fatigue strength of the sprayed plate specimens is only about half that of the bare ones. The static tests showed that the coating did not add to the strength of the base material. As illustrated in Fig. 5, metallographic examination of a few specimens revealed that fatigue cracks sometimes formed in the base metal without penetrating into the sprayed coating. Therefore, it would seem that the coating was not detrimental per se, but that the reduction in fatigue strength was caused by the notches produced by surface blasting in preparation for the coating. The spray-coated box girders had only slightly shorter lives than those of the comparably stressed bare girders, and there is little difference between the curves for the girders and the curve for the sprayed axial-stress specimens. Generally, the girder failures were initiated at rivet holes in the cover plates subjected to tensile stress. However, two sprayed girder failures were confined to the center section of a cover plate and did not involve a rivet hole. Consequently, it appears that the notches resulting from the surface blasting of the material before spraying were almost as severe as riveted construction.

Conclusions

Alclad specimens were found to have lower fatigue strengths than bare specimens in both sheet flexure and axial-stress fatigue tests. The reduction of the fatigue strength due to the cladding was as much as 50% for 7075-T6 and 33% for 2024-T3. The use of a sprayed coating on alloy 2014-T4 decreased the fatigue strength of axial-stress specimens about as much as did the cladding of the 7075-T6 material. However, the stress raisers present in riveted construction overshadowed the effect of the coatings, so that there was little difference in the fatigue strengths of beams and joints fabricated of bare and clad materials.

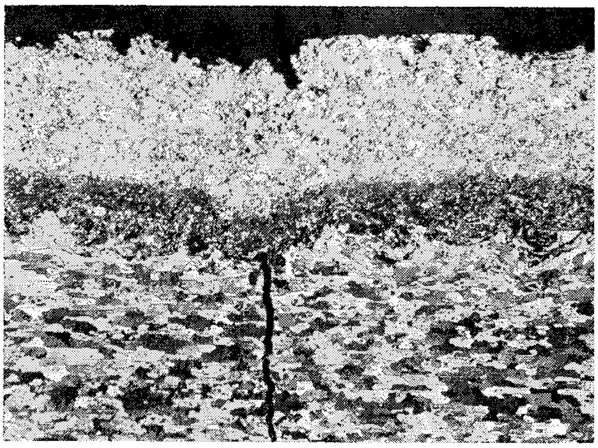

Fig. 5 Fatigue crack in base metal of spray-coated plate.

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Manned Space Station Orbiting in the Van Allen Belt

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The basic requirement for the design of the hull structure of a space vehicle is that it provide the requisite structural integrity for the launch phase and the orbital trajectory, strength of materials being primary. For a manned space vehicle three further design considerations are vital, primarily for safety of the crew: 1) micrometeoroid protection, 2) radiation protection, and 3) heat rejection. Engineering thought regarding micrometeoroid protection has been dominated for years by the concept of the meteoroid bumper introduced by Whipple.[1] The bumper is simply a thin secondary layer of metal on the space side of the vehicle, placed at a distance from the major surface of a few thicknesses of that surface. The function is to reduce the number of punctures by exploding the meteoritic particles far enough away from the structural surface that only fragments and vapor strike it. However, for a manned space station orbiting in the Van Allen belt, the hull design must be adequate to protect the crew from the effects of the electrons in the belt. The purpose of this note is to show that, in the light of recent results on the micrometeoroid risk, this danger can be dissipated by centering the design criteria on radiation protection and external heat transfer; in particular, a separate meteoroid bumper can be dispensed with.

In a recent paper, Whipple[2] revised his figures for micrometeoroid risk, as a result of the artificial meteor experiment of Trailblazer I. This revision brings the figures inferred from photographic and visual counts of meteors more into agreement with results from satellites and space probes. The paper entirely changes the conception of the problem of the micrometeoroid danger to a space vehicle. Briefly, the main conclusion is that Whipple's former figures[1,3] for the risk of penetration were too large by a factor of about 3000.

The impact of this revision is significant when radiation protection of humans is a design requirement.[4] In this case, a thickness of, for example, aluminum of the order of 1 cm is required to protect a human in a manned space vehicle from the electrons in the Van Allen belt.[5] This figure has been determined for an orbit at an altitude greater than about 200 km and less than a few earth radii, for a manned mission lasting several months. From the latest paper of Whipple, one finds a mean time τ for a micrometeoroid to penetrate an area of 1 m^2 of aluminum of thickness 1 cm, as tabulated in the first and second lines of Table 1, corresponding to most realistic and pessimistic of his estimates, respectively. It is obvious that, on the revised figures, astronomical times are required for one perforation in a square meter. A reasonable estimate of the total surface area of a manned orbital space station is 150 m^2, on the basis of present and projected capabilities of booster rockets. Corresponding values of the mean times for one penetration anywhere in the station are shown in the third and fourth lines of Table 1, for Whipple's most realistic and pessimistic estimates, respectively. It is noted that both times are long compared to any reasonable presumptive orbiting time of the station for human occupancy.

For a mean time τ of perforation for a particular area, the probability p_n of n penetrations in time t is given by the Poisson distribution

$$p_n = e^{-t/\tau}(t/\tau)^n/n! \tag{1}$$

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Thus, the probability p_0 of no puncture in the area in time t is

$$p_0 = e^{-t/\tau} \approx 1 - t/\tau \tag{2}$$

where the approximation indicated is valid for $t \ll \tau$. Probabilities p_0 of no perforation for the areas in question are tabulated in the last column of Table 1 for an orbit duration of one year. All probabilities are essentially 100%.

The figures of Table 1 make two things obvious: The micrometeoroid risk has been vastly overestimated in the past, and the shielding necessary to protect humans from the radiation in the Van Allen belt is adequate for any foreseeable micrometeoroid risk. The basic conclusion is that the separate meteoroid bumper on a space station, envisioned in current thought, is completely unnecessary. Although the figures of Table 1 have been calculated for aluminum, the resultant mean times τ for penetration and probabilities p_0 of no perforation are not changed materially for a skin of comparable specific surface mass (that is, 2.7 g/cm²). For a mission of duration longer than a few months, the thickness of skin required to shield against the electrons is greater, and the conclusion holds a fortiori.

Further, it is desired to stop the electrons incident on the hull in a material of the lowest possible atomic number (for example, polyethylene) to minimize production of bremsstrahlung. From this standpoint, an optimum distribution of mass corresponds to a layer of such material over the skin of metal required for structural integrity, on the space side. The presence of a thin bumper of a metal such as aluminum external to the polyethylene does not alter materially the figures of Table 1, whereas it increases the bremsstrahlung dose to personnel. The outer radiating surface required for external heat transfer should be made of a thermally conducting material of the lowest possible atomic number and thickness consonant with the required radiation of energy, to minimize bremsstrahlung production.

The general conclusions exemplified by Table 1 are in accord with experience gained since the space program was initiated, indicating that the hazard of micrometeoroid penetration of space vehicles originally was grossly overestimated. The data from Explorer XVI are particularly pertinent.[6] This vehicle, which transmitted data from December 16, 1962 to July 23, 1963, contained an experimental arrangement to investigate micrometeoroid penetration, involving 160 small pressurized cylinders of a beryllium-copper alloy having a total surface area of about 2 m². Of these, 100 cylinders had wall thicknesses of 0.0025 cm, 40 had walls 0.005-cm thick, and 20 had walls of 0.013 cm. During the 7 months in orbit, 44 of the cylinders with the thinnest walls and 11 of the cylinders with walls of intermediate thickness were perforated. However, none of the cylinders with the largest wall thickness (0.013 cm) was penetrated. These figures are consonant with those of Table 1.

In addition, the Echo balloon operated for over a year. Its skin consisted[4] of aluminized ethylene terephthalate of thickness 0.0013 cm. At altitudes as low as 1000 km, the relatively low rate of gas loss which occurred suggests a correspondingly low rate of micrometeoroid puncture of the thin plastic balloon.[7]

Table 1 Mean times τ for penetration and probabilities p_0 of no penetration of 1 cm of aluminum in one year

Estimate	Area, m²	τ, yr	p_0, %
Best	1	680,000	99.99985
Pessimistic	1	42,000	99.9976
Best	150	4,600	99.978
Pessimistic	150	280	99.64

Further, none of the Mercury capsules that was in orbit at an altitude of approximately 200 km has shown evidence of either micrometeoroid impact or penetration upon examination after recovery.[6] The pressure vessel of this capsule was fabricated from a titanium alloy 0.025-cm thick, and the capsule was enclosed within a covering of Inconel X 0.025-cm thick. Moreover, many satellites containing instruments have been in orbit for many years with little or no indication that their performance has been degraded by micrometeoroid impact or that they have been incapacitated from this cause.

Apparently, the only contrary evidence exists in the case of Explorer III. The failure of both transmitters on this vehicle coincided with a high measured rate of meteoroid hits during a shower. It has been suggested that the failures were caused by damage in meteoroid impact.[8]

It is admitted that some uncertainty exists as to the precision of the latest figures on micrometeoroid danger. The frequent and occasionally drastic revisions of the estimates of the micrometeoroid risk certainly are indicative of a poor confidence level of the results, reflecting the basic uncertainties of the physical problem (in fairness it must be mentioned that Whipple consistently has attempted to be conservative, and his estimates of the risk tend to decrease monotonically with time).[1–3] Until the extent of the hazard is unequivocally established, there seems no reason to incorporate a meteoroid bumper in the design of a manned orbital space station in the Van Allen belt.

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