A Consideration of Atomic Oxygen Interactions with the Space Station

Lubert J. Leger* and James T. Visentine†
NASA Lyndon B. Johnson Space Center, Houston, Texas

Significant surface interactions which are very likely due to exposure to atomic oxygen, the major component of the low Earth orbital environment, have been observed on recent space flights. These interactions are manifested as surface recession and, therefore, mass loss and appear to arise from oxidation of the materials involved. A computer model has been developed to compute atomic oxygen fluence (total integrated flux) for a generalized spacecraft in orbital flight based on Mass Spectrometer and Incoherent Scatter (MSIS) ambient density predictions. Calculations for Space Station surfaces using this model have been made. Assuming a constant altitude flight strategy, total fluence on ram-facing surfaces during a complete solar cycle is 1.2×10^{22} atoms/cm^2 and 6.7×10^{21} atoms/cm^2 for solar-facing surfaces with both sides exposed. Using material reactivities for composite materials and thin films developed from flight experiments, total recession for ram and solar inertial surfaces will be 0.036 cm (14 mils) and 0.020 cm (8 mils), respectively, per solar cycle. For a station life of 30 years, approximately three cycles will be experienced; the resulting recession appears unacceptable for certain surfaces. These effects must be accounted for if long-lived operation is to be expected.

Introduction

As a space vehicle moves in orbit about the Earth, it undergoes energetic collisions with atoms and molecules that comprise the orbital environment. Although the number densities of atmospheric constituents at typical spacecraft operating altitudes (300–500 km) are quite low, the high orbital speed produces flux densities large enough (10^{13}-10^{15} atoms/cm^2-s) for interaction with surfaces to produce drag effects and changes in optical and physical properties by scattering, adsorption, or chemical reactions.

Before the early Space Shuttle flights, interactions between spacecraft surfaces and the orbital environment were considered to be benign, especially for missions of short duration. The principal concern has been the induced molecular environment in which sensitive instruments, such as those aboard Spacelab, must operate to obtain useful scientific data. Spacecraft-generated gases, such as water vapor (H_2O) and carbon dioxide (CO_2), have strong emission spectra in the infrared and can produce significant backgrounds if the molecular column densities of these contaminants are not properly controlled. Additionally, these gases, as well as higher molecular weight species, can be returned to vehicle surfaces as a result of collisions with natural atmospheric constituents that lead to deposition on sensitive surfaces.

Previous studies have shown that the atmosphere at altitudes between 200 and 650 km (Fig. 1) consists primarily of atomic oxygen and that the relative concentration of atomic oxygen below 600 km increases with altitude. Recent Space Shuttle flights have demonstrated[1-3] that interactions between spacecraft surfaces and high-velocity (~8 km/s) oxygen atoms within the low Earth orbital (LEO) environment can produce significant changes in surface properties of many materials. These changes are directly related to fluence, or total integrated flux, incident on material surfaces. A computer model has been developed to estimate the fluence incident on spacecraft surfaces for various orbital flight conditions. This model, which has been used to predict fluence incidence on Space Station surfaces during a typical eleven-year solar cycle, will be reviewed and surface recession will be estimated using these calculations and atomic oxygen reaction efficiencies derived from previous Space Shuttle flights.

LEO Effects on Materials

Two flight experiments performed on the fifth and eighth Space Shuttle flights (STS-5 and STS-8) provide most of the current information regarding reactivities of materials with atomic oxygen in the LEO environment. A relatively large number of materials were exposed during these two flights

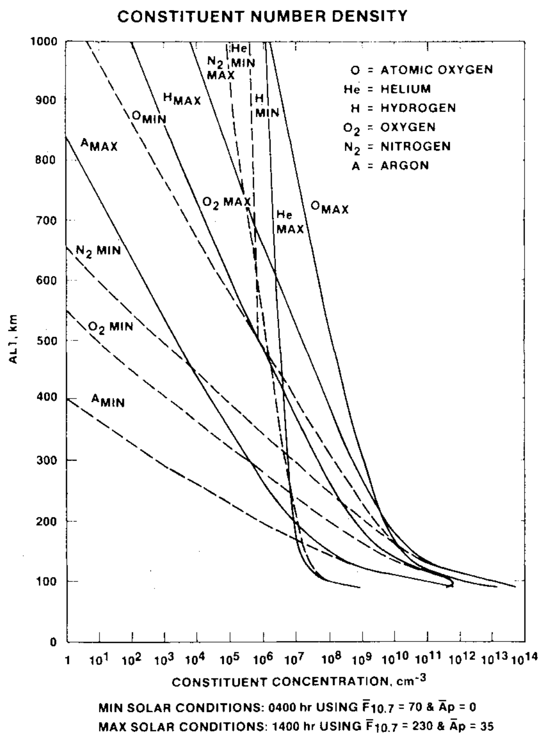

Fig. 1 Atmospheric composition from Ref. 9.

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*Head, Nonmetallic Materials Section. Associate Fellow AIAA.
†Senior Materials Science Technologist. Associate Fellow AIAA.

and were analyzed after flight. (See Refs. 1 and 3 for experiment descriptions.) Although the exposure times were about equal (40 h) for each mission, a considerable difference in flight altitudes (300 km for STS-5 compared to 225 km for STS-8) resulted in total accumulated fluences of 1.0×10^{20} and 3.5×10^{20} atoms/cm^2 for STS flights 5 and 8, respectively.

Surface recession (or thickness loss) for reactive materials was determined from changes in mass of the specimens and was found to be proportional to the fluence. For example, surface recession for unfilled organic materials was 1.8×10^{-4} cm for STS-5 specimens and 1.2×10^{-3} cm for STS-8 specimens. Qualitatively, these results can be summarized as follows:

1) Materials containing only carbon (C), hydrogen (H), oxygen (O), or nitrogen (N) have high reaction rates in the range of 2.5×10^{-24} to 3.0×10^{-24} cm^3/atom.

2) Perfluorinated and silicone polymers are more stable than the organics by at least a factor of 50.

3) The reaction rates for filled organic materials are dependent on the oxidative stability of the fillers. For example, materials filled with metal oxides have lower reaction rates than those filled with carbon.

4) From a macroscopic standpoint, metals, except for osmium and silver, are stable. Metals such as copper do form oxides, but at lower rates than for osmium and silver.

Because of the good stability of perfluorinated and silicone polymers and most metals, these materials are being considered for use as protective surfaces for reactive substrates. It should be noted, however, that the thickness of the metallized coatings and the effects of defects on protective coating performance must be carefully evaluated since attack by atomic oxygen can occur where these defects exist or by diffusion of atomic oxygen through thin, metallized films.[4] Material reactivities are relatively insensitive to surface temperature in the range between 25° to 125°C, probably because of the high kinetic energy (> 5eV) of the bombarding atoms. Although the impinging flux is reduced as the impingement angle relative to the surface decreases, it also appears from some of the results that the reactivity also decreases with decreasing impingement angle.[3] During STS-8, the effect of solar ultraviolet (UV) radiation on material reactivity was preliminarily evaluated for several types of polymer films. The results of this experiment indicate that radiation does not appear to have a significant effect on the environmental reaction rates for the three polymer surfaces studied. Further evaluations are planned.[5]

Quantitative reaction efficiencies for materials evaluated on these two flights were obtained by normalizing the surface recession to the accumulated fluence. Reactivities for typical spacecraft materials are shown in Table 1. These reactivities can be used (as discussed later) to assess spacecraft effects, provided the exposure fluence is known or can be estimated. It must be remembered that the reactivity data base is limited in both number of measurements made and total exposure. Reactivities are derived from preflight and postflight measurements and, therefore, represent average reaction efficiencies. For the purpose of this paper, it will be assumed that recession occurs uniformly from the material surface, that recession rates are not flux-dependent, and that only surface interactions occur with no changes in interior material properties. These assumptions are supported by the flight data reported in Refs. 1-3.

Table 1 Reaction efficiencies for composites, polymers, and organic films

Material	Reaction efficiency, cm^3/atom $\times 10^{24}$
Kapton	3.0
Mylar	3.4
Tedlar	3.2
Polyethylene	3.7
PMMA[a]	3.1
Polyimide	3.3
Polysulfone	2.4
1034C epoxy	2.1
5208/T300 epoxy	2.6
Teflon, TFE	< 0.05
Teflon, FEP	< 0.05

[a] PMMA = Polymethylmethacrylate.

Spacecraft Fluence Calculations

Model Description

A computer model has been developed to calculate the atomic oxygen fluence, or total integrated flux, incident on surfaces in Earth orbit. This model has been generalized such that surfaces selected for study can be oriented in any direction with respect to 1) a body coordinate system fixed to the spacecraft (E surfaces) that flies in a local vertical-local horizontal (LVLH) flight mode, 2) a solar inertial coordinate system (I surfaces) that rotates in two degrees of freedom (alpha and beta) to maintain Sun-pointing attitudes, and 3) a space-viewing coordinate system (B surfaces) that rotates in a single degree of freedom (alpha) to provide radiator attitudes for deep-space heat rejection. These surfaces are illustrated in Fig. 2 for a generic spacecraft and in Fig. 3 for a reference Space Station. In these illustrations, surfaces represented by Y_o and X_I are ram-directed and solar-oriented, respectively.

As the spacecraft is advanced in its orbit during the simulation, the Y_o and Y_I axes remain situated within the orbital plane. The relative velocity of oxygen atoms impinging on surfaces that rotate about these axes is then derived for the fluence computations.

In computing fluence incident on typical spacecraft surfaces, the spacecraft is initialized in a circular orbit by specifying 1) altitude, 2) orbit inclination, 3) Earth longitude and latitude of spacecraft position within the orbit plane, 4) local solar time or Greenwich mean time, and 5) year, month, and day of the start of the simulation. The orbital period is then divided into discrete steps and the state vector of the spacecraft under study is allowed to propagate using the classical laws of Keplerian dynamics.[6]

To maintain an accurate account of the position of the spacecraft in terms of Earth longitude and latitude, which is required for the atomic oxygen density estimations, the first-order theory of Kozai[7] is used to determine the orbital precession rate of the spacecraft. The velocity of the spacecraft, which determines the rate at which oxygen atoms strike its surfaces, is calculated relative to the atmosphere, which is assumed to rotate at the same rate as the Earth. Incremental exposures obtained in this way are summed over the duration of the simulation to obtain the total fluence incident on spacecraft surfaces.

Atomic oxygen number densities used to compute fluence were obtained from the MSIS-83 thermospheric model[8], which predicts atmospheric constituent concentrations as functions of input parameters such as altitude, time of year, latitude, longitude, local solar time, and solar activity conditions. To provide conservative estimates of accumulated fluence, 2σ variations of the long-range statistical averages of the solar activity indicators ($F_{10.7}$ and A_p) were used as inputs to the MSIS-83 model.[9] This approach has been previously used to compute drag effects on space vehicles and is appropriate for initial studies of atomic oxygen interactions with surfaces. It should be noted that using this approach for the atmospheric density predicted for cycle 22 is below the measured maximum density for the current cycle (solar cycle 21).

Flux was computed by multiplying the atomic oxygen number density by the component of velocity normal to the surface in question. Day/night and seasonal variations in the atomic oxygen number density, encountered during the simulation, were introduced by the MSIS model. Fluence F_T

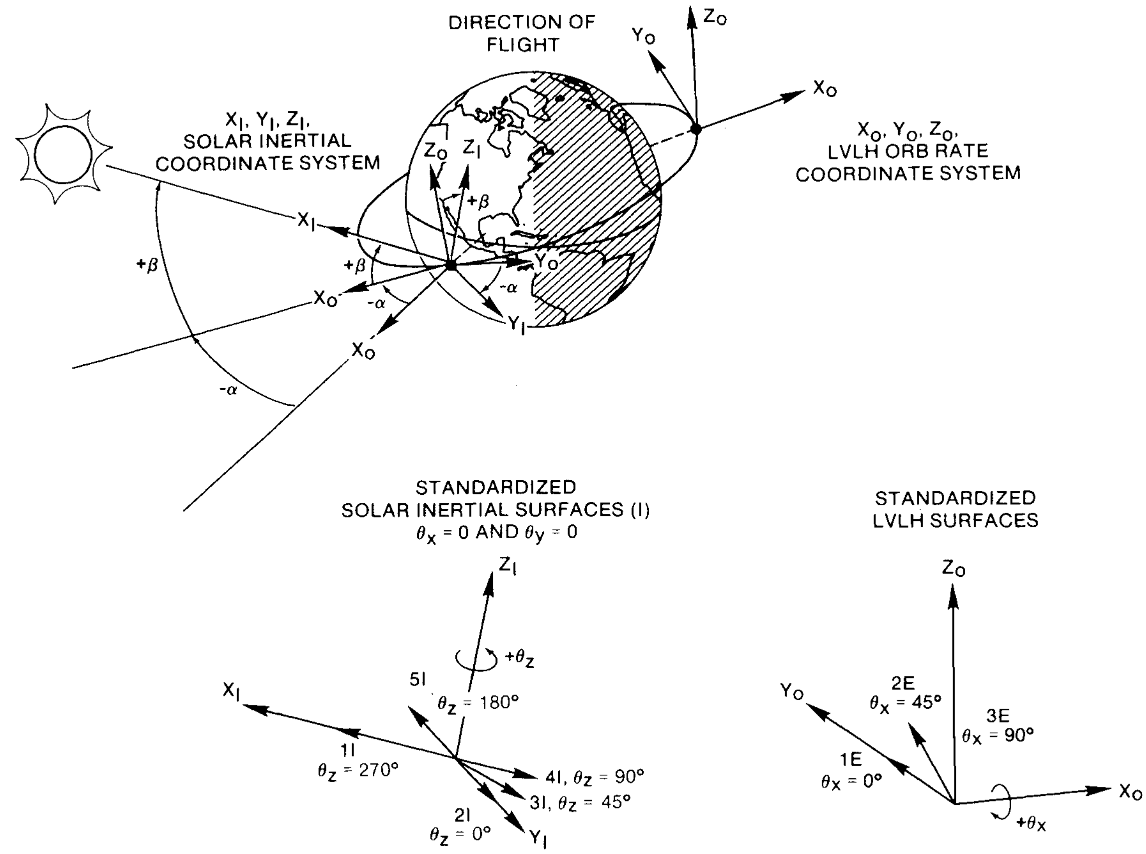

Fig. 2 Orientation of Earth-fixed (E) and solar inertial (I) surfaces.

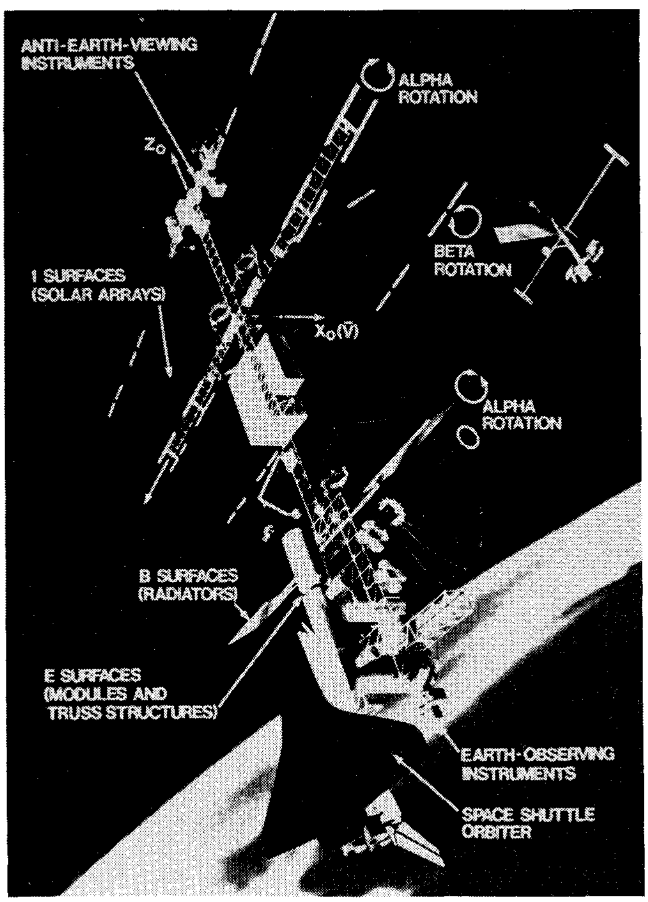

Fig. 3 Space Station design reference configuration from Ref. 10.

was then obtained by multiplying the incident flux by the interval of time dt over which the density and the velocity were assumed constant (approximately 4.5 min, or 20 calculations per orbital pass) and summed over the desired exposure time.

$$F_T = \int_0^t \Phi \mathrm{d}t \tag{1}$$

where Φ is the normalized atomic oxygen flux and t is the exposure time.

In computing surface recession for materials subjected to the orbital environment, the reaction efficiencies derived from previous Space Shuttle flights were used as follows:

$$\Delta x = F_T \times R_e \tag{2}$$

where F_T is accumulated fluence, R_e is reaction efficiency, and Δx is surface recession.

Parametric Study

A parametric study was performed to evaluate the effects of altitude, inclination, and solar activity on atomic oxygen fluence. Altitudes and inclinations selected for this study ranged from 150 to 900 km and from 0 to 89 deg, respectively. Solar activity parameters used in the computations represented low, medium, and high activity conditions.

Seven surfaces were selected for analysis as these parameters were varied; they included three E surfaces (ram and oblique effects), two I surfaces (solar and antisolar), and two B surfaces (deep-space and Earth-viewing). The results of this analysis comprise a generalized description of the manner in which changes in surface orientation, altitude, inclination, and solar activity affect total accumulated fluence. Fluence, as a function of altitude for various solar activities, is shown in Fig. 4. During nominal activity ($F_{10.7} = 150$;

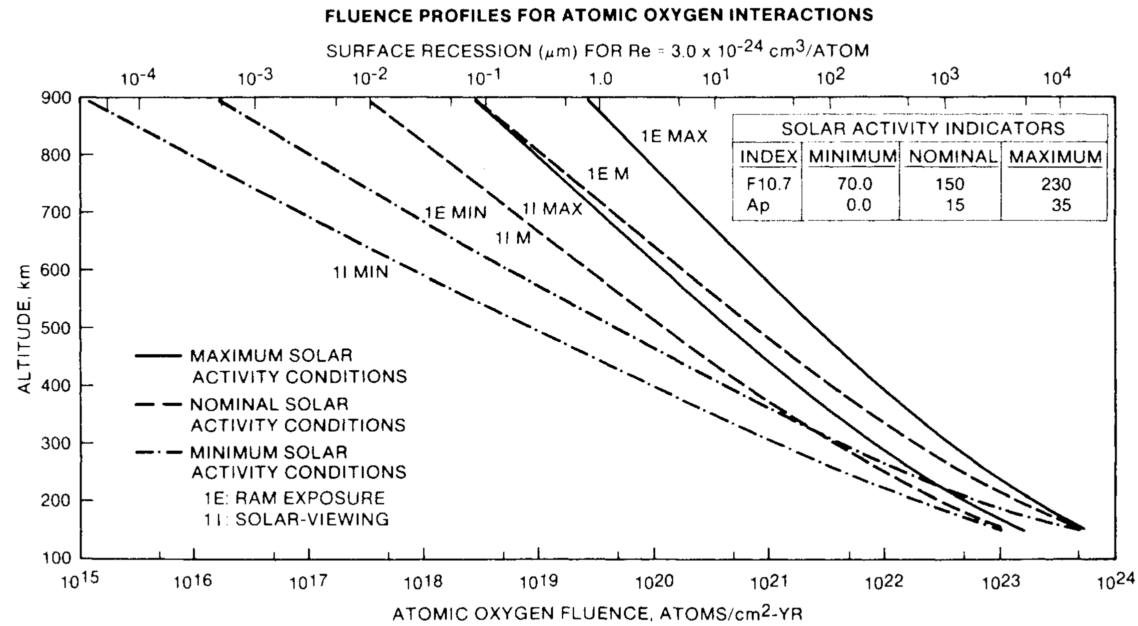

Fig. 4 Fluence profiles for atomic oxygen interactions.

$A_p = 15$), the fluence on ram-oriented surfaces increases from 3.1×10^{18} to 4.4×10^{23} atoms/cm^2 per year as the altitude is reduced from 900 to 150 km. As expected, the fluence increases with increasing solar activity. For example, at a nominal altitude of 500 km (Space Station), the yearly fluence on these surfaces increases from 4.6×10^{19} to 2.2×10^{21} atoms/cm^2 as solar activity increases from minimal ($F_{10.7} = 70$; $A_p = 0$) to maximum ($F_{10.7} = 230$; $A_p = 35$).

Fluence is also strongly influenced by surface orientation. For example, the fluence for surface 1E (ram conditions) situated in a circular orbit of 500 km during nominal solar activity is 7.4×10^{20} atoms/cm^2 per year. In comparison, B surfaces subjected to windward conditions at solar noon (Fig. 5) and I surfaces that are antisolar viewing undergo yearly fluences of 3.3×10^{20} and 2.7×10^{20} atoms/cm^2, respectively, or 45% and 36% of ram exposure. On the other hand, solar-viewing I surfaces and leeward B surfaces accumulate less fluence, 1.5×10^{20} and 1.4×10^{20} atoms/cm^2, respectively. This difference can be explained using Fig. 5. Solar heating effects produe a slight bulge in number density at approximately 40 deg east of solar noon. The former surfaces fly through this bulge and the latter surfaces are protected from it because of wake effects. During the night exposure, the relative orientations of these surfaces are reversed, but, since the nighttime number density is lower (4.2×10^7 as compared to 1.4×10^8 atoms/cm^2), the reverse sides undergo less flux, or lower fluence.

The results of inclination changes are shown in Fig. 6. During spring and fall equinoxes, the density bulge produced by solar heating lies along the Equator and decreases at higher latitudes. During the summer solstice (June 22), this bulge is 23.5 deg above the equatorial plane and orbits near this location are characterized by higher fluences.

Space Station Surface Effects

A preliminary Space Station reference configuration (power tower concept) and flight attitude were developed to form a basis for concept definition studies that began in early 1985. This configuration, which is shown in Fig. 3, and associated system descriptions have been used in the assessment of atomic oxygen effects on exterior surfaces. Although the final configuration may be affected by the study results, atomic oxygen considerations which follow should still apply since they are constrained primarily by orbital flight parameters.

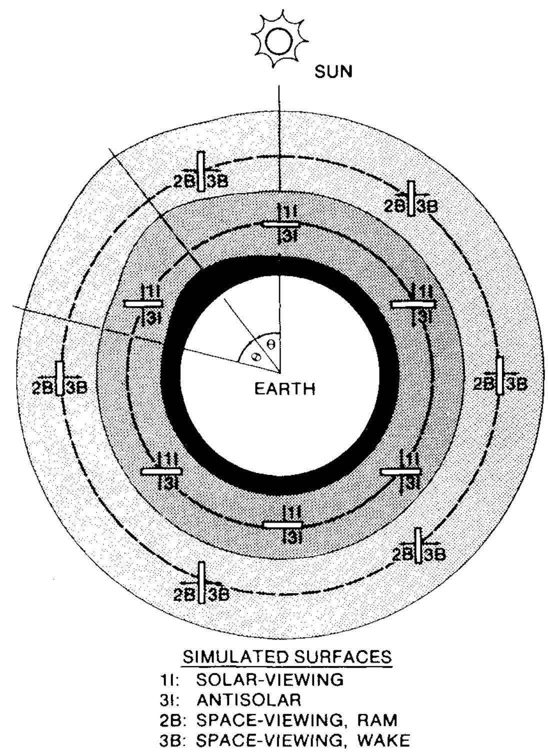

Fig. 5 Surface orientations relative to atomic oxygen density variations at solar noon.

The Space Station configuration consists of a truss tower structure to which a gimbaled power system is attached. Pressurized modules are attached at one end of the truss structure where the Shuttle Orbiter docks for equipment delivery and expendable resupply. The station operates in an LVLH flight attitude with the pressurized modules pointing continuously toward the Earth. With this flight attitude, it is obvious that Earth-related observations are made from the end containing the pressurized modules and that solar, stellar, and other anti-Earth viewing measurements are made from the opposite end. Lifetime considerations are dependent on the performance of specific systems; however, overall Space Station life should extend over several decades.

Basic Space Station surfaces selected for study are shown in Fig. 3. The surfaces include E surfaces, such as modules and truss components, which always face the velocity vector, I surfaces, such as solar arrays, which rotate in azimuth (a) and elevation (β) to track the Sun, and B surfaces, such as radiators, which rotate in azimuth to provide for deep-space viewing and optimum heat rejection.

Fluence calculations were performed assuming a launch date that corresponds to the beginning of a solar cycle (or a hypothetical January 1988 launch date, see Fig. 7). This launch date was selected for convenience in running the simulations since it is assumed that over a 30-year life, the station will undergo three solar cycles regardless of when it is launched.

Fluences for the surfaces under study were summed over the eleven-year solar cycle (January 1988 through January 1999) for maximum (500 km) and minimum (465 km) altitudes. Fluences computed for these altitudes (Figs. 8 and 9) represent maximum and minimum values that Space Station surfaces will accumulate during one solar cycle exposure. Assuming that the Space Station operates between these two altitudes with reboost occurring at 465 km, approximately two-thirds of the flight time will be spent at the higher altitude. Using these assumptions, the fluences that can be expected on station surfaces are shown in Table 2.

Truss Structure

The main connecting structure for the Space Station will consist of a truss network, which is either erectable or deployable. Each truss member will be sized in length using the packing concept selected for delivery to Earth orbit, but will be approximately 5 cm in diameter with a wall thickness of 0.125 cm. Because of stiffness and low thermal expansion requirements for the tower structure, an organic matrix/graphite composite material will most likely be used for truss tube construction.

During orbital flight in the LVLH attitude, one side of the truss tubes always faces into the velocity vector and is exposed to a fluence of 1.2×10^{22} atoms/cm^2 per solar cycle (Table 2). Although the reactivities of only a few organic matrix/graphite composites have been determined, they appear to be in the same range as organic films (3×10^{-24} atoms/cm^2); therefore, the total expected recession [Eq. (2)]

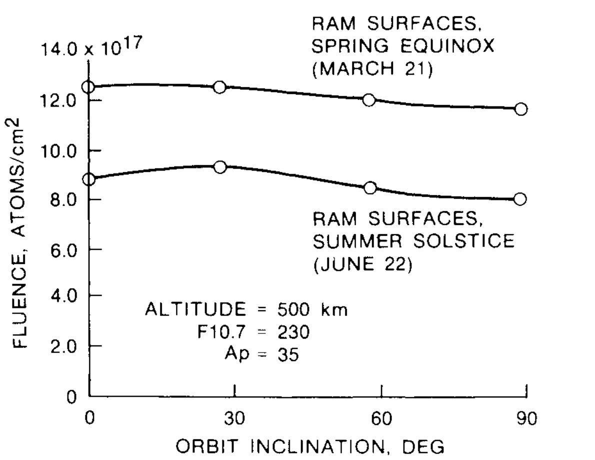

Fig. 6 Seasonal and inclinational effects on fluence (three orbits).

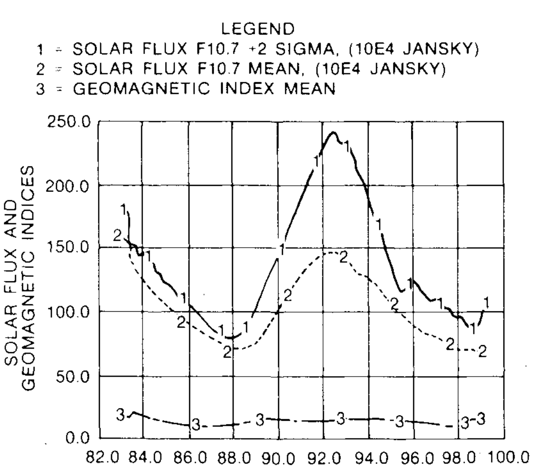

Fig. 7 Solar activity predictions for cycle 22.

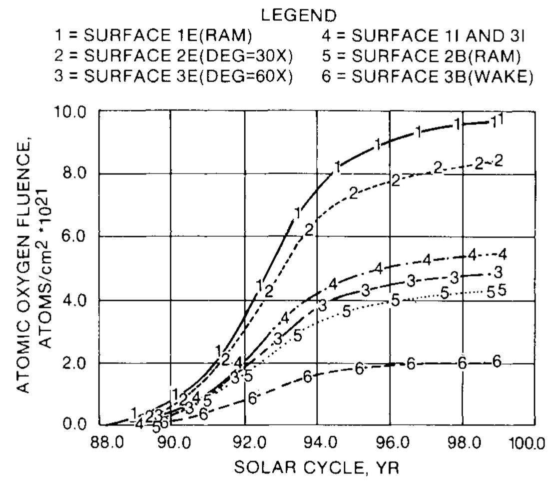

Fig. 8 Space Station fluence predictions for 500 km (270 n.mi.) altitude.

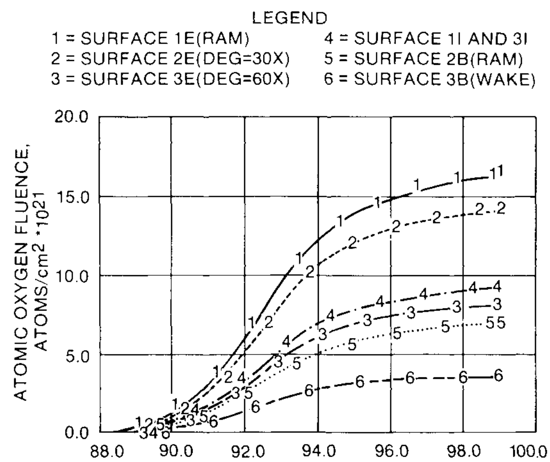

Fig. 9 Space Station fluence predictions for 465 km (250 n.mi.) altitude.

Table 2 Space Station fluence for 11-yr solar cycle

Surface	Fluence, atoms/cm^2
1E (ram)	11.8×10^{21}
2E (30 deg)	10.3
3E (60 deg)	5.9
1I (solar)	2.6
3I (antisolar)	4.1
1I + 3I	6.7
2B (windward)	5.2
3B (wake)	2.5
2B + 3B	7.7

for one solar cycle is approximately 360 μm (14 mils). For a full 30-year Space Station life, approximately 1080 μm (42 mils) of surface recession can be expected. The wake, or trailing side, of the truss members will encounter scattered flux from other members which may produce some recession, but considerably less than forward-facing surfaces. Total surface recession can correspond to as much as 84% of tube wall thickness and, since it will occur predominantly on one side, may produce some mechanical warping in the tubes in addition to stiffness or strength loss. Protection of the composite material from atomic oxygen attack will therefore be necessary.

Several approaches to providing protection for the truss tube composites seem viable and are based on the stability of perfluorinated polymers and certain metals discussed earlier. Candidate protective concepts would include 1) vapor-deposited metals, sputtered metals, or Teflon-base coatings applied to the outside truss wall, 2) applied metal foils such as aluminum, and 3) applied perfluorinated films such as Teflon. Since packaging and deployment of the truss structure will require considerable handling, the selected protective coating should be durable because scratches or other surface defects will allow atomic oxygen attack to occur and possibly cause significant damage. Selection of the protective coating should, therefore, most likely be based on durability and ease of application in addition to oxidative stability.

Solar Power Systems

Two concepts, solar voltaic and solar dynamic, are being considered for providing Space Station power. Solar voltaic systems directly convert solar energy to electrical power using solar cells. In the solar dynamic system, solar radiation is collected by concentrators and used to drive heat engines, which, in turn, generate electrical power. Solar energy collecting components will be articulated in two degrees of freedom to continuously track the Sun.

Solar Voltaic

The solar voltaic collector (Fig. 3) consists of large arrays of solar cells mounted on either a flexible or a rigid substrate. Current solar array systems (for example, those used on the Hubble Space Telescope) use thin films of Kapton (76 μm, or 3 mils) as a flexible solar cell support. In some regions of such arrays, both sides of the support material are exposed to the flight environment. Rigid arrays generally still use Kapton as the solar cell mounting substrate, but the film is bonded to a rigid structure. In this case, only one side of the Kapton would be exposed.

Silver or copper foil is used for connecting the solar cells to the electrical network. This foil is also relatively thin (76 μm) and some sections near the solar cell connections are exposed to the environment.

Solar voltaic system components seem to be the most susceptible to atomic oxygen effects because of the large extent of thin-film usage. For these systems, the average fluence per solar cycle per side (Table 2) is expected to be 3.35×10^{21} atoms/cm^2. For one-side exposure, this value corresponds to a surface recession of 100 μm and for a two-side exposure, the total is 200 μm, as discussed earlier. Typical flexible array substrates would therefore be completely removed in unprotected areas after exposure to approximately one-half of the solar cycle maximum density. Failure of the system might occur earlier than this time if the film is carrying significant load or has a preload condition. It is not clear what a loss of 100 μm [or for that matter, all of the Kapton, except in covered regions of the large (240 m^2) arrays proposed for Space Station] would mean. Obviously, the atomic oxygen effects are important to the solar voltaic system, and protective coatings such as perfluorinated films or other stable coatings will have to be considered. Such approaches will most likely affect the current manufacturing techniques for solar arrays.

Results of previous flight experiments reveal that silver foils oxidized to the extent of spalling at low fluence (3.5×10^{20} atoms/cm^2 for Space Shuttle experiments); therefore, the use of unprotected silver electrical interconnects on Space Station solar arrays seems unacceptable. Coating techniques for such interconnects are being developed for use on the Space Telescope and may be available for use on the Space Station. Again, as with substrates, such coatings may cause significant perturbations in manufacturing processes.

Solar Dynamic

The components most sensitive to atomic oxygen effects on the solar dynamic system are the reflector and absorber surfaces since minor changes in optical properties can significantly affect system performance. Current reflector coatings for ground-based solar dynamic power systems consist of aluminum overcoated with magnesium fluoride or silver with similar type overcoats. Such approaches appear applicable to space systems with rigid collectors. In the case of silver, however, protective coatings used on space systems must be free of defects and thick enough to prevent diffusion of atomic oxygen through the coating which would result in subsequent attack of the silver. Additionally, the optical property stability of magnesium fluoride coatings has been evaluated only for fluences as great as 3.5×10^{20} atoms/cm^2. The station power system fluence will be 2.6×10^{21} atoms/cm^2 per solar cycle (solar-inertial surfaces, one side exposed); consequently, more evaluations are required.

The previously mentioned coating systems do not appear to be applicable to flexible collectors since flexing of the substrate would damage the protective coatings and result in oxygen attack. This deficiency would be especially critical for systems using silver coatings. One approach to solving these problems would be to encapsulate the reflective coating between films of perfluorinated polymers approximately 25 μm thick. As with the magnesium fluoride, changes in optical properties of these polymers introduced by high fluence levels must be determined.

Coatings for collectors should be of less concern than for reflectors since these coatings are generally metal oxides. However, these collectors will be operated at relatively high temperatures (350°C) and their coatings must be thoroughly evaluated for reactivity with atomic oxygen to ensure adequate life.

Other Considerations

Thermal control coatings used on the Space Station must be carefully selected for long life since on-orbit extravehicular activity (EVA) refurbishment will be a difficult task. Organic matrix paints currently used on spacecraft do not seem to be good choices even though stable pigments are used. Exterior coatings that have good stability for atomic oxygen are inorganic matrix paints, perfluorinated coatings or films, and, for metal surfaces, chemical conversion coatings such as anodized aluminum. The anodized coatings appear particularly attractive because they should be stable to atomic oxygen exposure and, with some modification of the application process, a range of optical properties should be possible.

For radiator systems, two general classes of coatings, silver-Teflon and "black" metals, seem appropriate for consideration. Both of these coatings should have good stability to atomic oxygen reaction. Since these systems are very critically dependent on optical properties, further study of long-term behavior is necessary.

Considerations of Space Station atomic oxygen effects have included only the major components and some general issues. As the configuration and individual systems mature, a more detailed atomic oxygen assessment will be possible. With this detailed review, effects of exposure to an atomic oxygen environment on other components such as space-suit helmets, which are made of polycarbonate and susceptible to oxidation, will undoubtedly be found.

Conclusions

An assessment of the atomic oxygen fluence anticipated for Space Station surfaces has been made. From this assessment, surface recession estimates obtained using measured material reactivities are in the range of 360 μm for ram-facing surfaces and 100 to 200 μm for solar power system surfaces during each solar activity cycle. A full 30-year exposure would increase these surface recession estimates by a factor of approximately 3. For certain systems, such as the presently conceived structure, this extent of surface recession will probably limit performance. Solar power systems seem even more susceptible to the degrading effects of atomic oxygen. Development of surface protective coatings appears to be the most efficient approach to mitigating atomic oxygen surface interactions.

Coatings and coating techniques are available for use on almost all system surfaces considered. Most of the application processes, however, have only recently been laboratory-developed and need considerably more study before they are ready for hardware use. In some cases, such as flexible solar arrays, application of these coatings or protective surfaces to spacecraft systems may require extensive changes to manufacturing processes. Such complications must be addressed early in system development to ensure proper support of flight hardware design and development, which will be initiated in approximately two years.

Since atomic oxygen effects, which appear to be the most degrading aspect of the LEO environment for material surfaces, have only recently been extensively addressed, further study is obviously needed. The environmental interaction data base needs to be expanded and verified and the effects of various parameters such as solar radiation, temperature, and mechanical stress on reactivities need to be further studied through the use of flight experiments and ground-based laboratory investigations.

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