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Development of Meteoroid Protection for Extravehicular-Activity Space Suits

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The space suit used during extravehicular activities requires meteoroid protection to prevent perforation of the pressure bladder. The development of protective coverlayers for the Gemini and lunar-surface extravehicular activity (EVA) suits is described. The meteoroid mass, which must be absorbed in the coverlayer to satisfy the mission exposure time and the reliability requirements, was simulated by a hypervelocity glass projectile of equal penetrating energy. Textiles or "soft goods" that were compatible with suit fabrication techniques were impacted with the laboratory projectile to determine response to impact and resistance to penetration. An effective projectile breakup was achieved with nylon cloth; therefore, the bumper concept that was developed previously for metallic sheets was applied to the suit protection. Two configurations were developed, one of which used nylon felt and the other used neoprene as the primary energy absorber. The configurations provide an acceptable probability of no bladder perforations during a 24-hr exposure with an areal density less than 0.10 g/cm².

Introduction

EXTRAVEHICULAR activity (EVA) exposes an astronaut's space suit to the meteoroid environment for short periods. To prevent meteoroid penetration of the pressure bladder and subsequent decompression of the space suit, protection must be provided to absorb meteoroid impacts. Several techniques and methods for preventing puncture of the bladder were considered. Parameters such as weight, astronaut mobility in a pressurized suit, thermal protection, ease of fabrication, astronaut comfort, and schedules eliminated metallics and required that the protective coverlayer be compatible with the intravehicular suit. The short leadtime that was available for design of a Gemini protective coverlayer and the lack of information concerning hypervelocity impact into textile materials (soft goods) precluded extensive analytical studies to determine optimum materials and layup. Therefore, an engineering-design approach was taken, and the experimental impact tests were confined to textiles that were used or approved for fabrication of intravehicular space suits. The acceptable materials from the preliminary tests then were evaluated ex-

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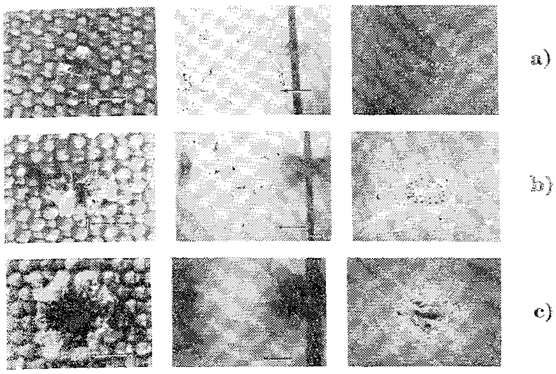


Fig. 1 Breakup and dispersion of a) 0.037-, b) 0.079-, and c) 0.157-cm-diam Pyrex spheres by nylon-cloth bumper. Bumper damage, projectile dispersion, and witness plate damage pattern are shown for each size: 1) bumper, 0.023-g/cm² nylon cloth (arrow indicates distance of 1/16 in.); 2) projectile passing through bumper ($V \simeq 7.4$ km/sec, $s = 12.7$ cm); 3) witness plate, 1100-0 aluminum.

perimentally in various layups that satisfied minimum areal density, astronaut mobility, and comfort requirements.

Two coverlayers resulted from the program. One was used on the first EVA (Gemini IV), and the other was used on all subsequent Gemini EVA flights and is applicable to lunar surface EVA. The near-earth meteoroid hazard to space suits, the hypervelocity impact experiments, and the meteoroid protective garments that resulted from the tests are presented in this paper.

Meteoroid Environment and Hazard

The model meteoroid environment used for design of the Gemini space suit has been documented.[1] The distribution of meteoroids in near-earth space is defined by the general equation

$$N = \alpha m^{\beta} \tag{1}$$

where N is the accumulative number of meteoroids per unit area per unit time of mass m and greater, and m is the mass of the meteoroid. The constants α and β are determined by experimental measurements and are evaluated for the sporadic meteoroids as $\alpha = 4.7 \times 10^{-15}$ (particles/m²-sec) and $\beta = -1.34$.[1] The average velocity and average density of the meteoroid environment model are 30 km/sec and 0.5 g/cm³, respectively.[1]

The meteoroid flux increases periodically because of passage of the earth through old comet orbits. The earth encounters several meteoroid streams annually, with the largest flux increase occurring in November.[1] The first meteoroid coverlayer was designed to provide protection during the worst stream period to avoid constraints on mission flight dates. However, the radar meteor data[2] and the Pegasus meteoroid penetration detectors[3] showed that there was no significant increase in the hazard because of meteoroid streams for masses less than 10^{-5} g. The probability of no penetration of the bladder of the space suit is

$$P_0 = e^{-NA\tau\eta k} \tag{2}$$

where A is the surface area of suit (2.32 m²), k is the confidence factor, η is the shielding of suit by earth (0.63), and τ is the length of exposure (8100 sec). The numerical values in parentheses are the design parameters for Gemini. We require $P_0 = 0.999$ with $k = 1.0$.

The design meteoroid mass m for a mission is obtained by combining Eqs. (1) and (2),

$$m = (\ln P_0/\alpha A\tau\eta k)^{1/\beta} \tag{3}$$

The resulting m, combined with the average velocity (30 km/sec) and the average density (0.5 g/cm³; spherical particle is assumed), gives the meteoroid energy that must be absorbed by the protective layers.

Experimental Simulation

An accelerated-reservoir light-gas gun was used to launch glass spheres to velocities of 6 to 7 km/sec. Glass is considered to be the best material available to simulate meteoroid penetration at hypervelocity. Low-density frangible materials will not withstand the stresses of acceleration to hypervelocity. Extrapolation to the EVA environment is accomplished by requiring that the laboratory projectile and the meteoroid that is simulated penetrate the same depth in identical targets. An empirical penetration equation that was developed for aluminum targets is used for the extrapolation,[4]

$$P = kd^{19/18}(\rho_p/\rho_t)^{1/2}(V_p/C_t)^{2/3} \tag{4}$$

where P is the penetration depth of projectile, d is the diameter of projectile, k is the constant depending on target properties and thickness, V_p is the velocity of impacting projectile, C_t is the acoustic velocity in the target material, ρ_p is the density of projectile, and ρ_t is the density of target material. By requiring that $P_m = P_p$, where the subscripts m and p denote the meteoroid and the laboratory projectile, and by assuming that the projectile and the meteoroid are spherical, the following relationship results:

$$m_m = (\rho_p/\rho_m)^{0.421}(V_p/V_m)^{1.895}m_p \tag{5}$$

Protection Development

When the protective coverlayer design effort was initiated in 1964, a literature search revealed that no applicable hypervelocity impact work had been done with soft goods except on nonrigid space structures by Reynolds and Emmons.[5] This work indicated that a woven cloth would shatter the projectile in much the same manner as a metallic bumper.[6] The dual-sheet bumper was the most efficient method of attenuating hypervelocity impact; therefore, this concept also was used for the protective coverlayer design. The first step was to evaluate the ability of thin layers of candidate nonmetallic materials to shatter the projectile and disperse the energy (per unit area) impacting the second sheet. The impact energy was confined to 0.5 to 5 joules, which simulates the meteoroid energy that must be absorbed by the coverlayer for the EVA exposure times.

The bumper effectiveness of each of the nonmetallic materials in Table 1 was evaluated by impacting one or more layers of the material with the simulated meteoroid. The projectile breakup and dispersion was determined qualitatively by measuring the depth and area of impact damage in an aluminum witness plate placed 12.7 cm down range from the bumper. The breakup and dispersion of spherical glass projectiles as the projectiles pass through nylon cloth is shown in Fig. 1. The performance is similar to metal bumpers, but less damaging debris is ejected from the cloth. The efficiency of the cloth bumper is greatly influenced by the thread size

Table 1 Nonmetallic materials tested for bumper effectiveness

Woven materials	Sheet plastics
Teflon	Polyethylene
Nomex nylon	Nylon
Fiber glass	Mylar
Dacron	Polycarbonate
Plastic-coated Nomex nylon	

and the weave. The projectile breakup and dispersion is a function of the bumper areal density at the point of impact. The projectile can impact one thread, two threads, or an interstice which causes data scatter. If the projectile diameter is equal to or less than the thread diameter, the data scatter increases. Also, if the weave is loose, the homogeneity and average areal density of the bumper are decreased.

The homogeneous sheet polymers in Table 1 are equal to the cloth as bumpers and eliminate the data scatter, but are unsuitable for "soft" suit fabrication. Nylon cloth coated with a polymer is superior to the uncoated cloth, but the increased stiffness adversely affects the mobility, and the coated cloth could not be used.

Woven materials of equal areal density have comparable bumper effectiveness; however, teflon and fiber glass were eliminated from further consideration. Teflon could not be easily adapted to suit fabrication techniques and the abrasion resistance of the available fiber glass cloth was insufficient. A 0.023 g/cm^2 nylon cloth (Nomex) was the exterior layer of the Gemini intravehicular suit and was therefore more acceptable than dacron. Although the areal density of the cloth was not optimized for the impact energy, it was an effective bumper and was selected as the exterior layer of the meteoroid protective coverlayer.

The second step was to achieve a constant spacing between the bumper and the second layer over the flexible suit area without affecting astronaut mobility. The materials in Table 2 were tested in combination with the nylon-cloth bumper to determine the most efficient absorber. The efficiency of the bumper absorber was evaluated qualitatively with an aluminum witness plate. A constant spacing between layers was most easily obtained with a foam or felt. These materials were also effective as a "mechanical" atmosphere to absorb energy from the expanding debris cloud. The felt was the best material for suit fabrication techniques and also offered some thermal insulation. The Nomex felt was a more efficient energy absorber than wool or teflon; therefore, a 0.03-cm-thick Nomex felt with one needle pass for low areal density (0.027 g/cm^2) was selected as the spacer-absorber layer.

The last step was to provide a backup layer to the configuration for reinforcement and to absorb any solid particles that filter through the felt. Two layers of 0.023 g/cm^2 nylon cloth supplied strength and additional areal density.

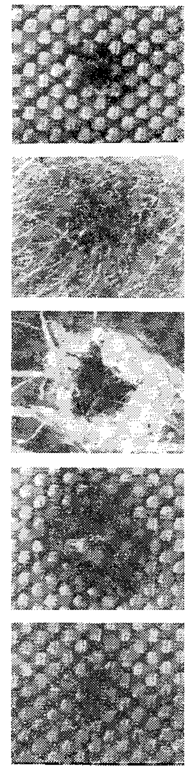
A thermal insulation, consisting of seven layers of aluminized Mylar 6.35×10^{-4} cm thick and separated by Dacron scrim, was added behind the felt. Although the insulation weighed 0.019 g/cm^2, no increase in protection was detected.

The suit layup was qualified for a 135-min exposure in near-earth orbit. To simulate flight conditions during the test, swatches of the layup were pressurized to 3.7 psia with oxygen and then impacted with projectiles, the energy of which was 8×10^6 ergs. The hypervelocity impact damage to each layer is shown in Fig. 2. This protective coverlayer weighs 0.096 g/cm^2 and was used on the first Gemini EVA mission (Gemini IV) but was considered too bulky for astronaut comfort and mobility.

A design modification program was undertaken to eliminate the bulk while maintaining the same reliability. Since the felt was contributing the greatest bulk, the felt was eliminated first. Without the spacing to decrease the energy (per unit area) that strikes the second layer, it was necessary to increase the areal density to absorb the same impact energy.

Table 2 Materials tested as spacer absorber

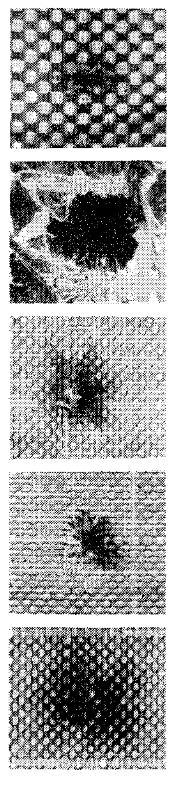
Polyurethane foam
Teflon felt
Nomex nylon felt
Wool felt
Ballistic nylon cloth
Open weave monofilament nylon



a) b) c) d) e)

Fig. 2 Impact damage to each layer of the EVA suit with nylon as the primary absorber (projectile: glass, 0.051-cm-diam, 6.30 km/sec): a) first layer, 0.023-g/cm^2 nylon cloth; b) second layer, 0.027-g/-cm^2 nylon felt; c) third layer, thermal insulation of seven layers, 0.00064-cm-thick mylar, 0.019 g/-cm^2; d) fourth layer, 0.023-g/cm^2 nylon cloth; e) fifth layer, 0.023-g/cm^2 nylon cloth.

The pressure bladder used in the suit is neoprene bonded to nylon ripstop (parachute material). The ripstop weighs 0.007 g/cm^2, and the neoprene weighs approximately 0.019 g/cm^2 with a total thickness of 0.025 cm. Hypervelocity impact tests with glass projectiles of 0.041 to 0.051 cm diam proved that two layers of this bladder material behind the nylon-cloth bumper provided the same protection as the nylon felt and the two layers of nylon cloth that were previously used. The result was a slightly lighter layup (0.075 g/cm^2) of considerably less bulk and with acceptable mobility. The thermal insulation was added behind the bumper layer to protect the neoprene from the extreme cold and also to take



a) b) c) d) e)

Fig. 3 Impact damage to each layer of the EVA suit with the neoprene bladder material as primary absorber (projectile: Pyrex, 0.044-cm diam, 7.25 km/sec): a) first layer, 0.023 g/cm^2 nylon cloth; b) second layer, thermal insulation of seven layers, 0.00064-cm Mylar, 0.019 g/-cm^2; c) third layer, meteoroid protection neoprene on ripstop, 0.025 g/cm^2; d) fourth layer, meteoroid protection neoprene on ripstop, 0.025 g/cm^2; e) fifth layer, pressure bladder neoprene on ripstop, 0.025 g/-cm^2.

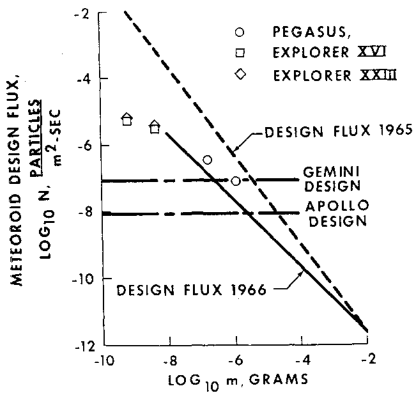


Fig. 4 Meteoroid design flux used for Gemini and Apollo EVA space suits.

advantage of any spacing that might be provided. The meteoroid protective coverlayer shown in Fig. 3 was used on the Gemini VIII mission and all subsequent Gemini extravehicular activities.

The greater efficiency of the bladder material for absorbing hypervelocity impact is attributed to the homogeneous and nonporous nature of the neoprene. The nylon-cloth bumper does not completely vaporize the projectile, and small projectile fragments pass through the porous nylon felt and cloth combination and perforate the pressure bladder; but the higher density, compact neoprene absorbs the fragments.

During the Gemini development period, an Apollo lunar-surface EVA suit also was being developed. The meteoroid design energy[1] for the Apollo exposure of 24 hr is simulated by a glass sphere of 0.16 cm diam at light-gas gun velocities. The layup required to absorb this energy is as much as $2\frac{1}{2}$ cm thick for lightweight materials and is totally unacceptable for a space suit. Fortunately, the Pegasus and Explorer satellites measured a lower meteoroid penetration flux[4] than was used for design of the Gemini protection. The decrease in penetration hazard (Fig. 4) was sufficient to use the previously developed Gemini suit protection and still achieve an acceptable probability of no meteoroid penetrations during the lunar surface EVA.[7] The Apollo suit has been redesigned because of other environmental factors to make the outer layers fire resistant. The general layup remained the same, but the exterior materials were changed to an improved fiber glass (Super Beta Cloth) and Kapton thermal insulation.

Conclusions and Recommendations

A meteoroid protective garment with acceptable mobility can be fabricated from textiles that will provide adequate protection for 24 hr or less space exposures. The development testing also demonstrated that nonmetallics provide more efficient hypervelocity impact attenuation than aluminum and can be adapted to meteoroid protection of space hardware other than EVA space suits.

These test data were generated in a relatively low-impact energy range and extrapolation to more hazardous missions is risky; however, it is apparent that the increase in bulk required will further restrict mobility. The constant volume or "hard" space suit currently under development will provide more meteoroid protection for the longer exposures with no decrease in mobility. The same bumper type configuration can be designed into the suit and the recently developed filament reinforced materials will provide the high-strength and light-weight that is required for efficient protection.

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