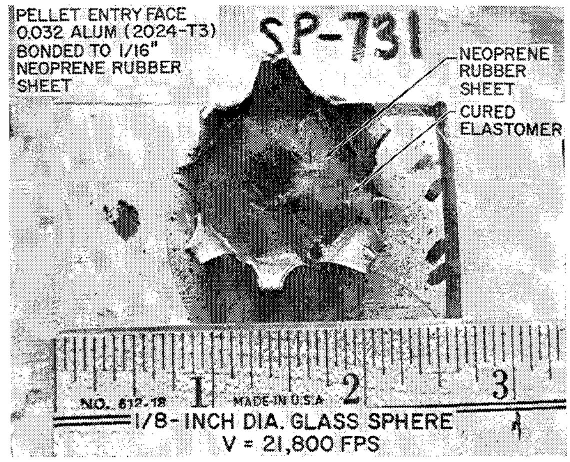


Fig. 4 Impact damage to chemically activated configuration.

Table 1 Summary of high-velocity ballistic test results using $\frac{1}{8}$-in. pellets

Panel configuration	unit wt, psf	Pellet material	V, 10^3 fps	Leakage rate, lb/day[a]
Fig. 5a,	1.43	Steel	24.7	1.3
Fig. 5b,	3.10	Steel	23.0	0
...[b]	2.84	Pyrex	22.5	...[d]
Fig. 5c,	3.09	Steel	26.0	0
...[c]	2.85	Steel	24.0	Not recorded

[a] Air leakage at pressure drop of 14.7 psi at room temperature.
[b] Similar to Fig. 5b except for depth of compartments ($\frac{1}{2}$ in. reduced to $\frac{5}{16}$, in. $\frac{7}{16}$ in. reduced to $\frac{3}{8}$ in.)
[c] Similar to Fig. 5c except nonmetallic face sheets replaced by 0.020-in aluminum (2024-T3).
[d] Rear face oi panel not perforated by projectile fragments.

by using volume-generating reactions (e.g., foaming elastomer resins) in the chemical configurations and by combining the best features of the mechanical and chemical self-sealing concepts.

Construction details of these modified panel configurations are given in Fig. 5, whereas a comparative summary of test results is given in Table 1. Ballistic testing of these panels was conducted at the Hypervelocity Impact Laboratory of McGill University, Montreal, Canada.

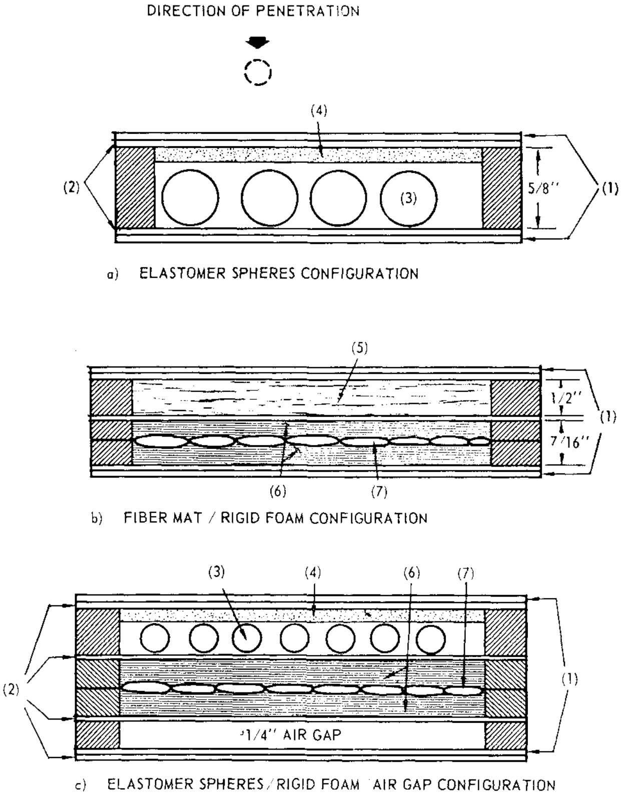
Discussion and Evaluation of High Velocity Test Results

Panel 5a is the lightest configuration (1.43 psf) of those currently evaluated. Although complete sealing (leakage rate of 1.3 lb/day after puncture) was not achieved, good leakage control was obtained in that the leakage rate through the unsealed hole ($\frac{3}{16}$-in.-diam) would have been approximately 600 lb/day.

The advantages of a leak-control system, even though not perfect, may become more evident when one compares the times required (with and without leak control) to decompress a 10,000-ft^3 cabin from 14.7 to 5 psia, a pressure below which the crew could not long survive without increasing the oxygen content of the atmosphere. As indicated in Fig. 6, the punctured panel 5a, without the leak-control feature (elastomer spheres), would decompress the cabin to a dangerous level in 1.3 days (no air augmentation assumed), whereas the self-sealing feature increases this time to 580 days. For those panel concepts in which complete self-sealing is achieved, this time would, of course, be increased indefinitely.

In the construction of each improved panel, the pellet entry face acts as a bumper shield and fragments the impacting particle. In addition, isolating the pellet entry face of panels 5b and 5c from the chemical compartment minimized shock-wave-induced damage to the front face of the panel. Although the nonmetallic rear face sheet of panel 5b is not isolated from the chemical compartment, it has not sustained severe damage at the highest impact velocity currently tested (23,000 fps). This is undoubtedly due to shock-wave attenuation through the thickness of the panel. However, at higher impact velocities, shock-wave attenuation may not be sufficient to prevent excessive damage to the rear face sheet, and it may become necessary to isolate it from the chemical compartment in a manner similar to panel 5c.

A panel similar to Fig. 5c, with the exception that 0.020-in. aluminum face sheets replaced the nonmetallic ones, was tested with a $\frac{1}{8}$-in.-diam steel sphere at an impact velocity of 24,000 fps. A simple puncture (hole) without petalling was produced in the front (entry) face, but the rear (exit) face was severely damaged and petalled (Fig. 7a). For purposes of comparison, Fig. 7b illustrates the damage to the punctured nonmetallic rear face sheet of panel 5c. Post-test examination of the metallic face panel indicated that the projectile



(1) FIBERGLASS EPOXY LAMINATE (3 PLY)
(2) NITRILE RUBBER SHEET (AMS 2312J–1/32" THICK)
(3) EXPANDED NATURAL RUBBER SPHERES (3M–EC–1878 – 3/8" DIA.)
(4) SPONGE RUBBER (1/8" THICK)
(5) ASBESTOS FIBERS (3R12)
(6) RIGID SILICONE FOAM RESIN (XR–6–3700)
(7) FOAMING CATALYST (NUOCURE 28) ENCAPSULATED IN MYLAR PLASTIC BAGS

Fig. 5 Combined system concepts with penetration resistance + self-sealing capability.

momentum transfer to the chemical compartment induced a rearward motion of the flexible chemical compartment wall (nitrile rubber sheet). This permitted the transfer of a distributed high impulsive load to the metallic rear face of the panel (local to the pellet exit hole) which resulted in the outward petaling of the face sheet. This is not surprising, because metals in general are more sensitive than nonmetallics to rapid crack propagation or petaling when subjected to distributed high impulsive loading conditions. Techniques for minimizing this damage, such as increasing the gap between the chemical compartment and metallic rear face (to minimize the impact induced momentum transfer to the rear

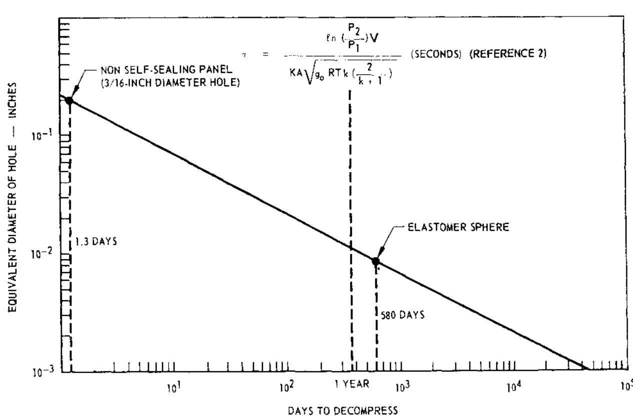


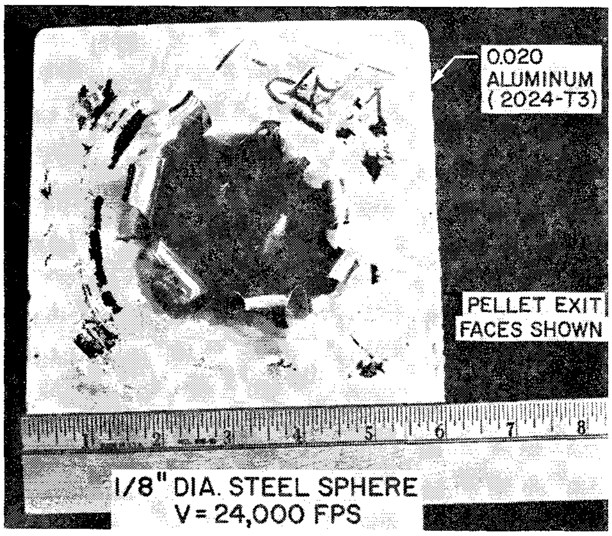
Fig. 6 Decompression of 10,000-ft^3 space vehicle from 14.7 to 5.0 psia: no air augmentation.

face) and improving its crack propagation resistance by laminating with nonmetallics, are currently being investigated.

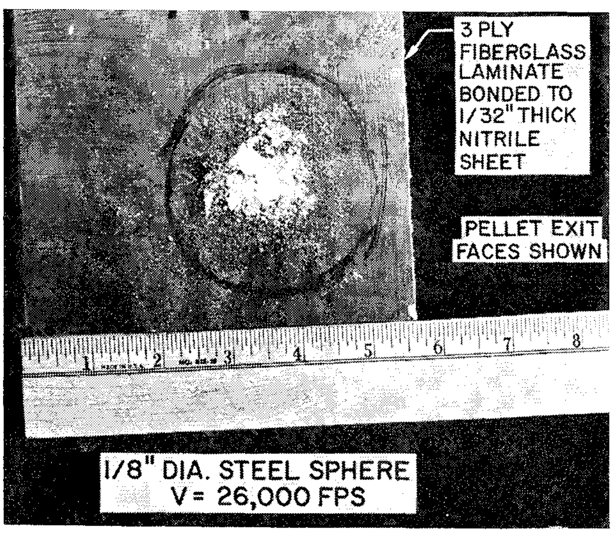
Panel configurations similar to Figs. 5a and 5b, with the exception that metallic face sheets will replace the nonmetallic ones, have yet to be tested at velocities above 20,000 fps. However, it is expected that the front faces of both panels will sustain simple punctures, whereas, due to shock-wave considerations, the metallic pellet exit face of panel 5b will petal. The construction of panel 5a is such as to minimize adverse shock-wave transmission to the rear face sheet. Therefore, for similar ballistic conditions, the metallic rear face of such a panel configuration should be less severely damaged than a metallic rear face of panel 5b.

In reference to the panel unit weights, as given in Table 1, it should be stated that the specimens tested were basically breadboard models, which were tested with the primary purpose of evaluating the various self-sealing concepts and demonstrating their feasibility. No attempt was made to optimize the panels for minimum weight. However, post-examination of the successfully tested panels indicates that they can be substantially reduced in weight without sacrificing their self-sealing capability. The chemically activated concepts in particular have consistently demonstrated an amount of chemical activity, upon panel puncture, in excess of that required to obtain effective sealing. Consequently, it appears reasonable to assume that a panel weight-optimization program will result in panel unit weights more competitive with nonself-sealing structures.

In Ref. 4, a preliminary comparative weight analysis was made between one of the initial self-sealing panels (Fig. 2a) with a unit weight (not including the structural front face of the panel) of 1.7 psf and various other systems for different mission times. The structural requirements were assumed to be satisfied by aluminum skins of thickness varying from 0.020 to 0.100 in. A 1000-ft^2 vulnerable area and a probability of zero penetration of 0.99 were considered. Within the range of structural skin thicknesses considered, the self-sealing system achieved a weight advantage over armor plate for mission times beyond a few days for the 0.020-in. skin or 2 weeks for the 0.100-in. skin. In comparison to an air-replenishment system (in which perforations are accepted, with provisions made for maintaining 14.7 psia without puncture repair), a weight advantage was indicated for mission times beyond 7 days for the 0.020-in. skin or 30 days for the 0.100-in. skin. For a bumper shield concept, in which a weight reduction of 30% over that of a single skin was assumed, a weight advantage by the self-sealing concept was achieved beyond periods of 10 and 90 days for the 0.020- and 0.100-in. skins, respectively. Therefore, within the limitations imposed by the assumptions made and uncertainties associated with the analysis, it can be said that self-sealing composite panels with unit weights (less structural skin) under 2 psf will show a decided weight advantage for mission times beyond a few months duration. Although downward revisions in the assumed meteoroid flux (Whipple's 1963A "best estimate") will increase the mission times required for a weight tradeoff, space vehicles with vulnerable areas greater than 1000 ft^2 will decrease it. Further reduction in weight trade-off times may be made with lower-weight self-sealing configurations and when allowances are made for any contributions to insulation, structure, and penetration resistance that may accrue from the use of self-sealing composites.

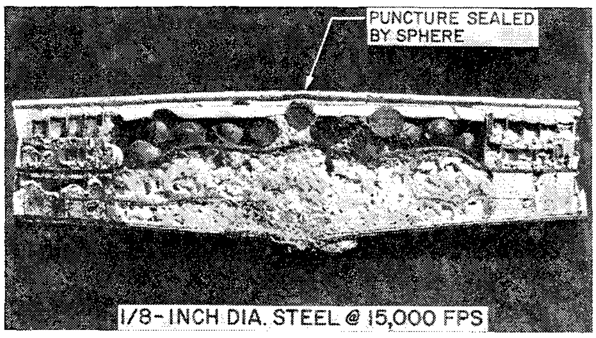


a)

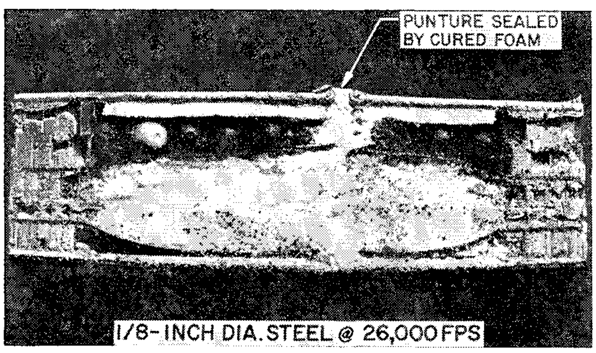


b)

Fig. 7 Comparison of damage to metallic and nonmetallic rear face sheets of self-sealing panels (elastomer spheres/rigid foam/air gap concept).



a)



b)

Fig. 8 Combined elastomer-spheres/rigid-foam concept.

Conclusions and Recommendations

The feasibility of fabricating successful self-sealing panels has been experimentally demonstrated by puncturing panel specimens with $\frac{1}{8}$-in.-diam steel spheres at impact velocities to 26,000 fps. Either mechanically or chemically activated sealing techniques may be successfully employed; however, the most effective technique appears to be a combined mechanical system in which elastomer spheres are used in conjunction with a foaming resin (Fig. 5c). In this concept, either the sphere or the chemical system can effect a seal, as is illustrated in Figs. 8a and 8b. The volume-addition feature (foaming resin) mitigates material loss along the pellet entry path and assists in achieving a complete seal should the elastomer sphere only partially seal the puncture.

Shock-wave damage to the panel face sheets can be minimized by the use of nonmetallic laminates and by isolating them from nearly incompressible materials (liquid chemicals) by air gaps or the interposition of a low-density, highly compressible material. Although metallic front face sheets may be tolerated on the panels evaluated (Fig. 5), shock-wave damage to the rear face sheets may best be controlled by use of nonmetallic laminates. The improved panel configurations (Fig. 5) enhance the penetration resistance of the structure by inducing projectile fragmentation and dispersion of impact-induced particles at the front face of the panel. In addition, some of the components of the combined mechanical-chemical concepts possess multifunctional capabilities in that they may make structural and/or insulative contributions to a space vehicle wall structure. Weight tradeoff considerations indicate that panel unit weights under 2 psf will make self-sealing structures attractive for the larger space vehicles and for mission times exceeding a few months duration.

Recommended areas of activity for furthering the development and evaluation of the self-sealing structure concept should include an investigation of the effects of the space environment on the self-sealing capability of candidate panel configurations and experimental testing with pellet diameters of $\frac{1}{16}$-in. or smaller at impact velocities of 30,000 fps and above. In addition, weight-optimized self-sealing concepts should be developed and integrated into realistic lightweight space vehicle structures with consideration given to fabrication problems, feasibility, and potential areas of space vehicle applications.

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