ther mode was found to be inherently safer than the other. No combination of range and mode was more conducive to errors than any other.

Discussion

The finding that fuel consumption levels, measured as Δv or velocity increment, were lower in acceleration mode than in pulse mode corroborates the results from the preliminary experimentation. Pulse mode is not inherently more fuel conservative than acceleration mode as one might presume from studying the appropriate NASA manuals.[1,2] This indicates that fuel can be used more efficiently in acceleration mode than pulse mode in a docking operation. This is probably due to the greater dynamic range with acceleration control allowing for greater flexibility and fine-tuning capability.

The asymmetrical transfer discovered here is important for researchers investigating the impact of control modes on spacecraft docking operations. This result should be regarded as a forewarning that investigators should be careful when designing experiments and formulating conclusions. The asymmetry illustrates an inconsistent main effect for which one must account before attributing a result to a control mode. In comparing different control modes, experimenters should be sure to provide sufficient intervening practice to prevent the effects of asymmetrical transfer from contaminating the experimental results.

The data from this study demonstrated that dockings could be performed faster, albeit at the expense of greater amounts of fuel, in pulse mode than in acceleration mode. Although the absolute values of time and fuel were specific to the thruster values that were used, this relationship should be preserved with different thrusters. A whole assortment of studies could be performed to examine the effect that thrusters with different magnitudes from the ones simulated here have on the data. An interaction between thruster size and range might also be revealed. What is clear, however, is that pulse mode is not definitively more fuel efficient than acceleration mode in all situations. Probably the most necessary conclusion to be made at this point is the requirement of further human factors and manual control experimentation before flight protocols are generalized for all vehicles in all situations.

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Atomic Oxygen Protection of Carbon and Polycarbonate Using Boron Carbide Coating

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Introduction

IT is now well established that the interaction of atomic oxygen in the low-Earth-orbit (LEO) space environment with spacecraft at orbital velocities causes severe mass loss from many polymeric materials, including polyimides and polycarbonates, used in the construction of spacecraft subsystems.[1] In this Note, work on the measurement of the effects of atomic oxygen erosion on polycarbonate/carbon composite optical filters and the evaluation of protective coatings for these filters is described. This includes the novel application of boron carbide (B_4C) as a protective coating against atomic oxygen erosion.

Reaction Efficiency of Carbon and Lexan

There have been a number of reports of the reaction efficiency of carbon with atomic oxygen from both space-based[2,3] and ground-based[4] experiments. There are comparatively few measurements of the reaction efficiency of polycarbonate materials in LEO or ground-based apparatus. Gregory and Peters[2] measured the reaction efficiency of CR-39 ($C_{12}H_{18}O_7$) in LEO. Hansen et al.[5] measured the weight loss of polycarbonate in a low-energy atomic oxygen asher, and Morel et al.[6] measured the reaction efficiency of Lexan ($C_{16}H_{14}O_3$) in a plasma asher experiment. All published measurements of reaction efficiencies are given in Table 1.

Given the uncertainties in the data base for the reaction efficiency of Lexan, new measurements of the reaction efficiency were carried out using two types of oxygen source: a supersonic atomic oxygen source[7] at 4 km/s, and an oxygen ion beam source at 20 eV[8] (the equivalent energy to a velocity of 8 km/s is 5 eV).

The supersonic source was flux and energy calibrated using a cylindrical mirror analyzer on the front of a quadrapole mass spectrometer.[7] This showed that the source gave a flux of $(1 \pm 0.5) \times 10^{14}$ oxygen atoms cm^{-2} s^{-1} at an energy of 1.0 ± 0.1 eV. As a cross check on the flux calibration, a sample of vacuum deposited carbon on glass was exposed to the source with one-half of the carbon sample covered. After an exposure of 2 h, the thickness of the covered portion of the sample was 1139 ± 53 Å and the uncovered portion 1034 ± 54 Å. Both thicknesses were measured using the Tolansky method with a Varian angstrometer. Taken together with the flux calibration, this gives a reaction efficiency for carbon of

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$(1.4 \pm 0.7) \times 10^{-24}$ cm^3 atom^{-1}. This is in reasonable agreement with the values given in Banks and Rutledge[9] and confirms the flux calibration of the source.

To check the reaction efficiency for Lexan, a sample of Lexan film of thickness 1558 ± 52 Å (the thickness was measured using a witness sample manufactured at the same time as the test sample) was exposed to the source for a total of 6 h. After exposure it was found to have lost 998 ± 161 Å. Taken with the flux calibration from the mass spectrometer this gives a reaction efficiency of $(4.6 \pm 2.4) \times 10^{-24}$ cm^3 atom^{-1}. This is higher than the plasma asher values given in Table 1 and close to the value for CR-39 given by Gregory and Peters.[2]

The ion beam source exposes samples to oxygen ions rather than neutrals and at rather higher energies than seen in LEO. In order to see what difference this might make, the reaction efficiency of oxygen ions with carbon and Lexan was first measured using an optical filter exposed to the beam with the energy set at 20 eV. The filter consisted of interleaved layers of carbon and Lexan of total thickness 2140 ± 70 and 4180 ± 180 Å, respectively. The filter was exposed to a flux of 3.4×10^{14} ions cm^{-2} s^{-1} of 20 ± 3-eV oxygen ions for 1680 s. The flux was monitored using an ion probe mounted close to the filter. After exposure, all of the carbon layers had been removed and measurement of the transmission of the remaining Lexan layer at wavelengths of 1580 and 1196 Å showed that 1650 ± 180 Å of Lexan had been eroded. Taking the Gregory and Peters[2] value for the reaction efficiency of CR-39 as the most reliable measure for polycarbonate, and a value of 1×10^{-24} cm^3 atom^{-1} as an average value for carbon, the LEO fluence of oxygen atoms required to cause this erosion is 2.4×10^{19} atoms cm^{-2}. Therefore, the 20-eV ion beam erodes the composite carbon/Lexan filter 41 times faster than would be the case in LEO.

It seems unlikely that the large increase in reaction efficiencies between 5-eV oxygen atoms and 20-eV oxygen ions with respect to carbon and Lexan is due solely to the increase in energy, especially considering the results from lower energy neutral sources reported here and elsewhere.[10,11] It is more likely that there is a difference in the reaction mechanism of neutral oxygen and ionic oxygen with carbon.

The measurement of reaction efficiency using the supersonic atomic oxygen source indicates that there will be some danger of erosion of the filters even if the oxygen atoms lose 80% of their energy in reflections off surfaces between the filters and the LEO environment. It was decided, therefore, that a conservative approach would be taken to the construction of the filters and a protective layer should be applied.

Aluminum as a Protective Coating

A recent report by Banks and Rutledge[9] shows the importance of defects in protective coatings and how coatings can be undercut at defect sites eventually leading to cracking and the loss of the coating over a wide area. Scanning electron microscope images of the aluminum coated filters had already revealed that pinholes were present in the aluminum coating, but the loss of protection for these small areas was thought to be acceptable.

A laboratory evaluation of whether these pinholes were a problem was undertaken using the ion beam facility mentioned earlier. A carbon/Lexan filter with a 500-Å aluminum coating was exposed to a flux of 2×10^{15} ions cm^{-2} s^{-1} at an energy of 8 eV for 4800 s. After exposure, the filter was seen to have many areas where the carbon/Lexan film had been completely removed, causing the aluminum layer to crack and peel away. Detailed inspection of the erosion sites showed that the erosion had occurred at folds in the Lexan layer. These areas had been identified as sites of pinholes through the aluminum coating by examination with a scanning electron microscope. The pinholes are thought to occur on the folds because they form ridges on the surface of the filter that are not as well covered by the deposited aluminum as are the flatter areas of the filter. The 500 Å of aluminum can be seen, therefore, to offer limited protection against atomic oxygen in these circumstances, and the option of boron carbide coating was pursued.

Boron Carbide as a Protective Coating

To determine whether an electron beam deposited layer of boron carbide would be affected by atomic oxygen, a sample deposited on a glass slide was exposed to the ion beam for the same fluence and ion energy as the aluminum coated carbon/Lexan filter. The film of boron carbide was observed to be intact after exposure and seemed to have the same chemical ratio before and after exposure, as evidenced by X-ray photoelectron spectroscopy (XPS). The XPS analysis also showed traces of molybdenum on the sample. This was thought to be due to the oxygen ions sputtering the control grids of the ion source due to the high retardation voltage required for an 8-eV beam. The layer of molybdenum was thin and was not thought to have seriously influenced the results of the tests on the aluminum coated filter.

Owing to the difficulties of producing a satisfactory B_4C coating on the the carbon/Lexan filters, only a limited number of flight quality filters were produced. In order to fully evaluate the protective qualities of the B_4C layer, a filter with only a partially adhered coating of 1000 Å of B_4C was exposed to a flux of 3.5×10^{14} ions cm^{-2} s^{-1} of 20-eV ions for 1680 s in the ion beam facility. Given the acceleration factor discussed in a previous section, this was equivalent to an LEO fluence of 2.4×10^{19} atoms cm^{-2}.

As expected, where the B_4C coating was not well adhered, the filter was badly eroded. However, in those places where the coating was complete, the filter appeared largely intact, as shown by microscopic inspection of the optical transmission of the filter. Where erosion sites did occur in the well-coated portion, they were again observed to be along folds in one or more layers of the Lexan substrate. The number and extent of erosion sites were both much less than seen in the aluminum coated filter. A slight discoloration of the B_4C coating was seen after exposure; this could be due to loss of carbon from the B_4C matrix. Unfortunately, this could not be confirmed by XPS measurements due to the size of the filter. Contamination was ruled out by the presence of a witness mirror in the test chamber. This was visually inspected before and after the exposure and no discoloration was observed.

Summary and Conclusion

Comparison of the reaction efficiency of carbon with atomic oxygen measured by experiments in LEO and lower energy ground-based atomic oxygen sources and that measured by exposing carbon to an ion beam at 20 eV shows that there is at least a factor of 40 increase in reaction efficiency between 1-5-eV atomic oxygen and 20-eV ionic oxygen. The conclusion

Table 1 Previous measurements of reaction efficiencies of carbon and various polycarbonates

Source type	Material	Reaction efficiency, cm^3 atom^{-1}	Reference
Plasma asher	Lexan	7.6×10^{-26}	Morel et al.[6]
Plasma asher	Polycarbonate	5×10^{-25}–5×10^{-24}	Hansen et al.[5]
LEO (STS-8)	CR-39	6×10^{-24}	Gregory and Peters[2]
LEO (various)	Carbon (various)	0.9–1.7×10^{-24}	Banks and Rutledge[9]

from this comparison is that some care must be exercised in interpreting measurements of reaction efficiency using ion beam sources as being representative of the situation in LEO. However, ionic oxygen sources, such as the one used for the work reported in this Note, do offer a good accelerated test for materials development for space applications. The measurement of the reaction efficiency of Lexan using a supersonic atomic oxygen source at 1 eV is consistent with the value of that for CR-39, a similar polycarbonate material, measured by Gregory and Peters[2] in an LEO experiment.

A carbon/Lexan optical filter coated with 500 Å of aluminum as a protection against atomic oxygen erosion has been exposed to an 8-eV oxygen ion beam. The failure of the aluminum to protect this filter shows that the presence of even microscopic pinholes through a coating seriously impairs its protective qualities and leads to the eventual loss of the coating over an area very much larger than the size of the original pinhole. A boron carbide layer exposed to the same ion beam was shown to be unaffected by the oxygen ions. A filter with 1000 Å coating of B_4C has been exposed to a 20-eV oxygen ion beam and, in the portion of the filter where the coating was well adhered before exposure, little damage has occurred. It is concluded that B_4C is unreactive with respect to atomic oxygen erosion and that a 1000-Å layer will offer almost complete protection with very few pinholes through the coating.

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