Self-Sealing Spacecraft Structures

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Approximate system weight comparisons indicate that, for the more ambitious space projects, a structure that provides meteoroid penetration resistance only can impose weight penalties of increasing seriousness as mission times rise beyond several weeks. Structural composites using elastomeric materials reliably demonstrate in the laboratory a capability of self-sealing compatible with system requirements for longer missions. A variety of structural configurations, primarily variations on a honeycomb core concept, successfully sealed following penetrations at speeds from 8000–20,000 fps. Other concepts, such as elastomeric spheres (to seat in damage holes), prestressed (compressed) sealants, and chemical systems, which expand on impact-triggered catalytic or foaming action, show varying degrees of promise.

Introduction

WITH the advent of space excursions of longer duration, the meteoroid environment must receive careful attention. To date, only scant information for significantly lengthy durations is available to compare with existing predictions. The subjects of meteoroid environment observation methods, flux, and distribution have been covered by many investigators (excellent treatments may be obtained in Refs. 1–6), but quantitative evaluations in the form of threshold meteoroid flux vs mass estimates vary widely, as illustrated in Fig. 1. One can appreciate the bewilderment of the designer in the face of such scatter in the data. It must be stated, however, that these estimates represent a variety of detection techniques and assumptions. The most authoritative estimates are attributed to Whipple.[1] The most recent satellite data of Explorer XVI (not presented here) appear to span the gap between the Whipple 1963A and Watson 1941 estimates.

To summarize briefly the implications of the environment, one might say that the greatest danger is expected from the so-called microparticles and that, in view of the existing uncertainties, provisions will have to be made for inadvertent perforation of the structural shell. This latter conclusion is especially applicable to long missions and large vehicle size. Finally, the biomedical aspects of a penetration-induced decompression may require crew response in a matter of seconds following the event.[7] Self-sealing systems with instantaneous response and requiring no extraneous crew monitoring are logically suggested as a means of "designing around" the environment. Since damage prevention and damage control are obviously not substitutive "across-the-board," what are the logical areas of applications? Moreover, can successful self-sealing performance be reliably obtained against hypervelocity impacts? The answers to these and other questions can be found by methodical and rigorous evaluation of various concepts, which by nature must be compatible with the function of the structure.

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Relative Weight Comparisons

One method of observing the utility of self-sealing is to compare the expected weights of various systems for different mission times. Such an analysis has been made for the following systems employing aluminum skins: 1) an air replenishment system with provisions for maintaining a 14.7 psi air atmosphere with no provisions for repair; 2) an armor plate structure with a zero penetration probability $P(0)$, of 0.99; and 3) a self-sealing structural composite. The Whipple 1963A "best estimate" flux data were assumed. The air replenishment system is assumed to have the capacity to replace air at a rate necessary to maintain the specified pressure to offset the predicted loss from hole production flux, with an equipment weight penalty of 40% of the lost mass.[8] Ideal nozzle flow was assumed in calculating the mass loss. The armor-plate concept is applied to a vehicle of 1000 ft^2 of exposed surface area. The penetration relationship selected for ease of computation is that of Rodriquez,[9] which is a generalized form of that of Kornhauser.[10]

The self-sealing systems employ an elastomeric sealant confined in a honeycomb-core sandwich and will be described in detail later. Successful laboratory specimens of this type have been fabricated with a unit weight of 1.7 psi (not in-

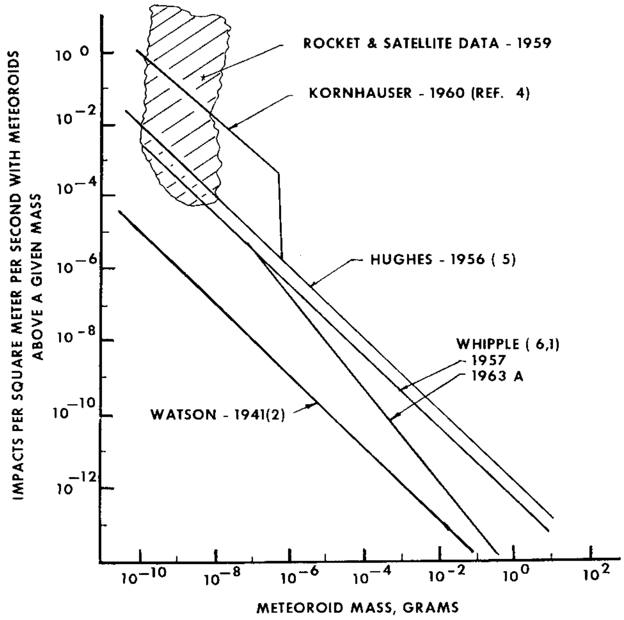

Fig. 1 Meteoroid flux estimates.

cluding the metallic face). This current optimum has been used for the weight analysis.

An average meteoroid velocity and density of 22 km/sec and 0.44 g/cm^3, respectively, taken from Whipple, are assumed. The complete analysis is shown in Fig. 2. The air replenishment concept becomes noncompetitive at mission times beyond 1 month. For times greater than 2 weeks, the 0.100-in. system is actually lighter than its companion 0.020-in.-skin system, since only the less frequent, more massive perforations are experienced. A comparison of armor plate and self-sealing yields interesting results. For the range of sealant constructions between 0.020- and 0.100-in. aluminum face thicknesses, a weight advantage over armor plate is predicted for mission times beyond a period from 2 days to about 2 weeks. Moreover, the 0.020-in. air replenishment concept would still be lighter up to about 2 weeks.

It becomes apparent that the weight tradeoff point for self-sealing configuration occurs for mission times beyond 2 weeks. Hence, for near-earth performance, vehicles could use these structures to a weight advantage, assuming that the particle-flux rate is not significantly altered. Some further optimizations in the self-sealing geometries can be expected, but their effect should not be drastic either. Hence, the weight picture of armor vs self-sealing, as presented here, is considered quite realistic.

The "bumper" concept has not been analyzed here because of the scarcity of data at this time. It can be reasonably stated that considerable weight saving can be effected if one were to apply the laboratory optimums.[11] Indeed, factors of 50% and higher have been reported. However, it is interesting to note that these optimums occur at geometries where a considerable percentage of the total penetrated depth (bumper plus witness plate) is in the rear wall. This situation may be intolerable for cryogenic tankage where the residual energy of penetration (past the bumper) may be severe enough to initiate shock effects in the confined fluid. Applying this further to manned capsules, one needs to be concerned about structural wall-crack formation, with or without a bumper, since a penetration-resistant structure may not necessarily be leak-proof. However, nonoptimum bumpers may be employed. For this reason, a factor of 30% weight savings may be a more realistic assessment of bumper efficiency. With this factor applied directly to the armor-plate curve of Fig. 2, the weight tradeoff for bumper vs self-sealing occurs between 10 days and 3 months for self-sealing configurations using aluminum skins of 0.020- to 0.100-in. thickness for the structural requirement.

The exact numbers discussed in the system weight comparison (Fig. 2) are admittedly open to argument in view of the uncertainties and assumptions mentioned earlier. However, one glaring conclusion remains from this quick look at the various design alternatives. This is that weight advantages for self-sealing accrue only for the so-called longer missions and larger vehicles. Moreover, the comparison does not show how combinations of self-sealing and damage prevention methods may be combined to exhibit weight advantages. This can probably best be shown by analysis for specific design objectives[12] in a tradeoff study.

Sealant Materials and Requirements

In general, sealant materials in this application must satisfy the many requirements imposed upon static seals as to environmental operation. The notable exception here is the response to hypervelocity impact. A layer of sealant material, upon being impacted, is subjected to volumetric compressions resulting in shock pressures that can easily reach the megabar range (a situation akin to the impact of metals). Upon complete perforation, the shock history results in fracture and tearout of the elastomer (in the case of a solid) which must be minimized. The use of liquid polymers as sealants, which cure or harden in a process activated by impact, poses unique problems owing to the incompressibility of the material. In the cases of both liquid and solid usage, a desire to achieve a viscous response to effect hole closure aggravates the shock by introducing incompressibility. Hence, means must be provided to reduce shock pressures in the sealant. Here, theory suggests the use of extremely low-density self-sealing elastomers. Also, a confining structure must be provided which attenuates the shock which ultimately "feeds" into the sealant. Figures 3 and 4 show the impact and exit faces, respectively, of a perforated panel consisting of aluminum face sheets confining a layer of solid elastomer. The remarkable degree of recovery is evident following the 7000 fps perforation. However, the absence of sufficient attenuation results in a rather undesirable exit face damage, which is aggravated at higher impact speeds.

This attention to composite structures suggests a multifunction aspect of self-sealing. The use of elastomers for specific radiation shielding applications has received some attention. The requirement for thermal insulation certainly appears to be compatible with the need for shock attenuation, not

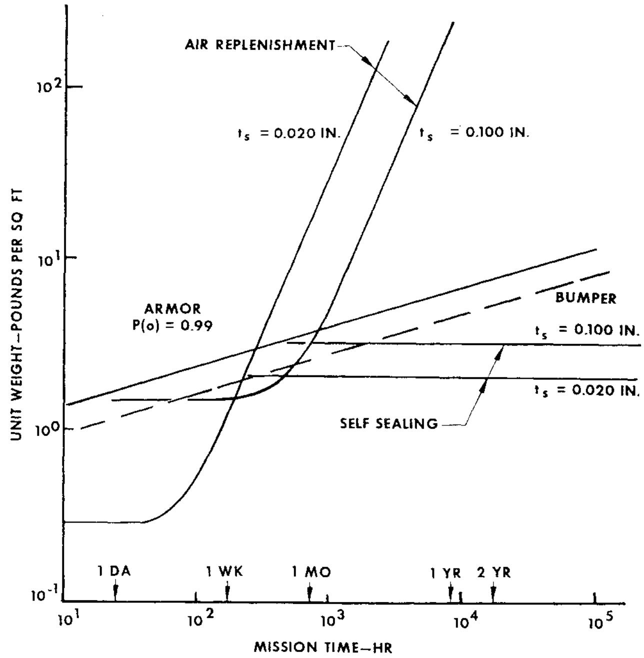

Fig. 2 System weight comparison.

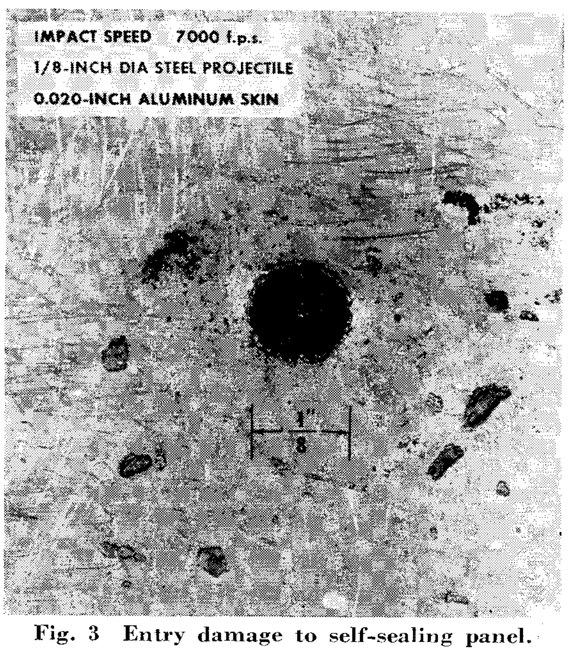

Fig. 3 Entry damage to self-sealing panel.

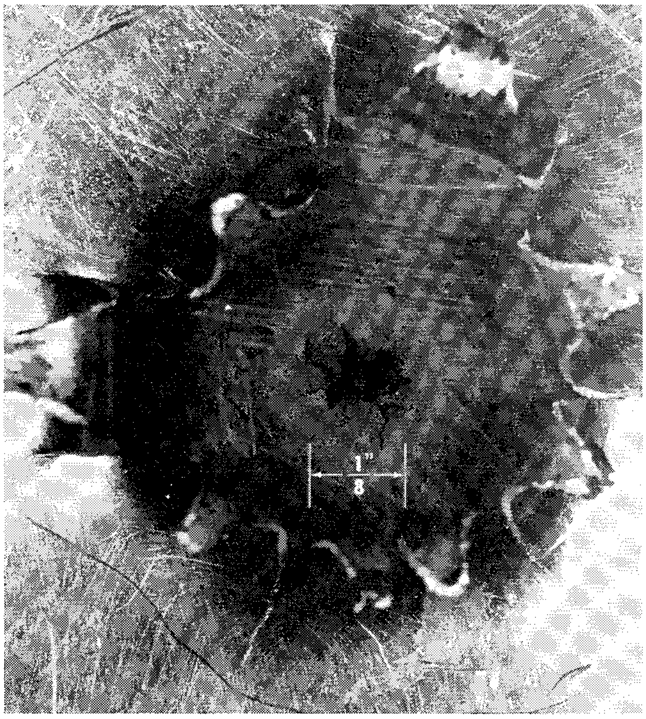

Fig. 4 Exit damage to aluminum rear wall.

only in self-sealing, but also as a core material in meteoroid bumper structures.

Initial firings were conducted into unsupported disks of cured sealant materials at moderate velocities to observe isolated response. A variety of responses was noted depending on the material used. Figure 5 shows typical surface damage in what is considered a brittle silicone rubber. (Where possible, a circular grid was molded onto the surface of the disk to monitor surface strains.) Figure 6 shows the identical situation for a highly successful polysulfide sealant. The cross-sectional view of a perforation in a $\frac{1}{4}$-in. silicone rubber is shown in Fig. 7. The displacement of the material back along the pellet direction cannot be explained in terms of wave theory. One simple explanation is that the short-duration heat pulse, upon puncturing, melts the surrounding material, and the subsequent air flow across the slab initially forces material back along the particle path. In any event, this displacement of the material back into the hole assists the sealing process.

Another evaluation technique involved the controlled sinusoidal excitation of sealants and the determination of elastic (recovery) and dissipative (loss) properties. Using conventional electrodynamic shakers to determine the properties, a positive correlation was observed between high-loss characteristics and successful self-sealing capability.

Survey of Self-Sealing Concepts

All of the concepts discussed here were initially subjected to perforations at 7000–8000 fps. Lead, steel, and glass projectiles of $\frac{1}{8}$-in. diam were used. The particle accelerator range was evacuated to approximately 200 μ for each shot. The exit side of the specimens were exposed to ambient conditions, so that sealing was being observed across essentially a 14.7 psi pressure differential. Immediately after firing, sealing was qualitatively checked by ear. Following this, leakage rates from a known volume container over a spectrum of pressure differentials were measured using laboratory-type flowmeters. Further testing of the more promising configurations was then conducted at hypervelocity facilities at velocities of 20,000 fps. The conventional sealant materials initially investigated included commercially available products, such as the General Electric room temperature vulcanizing (RTV) series materials in both liquid and cured form.

The Honeycomb-Core Sealant Concept

The basic configuration is shown in Fig. 8. It consists of a metallic face sheet and a reinforced neoprene backstrip confining a phenolic fiberglass honeycomb core. The core is filled with the sealant, and proper surface treatments are used to insure good sealant-to-core and -face bonding. A rubber backup strip, with a good bond to the core-sealant, seems to be a necessity. Early experiments, which included shots into panels with metallic rear faces, exhibited severe damage on the pellet exit side (see Fig. 4). In most cases, sealant material local to this area was also observed to be severely damaged, and hole closure was not achieved. When neoprene was

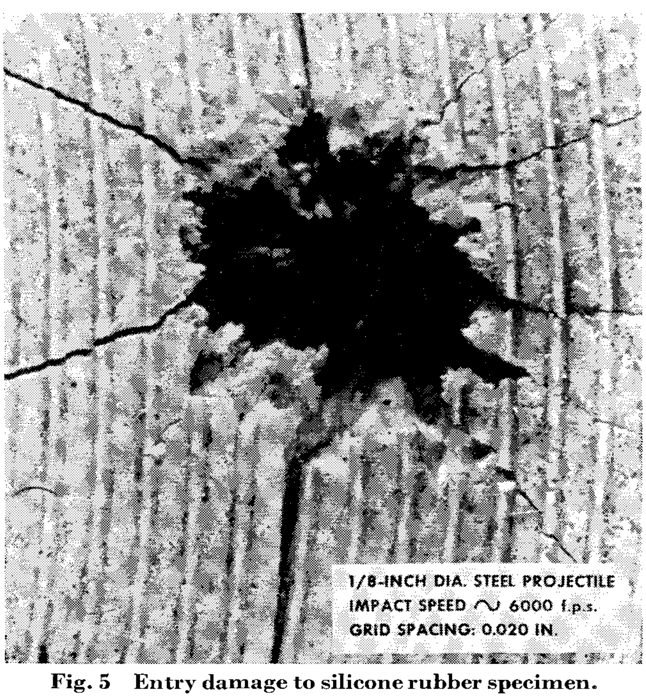

Fig. 5 Entry damage to silicone rubber specimen.

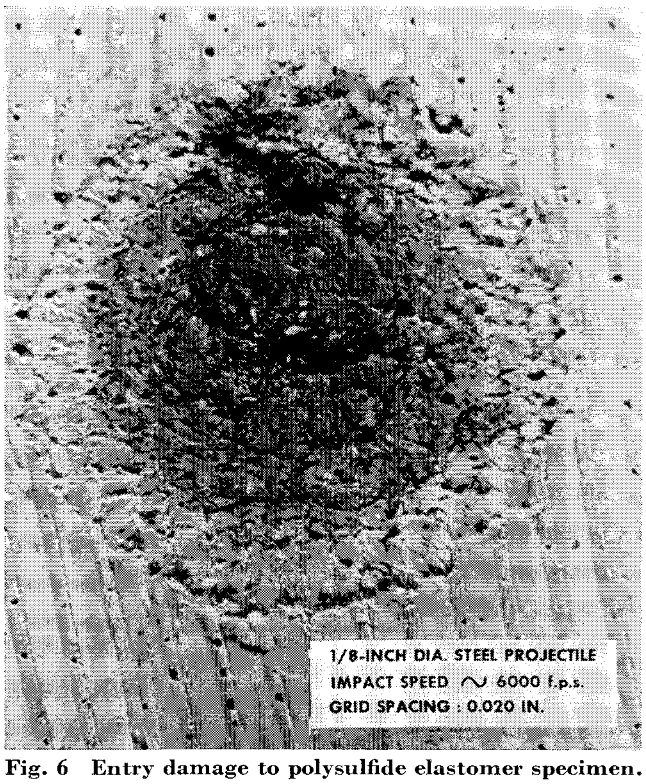

Fig. 6 Entry damage to polysulfide elastomer specimen.

substituted, immediate improvement was observed in the form of decreased deformation of the backup sheet and adjacent sealant. Since the area bounded by the backup strip represents a free surface with expected shock-wave reinforcement due to reflection, it is apparent that a dissipative material is required. The resiliency of the neoprene further permits recovery from radial deformations due to the passage of the particle and enhances hole closure.

The function of the honeycomb core is to contain the sealant and provide damage confinement through the addition of bonding surfaces in the sealant volume. However, aluminum honeycomb geometries exhibited massive damage. Radial collapse of the cell walls as much as twelve times the projectile diameter, with attendant sealant damage, was observed. Again, the need for a more dissipative material was apparent. The use of phenolic fiberglass core, with attention to maintaining good core-to-sealant bonding, was seen to greatly alleviate the damage. Subsequent firings resulted in little or no core damage, and localization was achieved.

A highly successful configuration consists of a 0.020-in. aluminum face, $\frac{3}{16}$-in.-thick core, with $\frac{3}{16}$- or $\frac{1}{4}$-in. cells filled with a polysulfide elastomer, and a $\frac{1}{16}$-in. fiber-reinforced neoprene backup sheet. The self-sealing weight contribution is 1.7 psf, and the over-all weight is approximately 2.0 psf. Best results are observed when the bonding agents used are the same material as that of the sealant. Since all tests were conducted with $\frac{1}{8}$-in.-diam projectiles, it is conceivable that some further weight reduction may be achieved with more realistic (viz., smaller) projectile sizes.

Isolation of the sealant layer from the metallic face sheets greatly improves self-sealing performance at the hypervelocities. This improvement in performance, which can be explained qualitatively in terms of shock-wave theory, can be accomplished by the interposition of a low-density layer. Again, a multipurpose aspect of these composite structures is suggested.

An example of successful self-sealing following a 20,000 fps penetration in the mechanical configuration is shown in Fig. 9. The backup sheet has been pulled back to show the localized interior damage. In every instance shown, the sealant material is seen to be deposited in the entrant hole, and the exit damage is quite remarkably localized.

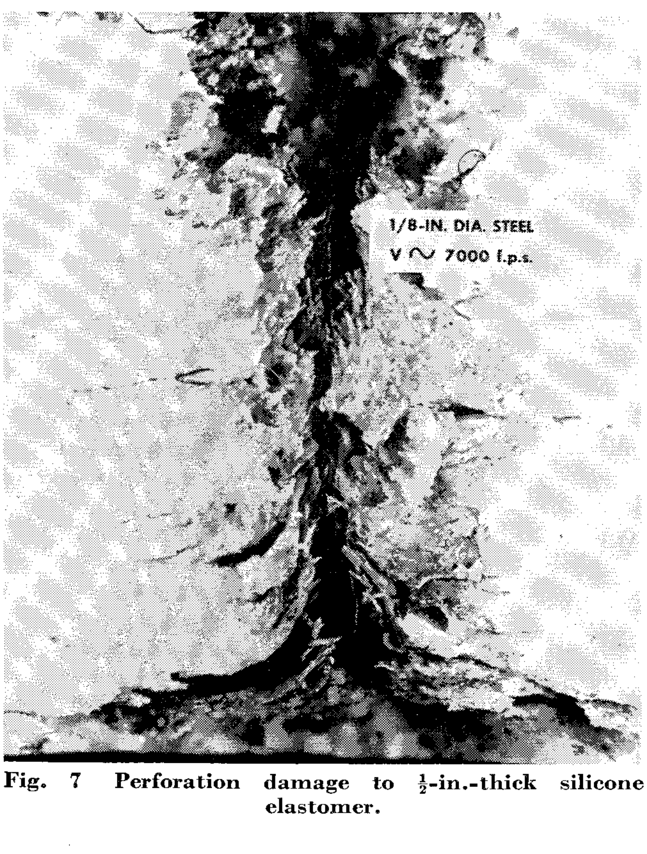

Fig. 7 Perforation damage to $\frac{1}{2}$-in.-thick silicone elastomer.

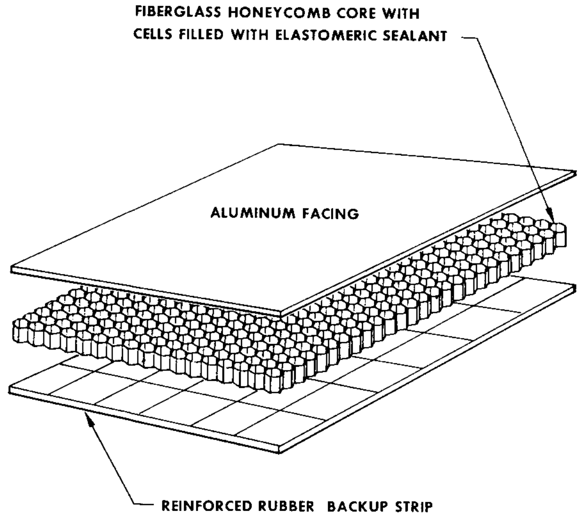

Fig. 8 Basic honeycomb-core self-sealing concept.

Residual leakage rates for the successful panels were measured by observing the pressure drop from a known volume container capped with the penetrated specimens. Leakage rates as low as 2.0 lb/yr to zero have been observed. Average leakage rates have been found to be on the order of 1 to 2 lb/day, which is an improvement of better than 99% over the observed rates through the penetrated aluminum face sheet hole. In many instances, the specimens showed a detectable leakage rate across a 14.7 psi pressure differential, but exhibited almost complete sealing at 4 to 5 psi internal pressures.

Elastomeric Sphere Concept

The concept just described relies on both the energy dissipation and the recovery of the sealant material for successful operation. For extremely localized damage, the recovery of the material in the domain of infinitesimal deformations is utilized to effect hole closure. It is conceivable that, under certain environmental conditions and with massive face sheet and sealant damage or tearout, macromotion of the

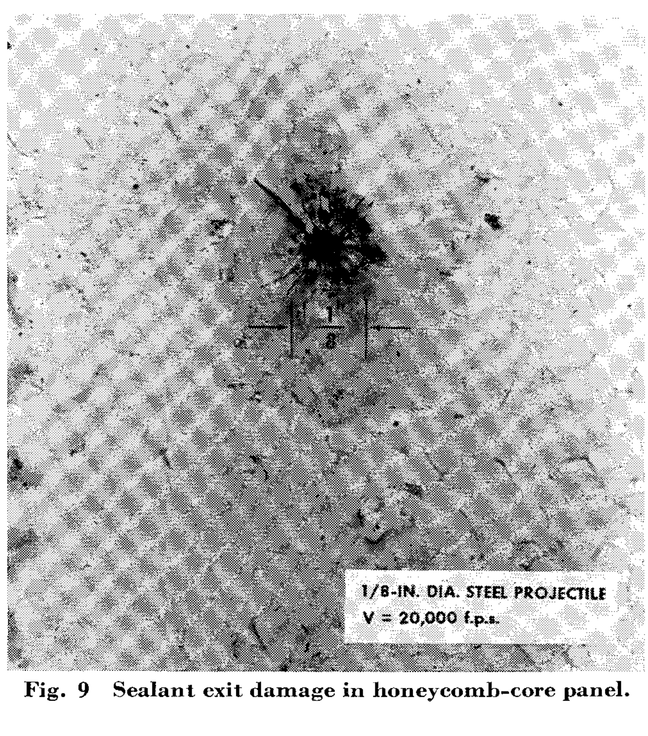

Fig. 9 Sealant exit damage in honeycomb-core panel.

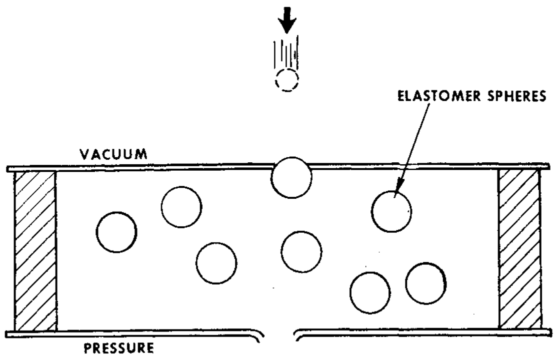

Fig. 10 Elastomeric spheres self-sealing concept.

sealant into the perforated zone will be required. For this reason, the elastomeric sphere concept was investigated. Here, the conventional sealant is replaced by discreet elastomeric spheres to a predetermined packing density (see Fig. 10). Upon penetration, the pressure differential between the inside cabin and the vacuum of space forces the balls toward the entrant hole and effects the sealing. Ball size, packing density, and material will control the mobility of the spheres and the sealability. This concept exhibited residual leakage rates that are comparable with the mechanical system described earlier.

Other Systems

A number of alternate concepts, developed to fit a variety of requirements, have been successfully tested. They may be classed as mechanical or chemical depending on the mode of activating the sealing process. One highly successful approach is to prestress the sealant in compression. This enhances the sealability of materials which have desirable thermal or vacuum properties but which exhibit brittle-type fractures or low-shear strength characteristics under dynamic conditions when simply confined. The relatively low-modulus characteristics of the elastomers facilitate the buildup of moderate internal stresses with appreciable strain recovery in the penetration hole. The prestressing can be accomplished in a variety of simple and ingenious ways.

One prestressing technique uses an elastomer and foaming reagent that causes an unconfined volume expansion of 200 to 300% upon curing. The structural panel is filled with the uncured sealant compound to a volume fraction that will produce a desired prestress level. Face plate bonding is accomplished with a material whose softening point is above the cure temperature of the sealant. The sealant is then cured at the required heat. This technique has shown successful sealing characteristics with a high degree of reliability but is limited to situations when material tearout is minimal.

Chemical concepts rely on the dynamic action of the penetrating particle to initiate a reaction that closes the hole. In one concept, shown in Fig. 11, an uncured polymer is separated from the catalyst by a thin, nonreactive membrane. Upon complete perforation, the pressure differential across the panel forces a mixture of polymer and catalyst through the hole. Very fast curing mixtures have been used with complete and repeatable sealing action. In another method, small bags of catalyst are interspersed in the sealant void (see Fig. 12). This seems to localize the curing action to the area of the penetration. Bag size is an important factor in this method. For very uniform distribution of the catalyst in the uncured elastomer, microencapsulation techniques can be adopted. In all of the chemical concepts where the sealant materials are initially fluid, careful attention must be given to the rheological or flow properties of the polymer. The viscosity of the material must permit an initial gradual flow through the hole without excessive loss. Cure rate must obviously be rapid enough to "set up" the material in the hole. Environmental stability must be carefully considered against mission time, since degradation can severely alter flow rates and, hence, sealability.

The more recently developed foam systems provide massive volume addition in case of extreme damage. Here, both rigid and flexible formulations, activated upon penetration and providing volume expansions of ten or greater, have exhibited superior self-sealing capability in the laboratory. In conjunction with the proper confining structure and with the development of long shelf life, the use of rapidly activated foams as self-sealants is extremely encouraging.

Conclusions and Recommendations

The need for self-sealing structural systems has been described in view of the many uncertainties in the meteoroid environment assessment. Practical and successful self-sealing composite structures have been developed in the laboratory which can provide a greater degree of safety with the added feature of self-repair to minimize crew responsibility. Weight considerations appear attractive for the longer excursions and larger vehicles, where the term "longer" applies by present calculations to mission durations beyond 2 to 4 weeks.

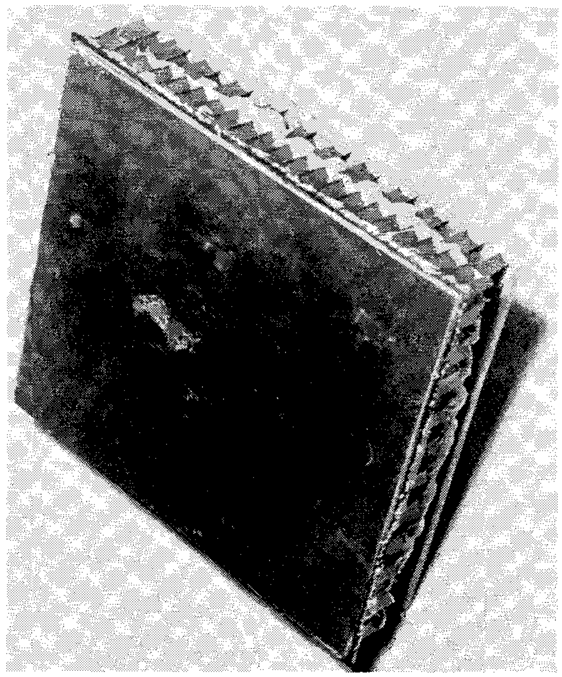

Fig. 11 Chemical membrane concept.

As armor and self-sealing structures obviously cannot be discussed as competing systems, the use of the latter may at first appear restrictive. However, for specific vehicles areas with a low frequency of occupancy (e.g., passageways, airlocks, etc. . .), weight tradeoffs may well favor the use of self-sealing structures per se, or as a complement to a modified protective system. This marriage of applications highlights the multifunctional aspects of the use of elastomers in composite structures, wherein thermal and radiation protection may be encompassed.

The development of successful self-sealing structures has, to date, been achieved through the combined efforts of both the chemist and the engineer. Careful attention to the rheological properties of sealants in both liquid and solid state is required. Material behavior in the space environment of vacuum and radiation exposure will merit continued and intensive scrutiny. The design of the compatible enclosing structures for the sealant is extremely important to reliable

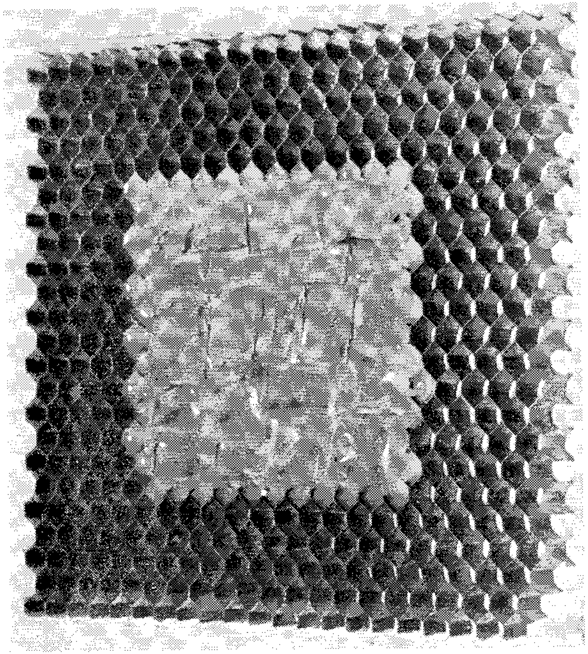

Fig. 12 Chemical bag concept.

performance at impact speeds of 20,000 fps. Finally, successful performance at speeds beyond this range and into the meteoroid regime is still required and will receive further study.

References

[1] Whipple, F. L., "On meteoroids and penetration," Ninth Annual American Astronautical Society Meeting, Los Angeles, Calif. (January 1963).

[2] Watson, F. G., *Between the Planets* (Harvard University Press, Cambridge, Mass., 1956), pp. 75–110.

[3] Krinov, E. L., "Principles of meteorites," *International Series of Monographs On Earth Sciences* (Pergamon Press, New York, 1960), Vol. 7, pp. 32–186.

[4] Kornhauser, M., "Current estimates of the effects of meteoroids on the skin of a satellite vehicle," ASVE Memo. 3, Missile and Space Dept., General Electric Co. (February 1960).

[5] Hughes, R. F., "Meteoroid impacts and their effects on ballistic missiles," Real Gas Tech. Memo. 13 (July 1956).

[6] Whipple, F. L., "The meteoric risk to space vehicles," *Vistas In Astronautics* (Pergamon Press, New York, 1958), pp. 115–124.

[7] Konecci, E. B., "Decompression events in biosatellites," ARS Paper 638-58 (June 1958).

[8] Carter, J. W. and Bogema, B. L., "Inflatable manned orbital vehicles," *Proceedings of the Manned Space Stations Symposium* (Institute of the Aerospace Sciences, New York, 1960), pp. 188–196.

[9] Rodriquez, D., "Meteoroid shielding for space vehicles," Aerospace Eng. **19**, 20 (December 1960).

[10] Kornhauser, M., "Prediction of cratering by meteoroid impacts," *Proceedings of Fourth Annual Meeting of the American Astronautical Society* (Plenum Press, Inc., New York, 1958), p. 179.

[11] Wallace, R. R., Vinson, J. R., and Kornhauser, M., "Effects of hypervelocity particles on shielded structures," ARS Paper 1683-61 (1961).

[12] D'Anna, P. J., "A combined system concept for control of the meteoroid hazard to space vehicles," AIAA Paper 63-196 (June 1963).