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In-Space Technology Development: Atomic Oxygen and Orbital Debris Effects

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James T. Visentine and Andrew E. Potter, Jr.

FOREWORD

NASA has initiated a number of studies to understand the effects of long-term exposure of new-generation spacecraft to the natural and "manmade" flight environment. The size and cost of these programs require that these spacecraft maintain their operational performance and undergo minimum refurbishment over their design lifetimes. Particular concerns addressed by these studies are 1) atomic oxygen interactions with surfaces and 2) orbital debris impacts with spacecraft components such as composite structures, crew habitation modules, space suits, and pressure vessels. Earlier flight experiments and laboratory studies have shown that atomic oxygen, the principal constituent in the low Earth orbit environment, can interact with many materials to produce mass loss and surface recession; and collisions of manmade debris with orbiting structures can result in surface damage, and in some cases, can produce catastrophic failure of critical spacecraft systems. The results of these studies together with examinations of hardware returned from the Solar Max repair mission and recent models of the manmade orbital debris environment indicate many materials will require protection from solar ultraviolet radiation and atomic oxygen. Furthermore, particles of orbital debris are increasing at rates sufficiently high to require new shielding geometries for suited crewmen and future spacecraft.

In addition to these effects, other studies have shown that interactions of spacecraft surfaces with the natural environment can generate excited molecules, which produce emissions, or "glow," in the far ultraviolet and infrared wavelengths and may interfere with astronomical observations conducted during future spaceflight missions. It is now assumed these emissions arise from interactions of atmospheric nitrogen with oxygen atoms reflected off spacecraft surfaces. By means of an atom-exchange process, these constituents form adsorbed N_2 and NO_2 in excited states which are then emitted by these surfaces. As these molecules decay to their ground states, they are believed to generate ultraviolet and infrared emissions such as those observed by unmanned satellites and photographed by flightcrews during earlier Space Shuttle missions.

The results of these studies, together with in-space technology experiments to develop an orbital debris collisional warning system and gain greater knowledge of glow and recession mechanisms, will ultimately lead to the proper design of future NASA spacecraft. These are the subjects of review and discussion in this technical memorandum.

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ACKNOWLEDGMENTS

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INTRODUCTION

The early concept development period for major space programs is typically characterized by optimistic identification of development problems and their solutions. Very often, significant development issues are not understood until the design phase, when changes are difficult and produce significant program impacts. It is important, therefore, to emphasize problem identification early in the concept development phase of spaceflight programs.

Concept development for the United States Space Station Freedom has been in progress since 1983. The baseline configuration and program definition have been established, with design activities having begun in 1987. During this period, many development issues were identified and were addressed during advanced development. Compatibility of the Space Station hardware with the space environment was deemed a major materials development issue. Included within this compatibility issue were long life, thermal cycling, effects of atomic oxygen (AO), high-velocity particle impacts, and ultraviolet (UV) radiation on exposed surfaces. Activities currently underway to address these concerns are reviewed in the discussions that follow, with particular emphasis on atomic oxygen effects and potential hazards from energetic impacts with orbital space debris.

ATOMIC OXYGEN APPLICATIONS TO THE SPACE STATION

Predictions of atomic oxygen effects on Space Station surfaces (figure 1) require only the reaction efficiencies of the materials involved and the expected atomic oxygen fluence. Initial conceptual studies assumed a constant flight altitude of 475 km. Computations of fluence for this flight scenario have been reported in earlier NASA documents[1,2] and show major effects on Space Station components. For example, primary structural elements composed of graphite/epoxy composites 0.15 cm thick would lose more than 50 percent of their forward-facing surfaces. Other surfaces, such as organic film supports for solar cells in flexible solar arrays, undergo material loss and major changes in surface morophology (figure 2) when exposed to atomic oxygen. Recent computations indicate these surfaces would be completely removed in little more than one year of exposure during conditions of maximum solar activity.

Recently, a constant ambient density flight scenario was baselined for Space Station Freedom. This new strategy allows altitude variations from 475 km, during solar maximum ($+2\sigma$) conditions, to approximately 340 km during solar minimum conditions (figure 3). This lower operational altitude provides significantly greater payload delivery capability to the Space Station by the Space Shuttle and results in reduced overall program costs.

Unfortunately, operation at lower altitudes increases the exposure to atomic oxygen because of increased ambient density. For an atomic oxygen density of 2×10^8 atom/cm^3 (the expected Space Station flight density), the fluence is 3.8 times greater than the constant altitude (475 km) fluence. The recession of surfaces due to fluences shown in table 1 is very large and presents a significant need for new materials and protective coatings for Space Station surfaces.

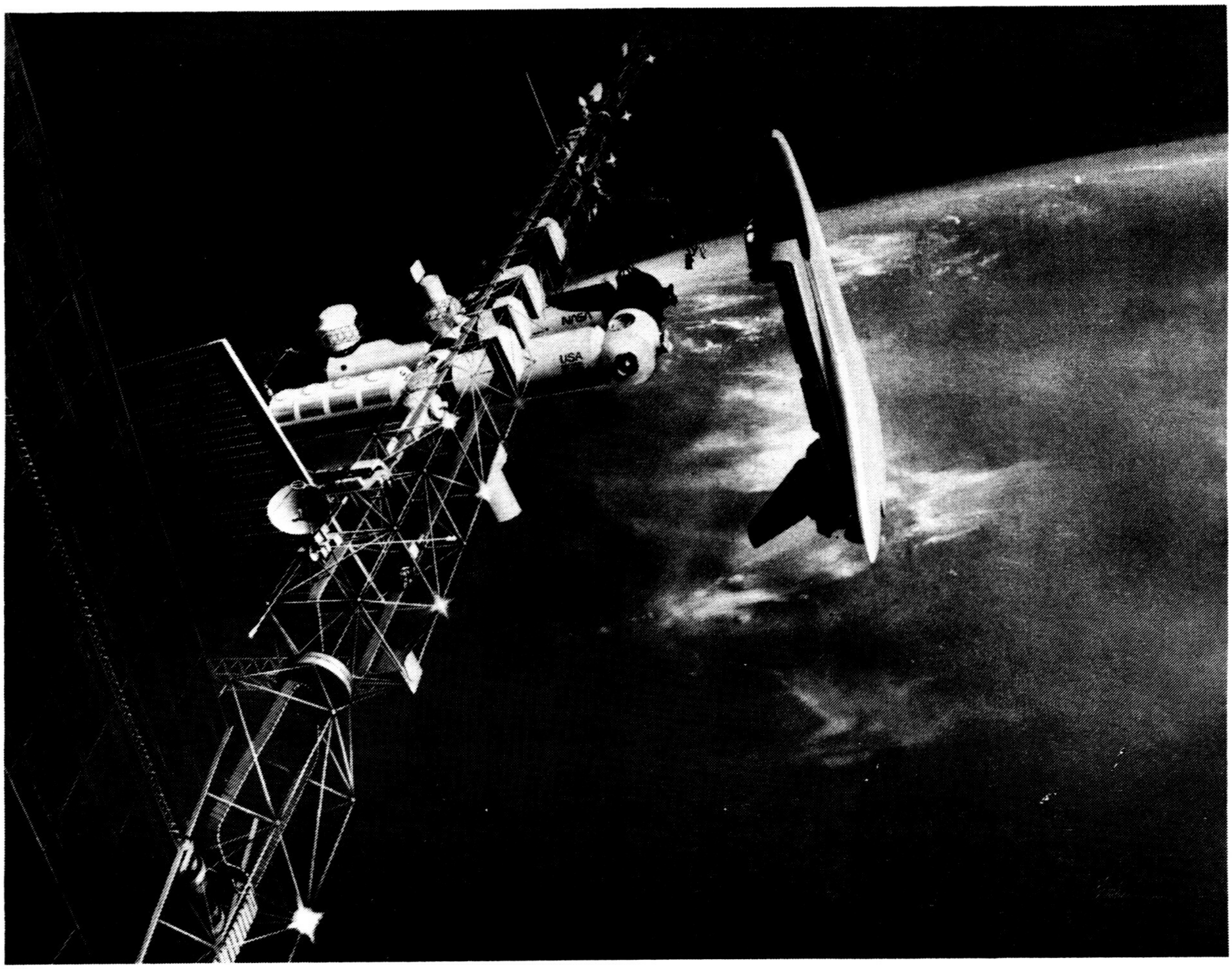
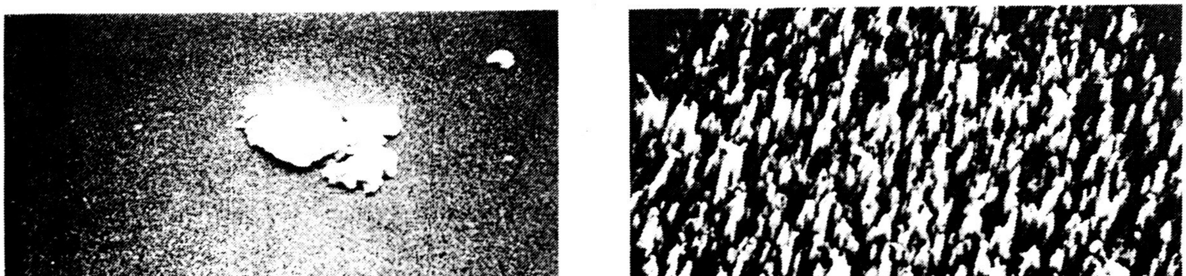


Figure 1.- Space Station Freedom.



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EXPOSED, SEM: 10 000X

Figure 2.- comparisons of STS-8 Kapton specimens (12.7 µm) before and after atomic oxygen exposure, normal impingement.

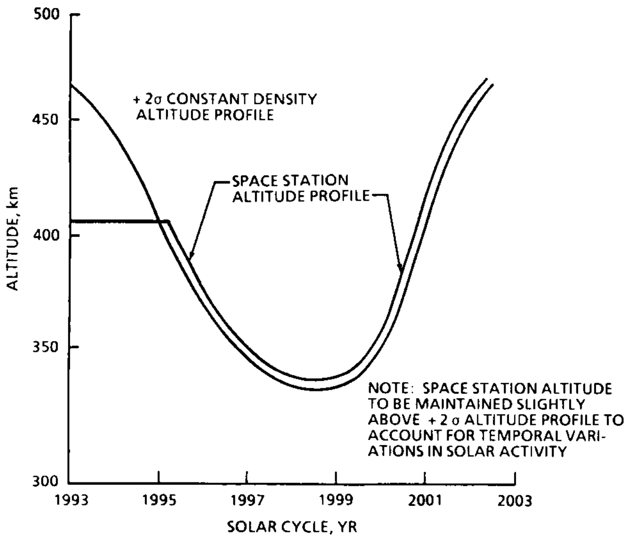


Figure 3.- Space Station altitude variation.

GROUND-BASED SIMULATION NEEDS

Reactivities used to predict surface recession for Space Station materials were derived by exposing these materials during Shuttle flights of limited duration and low atomic oxygen fluence. These inflight investigations remain important to data base development; but, unfortunately, the Shuttle is limited in its usefulness in evaluating coating life. For example, even during conditions of maximum solar activity, a 7-day mission at an altitude of 222 km would result in an atomic oxygen fluence of only 1.3×10^{21} atom/cm^2, assuming maximum (normal incidence) exposure. Yet fluences for long-duration missions, such as the Space Station, will be in the range of 10^{22} to 10^{23} atom/cm^2. Therefore, studies must be conducted to determine the validity of extrapolation to high fluence conditions, using reactivities derived from low fluence exposures. To aid in these investigations, atomic oxygen simulation facilities are being developed using various techniques to accurately simulate the low Earth orbit (LEO) environment.[3] These facilities will be used to study 1) material interaction rates as functions of time, 2) the interaction mechanisms leading to surface recession, and 3) the full life (10^{22} to 10^{23} atom/cm^2) effects of atomic oxygen on exposed surfaces and protective coatings. These facilities must produce a beam of neutral atomic oxygen at energy levels typical of orbital conditions (5 eV). In addition, these facilities must be capable of producing fluxes in the range of 10^{16} to 10^{17} atom/S-cm^2, if material reactivity studies at typical Space Station fluences are to be conducted within reasonable periods of time. For example, assuming an incident flux as high as 5×10^{16} atom/S-cm^2, materials must be exposed for approximately 50 hours to obtain fluence levels typical of Space Station solar inertial surfaces.

The variety of approaches used throughout the country and the high level of activity to produce high-fidelity oxygen beams have provided at least two facilities (Los Alamos and Physical Sciences Corporation) in which material selections and protective coating evaluations can be conducted. Studies are now underway in the laboratories to evaluate

Table 1.- SURFACE RECESSION PREDICTIONS FOR SPACE STATION COMPONENTS

		CONSTANT ALTITUDE (465 km)		CONSTANT DENSITY (2×10^8 ATOMS/cm^3)	
MATERIALS	LIFETIME, YR	FLUENCE, ATOMS/cm^2	RECESSION, cm (mil)	FLUENCE, ATOMS/cm^2	RECESSION, cm (mil)
GRAPHITE EPOXY STRUCTURAL MEMBERS, FORWARD FACING SIDE	30	3.6×10^{22}	8.6×10^{-2} (34)	*1.5×10^{23}	3.4×10^{-1} (132)
SOLAR POWER ARRAYS FRONT & BACK, EXPOSURE	20	1.3×10^{22}	3.8×10^{-2} (15)	*5.5×10^{22}	1.7×10^{-1} (65)
RADIATOR SURFACES FRONT & BACK, EXPOSURE	20	1.5×10^{22}	—	*6.3×10^{22}	—

*CONSTANT DENSITY RESULTS IN APPROXIMATELY 4 TIMES MORE FLUENCE candidate Space Station materials under conditions of full-life (15-30 years) exposure.

SPACE STATION
MATERIAL EVALUATION STUDIES

Flight experiments were conducted during Space Shuttle missions STS-5 and STS-8 to develop a fundamental understanding of the deleterious effects which result from exposure of a variety of materials to atomic oxygen, the principal constituent of the LEO environment. These experiments have demonstrated that, although the ambient density of atomic oxygen is quite low (10^9 to 10^7 atoms/cm^2) at altitudes where LEO spacecraft typically operate (300 to 600 km), the high orbital speed of the vehicle can result in incident fluxes (10^{14} - 10^{15} atoms/S-cm^2) and collisional energies (translational energies equivalent to ~ 60,000 °K) large enough to interact with and degrade many material surfaces.

Results of these earlier experiments[4] have also shown that prolonged exposure of sensitive spacecraft materials to the LEO environment will result in degraded systems performance or, more importantly, will lead to requirements for excessive on-orbit maintenance, with both conditions contributing significantly to increased mission costs and reduced mission objectives. These problems are especially important for future DOD space-based platforms launched by expendable vehicles and delivered to orbits not easily accessible for maintenance by the Space Shuttle. In addition, our laboratory and flight results represent a relatively immature data base, and the synergistic aspects of atomic oxygen, UV radiation, ionizing radiation, and micrometeoroid or space debris impacts are not adequately understood.

Materials most adversely affected by atomic oxygen interactions include organic films, advanced (carbon-based) composites, thermal control coatings, organic-based paints, optical coatings, and thermal control blankets, commonly used in spacecraft applications. In addition to causing changes in the mechanical, electrical, and optical properties of these materials, atomic oxygen can also interact with spacecraft surfaces to produce chemiluminescence, or "glow" within the ultraviolet (1100 to 4000 Å), visible (4000 to 8000 Å), and infrared (1.2 to 5.5 μm) wavelength ranges. These emissions can, in turn, interfere with or obscure low-light-level observations made aboard the Space Station and obtained from orbiting satellites. To obtain a more basic understanding of these and other environmental effects, NASA has two noteworthy experiments under development: 1) the EOIM-3 (Evaluation of Oxygen Interactions with Materials, third series) flight experiment to obtain accurate reaction rate measurements for a large number of materials used in Space Station applications; and, 2) an OAST spacecraft glow experiment to quantify glow brightness as functions of orbital altitude and surface temperature and study the interaction mechanisms responsible for the glow emissions.

EOIM-3 Atomic Oxygen Effects Experiment

The EOIM-3 materials technology experiment, which is now manifested on STS-44 for flight during January 1991, has as its co-investigators, the Johnson Space Center (JSC), Ames Research Center (ARC), Goddard Space Flight Center (GSFC), the Jet Propulsion Laboratory (JPL), Langley Research Center (LaRC), Lewis Research Center (LeRC), and Marshall Space Flight Center (MSFC), as well as The University of Alabama at Huntsville (UAH), Aerospace Corporation, the Air Force Geophysics Laboratory, Canada, the European Space Agency, and Japan. It consists of active sensors and passive exposure trays (see figures 4 and 5) installed on a payload support structure mounted in the Orbiter cargo bay. The active sensors will be used to study atomic oxygen interaction mechanisms that lead to unwanted changes in material properties and will enable accurate reaction rate measurements to be made for materials provided by the participating laboratories. The passive trays, which allow many materials to be evaluated, will contain approximately 1,100 disk specimens that will be analyzed after the flight is completed.

To implement the experiment objectives, a mass spectrometer operated from inside the Orbiter crew compartment will be used to measure the ambient oxygen density during the exposure period and identify reaction products generated by AO interactions with the material surfaces. During the mission, controlled exposure will be accomplished by flying the Orbiter with its payload bay into the velocity vector for 40 hours at a reduced altitude of 220 km, or 120 nmi. During the exposure period, the mass spectrometer will first be rotated to view along the orbital velocity vector (AO neutral density measurements) and then toward a rotatable carousel, which will sequentially expose material samples to the mass spectrometer for analysis. Materials used within the carousel sectors will be isotopically labeled

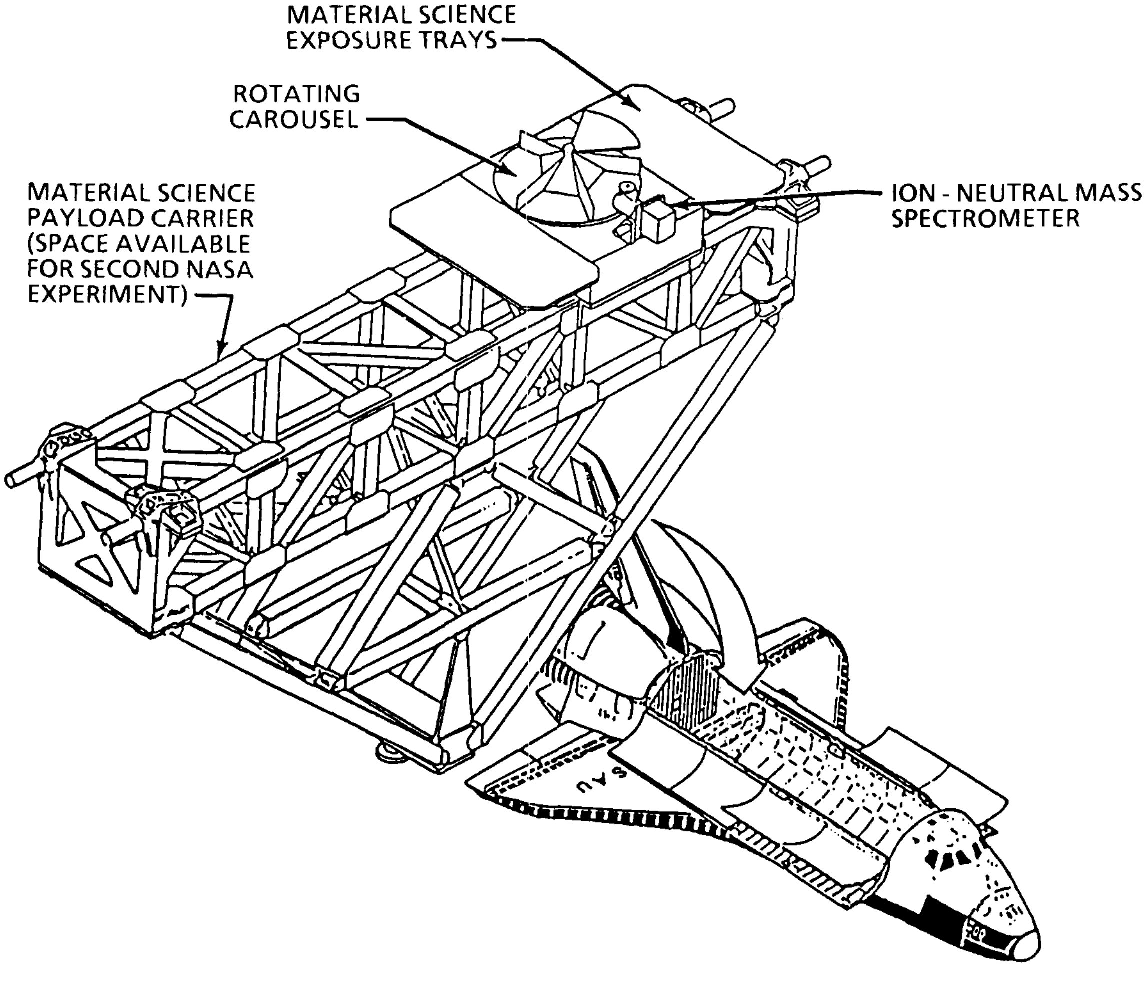


Figure 4.- EOIM-3 Atomic Oxygen Effects Experiment.

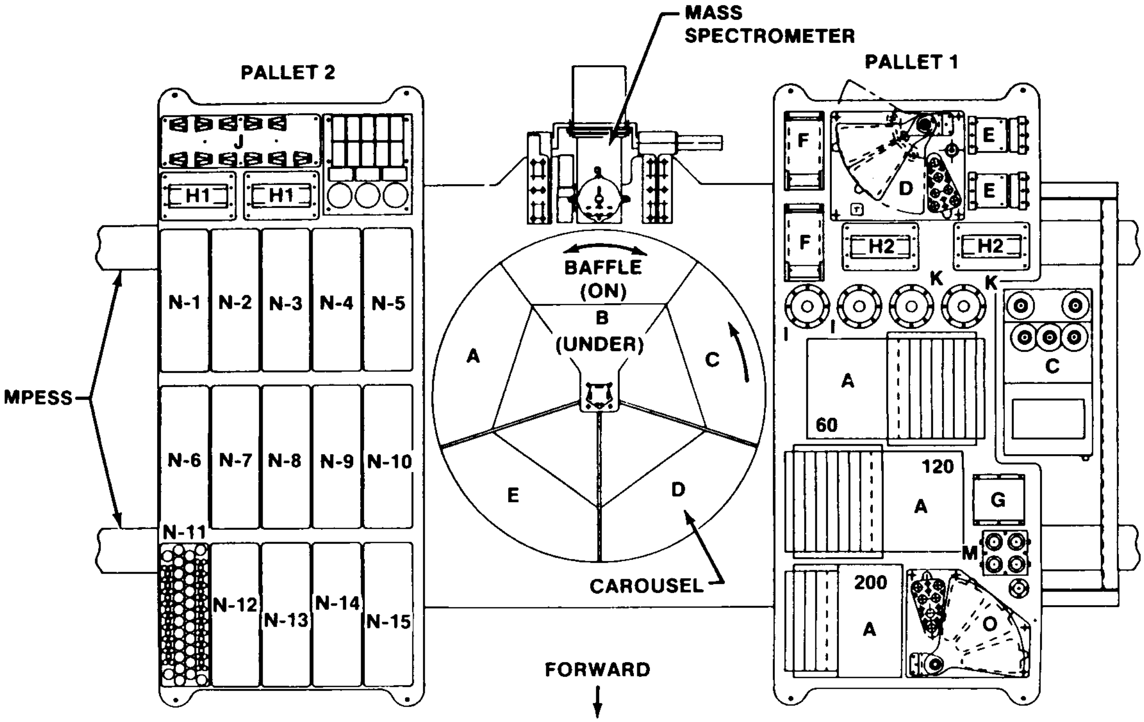
prior to flight to distinguish the atomic oxygen reaction products from common background gases generated within the Shuttle cargo bay.

Additional sensors and heated exposure trays will be used to study the effects of temperature, mechanical stress, and solar radiation on reaction rates. A sensor which exposes samples first to daylight and then to nightside orbital passes will be used to determine if solar energy accelerates the interaction process. Scatterometers will also be provided to estimate AO energy accommodation on surfaces and define atom-surface emission characteristics, as related to surface recession.

Deployable Satellites

A small spacecraft (Get-Away Special class) is being developed by Globesat, Inc. and Utah State University for the purpose of collecting long-term data on the interaction of atomic oxygen with selected material specimens in orbit. This program is presently in the definition phase under a contract from the NASA Langley Research Center (LaRC), with technical assistance being provided by the Jet Propulsion Laboratory (JPL). The definition study will be completed in June of 1989, and the development phase is scheduled to begin in the fall of 1989. The spacecraft should be ready for flight one year later.

As presently defined, the spacecraft is configured for a standard Get-Away Special (GAS) cannister in the cargo bay of the Space Shuttle, with a deployment altitude of approximately 300 kilometers. During its orbital lifetime of about one year, the spacecraft will be stabilized with one sample-covered face in the ram direction and one sample-covered face in the wake direction by means of either a gravity-gradient, torque-rod and transverse-boom method (figure 6) or a



EXPERIMENTS:

A - HEATED PLATE (JSC), 3 EA
B - ATOM SCATTERING EXPERIMENT (UAH), 1 EA
C - ENVIRONMENT MONITOR PACKAGE (GSFC), 1 EA
D - SOLAR UV EXPERIMENT (JSC), 1 EA
E - STATIC STRESS FIXTURE (MSFC), 2 EA
F - UNIFORM STRESS FIXTURE (MSFC), 2 EA
G - ATOMIC OXYGEN MONITOR (MSFC), 1 EA
H1 - COMPOSITE STRESS FIXTURE (LaRC), 2 EA
H2 - COMPOSITE STRESS FIXTURE (JSC), 2 EA
I - SCATTEROMETER (JPL), 2 EA
J - MECHANICAL STRESS FIXTURE (LeRC), 11 EA
K - REFLECTOMETER (LeRC), 2 EA
L - PIN-HOLE CAMERA (LeRC), 1 EA
M - SCATTEROMETER (AEROSPACE CORP.), 1 EA
N - SAMPLE CARRIERS, 15 EA
O - VARIABLE EXPOSURE TRAY, 1 EA

Figure 5.- Active and passive experiments for the EOIM-3 material science exposure trays.

miniature momentum wheel. Some of the samples on each face will be exposed to solar illumination, and a duplicate set will be shielded therefrom.

Data and images from onboard experiments will be telemetered to Earth at monthly intervals for one year. Atomic oxygen fluence will be measured by means of osmium gauges recently developed by JPL. The composition and density of atmospheric constituents will be measured by a neutral mass spectrometer. Erosion rates of some of the specimens will be measured by quartz-crystal microbalances. Scatterometers will provide data on the performance of optical and thermal-control coatings. The change in the elastic index of composite specimens will be measured by ultrasonic techniques, and the decrease in thickness of similar specimens will be measured by a CCD camera and associated fiber optics.

OAST Spacecraft Glow Flight Experiment

Crewmen assigned to the third Space Shuttle mission (STS-3) were instrumental in the discovery of a "bright red halo" extending outward from the vertical stabilizer and orbital maneuvering engine pods of the Orbiter. The red glow was filmed, fortuitously, while the astronauts were photographing an electron beam source for a space plasma experiment during its operation in the cargo bay of the Orbiter. It was also observed during these photographic sequences that the glow region became brighter when primary attitude thrusters were fired, and it persisted for a short time after the firing sequences were terminated. The spacial extents of glow above Orbiter surfaces during quiescent and thruster firing events are shown in figures 7 and 8, respectively.

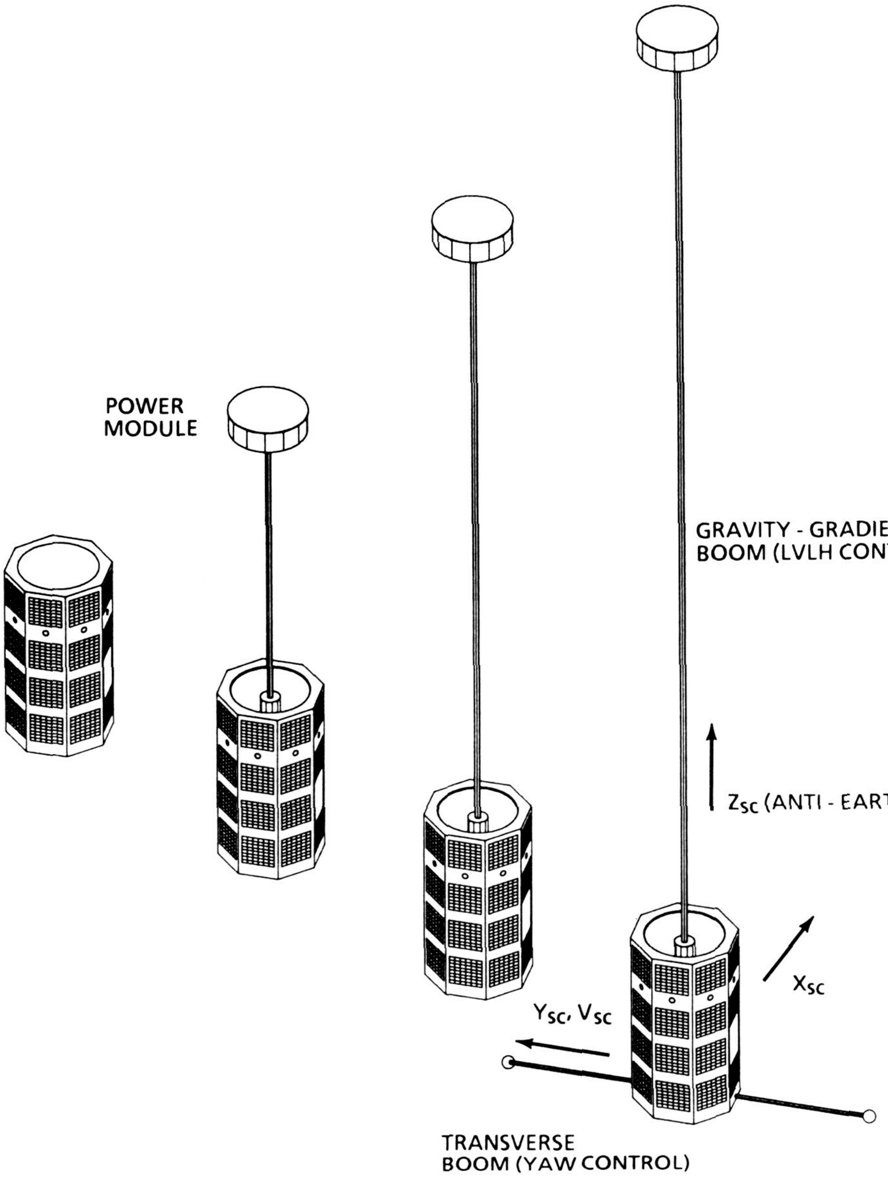


Figure 6.- Attitude stabilization deployment sequence for the Gravity-Gradient, Surface Reaction Satellite.

Simultaneously, investigators from the University of Michigan assigned to the Atmospheric Explorer Satellite Program were investigating anomalous glows in photometer channels which were more intense in the ram, or forward-facing, direction. The glows they saw were brightest in the red wavelengths. Since the satellite was in an elliptical orbit, the glows became very bright at low altitude and dimmer at higher altitudes, indicating the atmosphere was likely responsible. These investigators found the intensity to vary directly with atomic oxygen densities at altitudes above 170 km. Below 170 km, they noted a significant increase in the scale of glow brightening versus altitude change. These investigators had reported earlier during the Shuttle era (1977) that spacecraft-related glows were a potential contamination source for this satellite. The emissions were later found to significantly interfere with the scientific data it had provided.

These findings so intrigued the scientific community that they responded with a host of theories to explain the phenomena. A search of laboratory and earlier satellite data revealed a number of possibilities.[5,6] Of interest was the citing of some early glow phenomena (1958) reported on sounding rockets ascending

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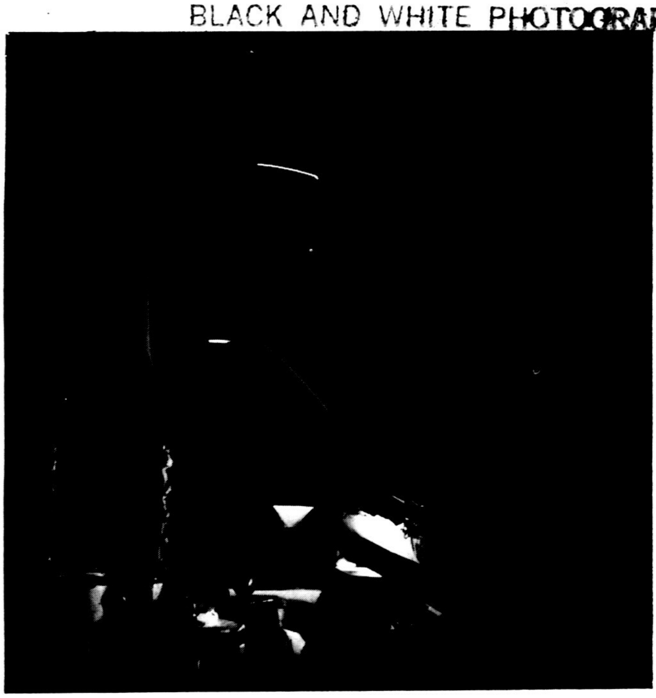

Figure 7.- Nightside photograph obtained during STS-3 mission, showing luminosity, or "glow," on the vertical stabilizer and OMS pod of the Orbiter.

Figure 8.- Subsequent glow photograph, obtained during the firing of a primary attitude control thruster aboard the Orbiter. Note the extent to which the luminescent region produced by gas-phase collisions fills the sky.

through the atomic oxygen maximum, near 95 km altitude. The sparsity of information required expansion for classification of the phenomena.

Investigators from Lockheed collaborated with Stanford University to make additional measurements of Shuttle glow on STS-4 and STS-5 with improved instrumentation, which included an image intensifier and filters to further characterize the spectrum. Lockheed also collaborated with NASA, the Air Force, and Canadian investigators to continue the investigation with hand-held instrumentation, which was easily modified and improved from one Shuttle mission to the next. Improved instrumentation was reflown on STS-8, STS-9, STS 41-D, STS 41-G, and STS-51-D where spectral measurements, intensities, and some altitude information were gathered on the phenomena. As an example, a photograph of the "red glow" observed during the STS-8 mission is shown in figure 9. This glow, which appears above the Orbiter OMS pods and vertical stabilizer, was obtained by flying the vehicle with its payload bay into the velocity vector at a reduced altitude of 222 km. Spacecraft-atmosphere interactions have been found to be important precursors to the glow. Spectral measurements suggest that most of the Shuttle "red" glow is continuum. Laboratory data of the NO_2 recombination spectrum has much similarity to the observed spacecraft spectrum. A popular theory (outlined in figure 10-b., lower portion of the illustration) suggests that atmospheric N and O recombine on the surface to form NO, which catalytically recombines with ram atmospheric O to form NO_2 in the excited state. After investigating a number of Shuttle flights, it was learned that cold surface temperatures associated with the insulated tile surfaces (which cool quickly when radiated to deep space) likely contribute to glow intensity (figure 11). Note in figure 11 the glow intensity from three Shuttle flights is shown to change significantly. The change is consistent with the change seen in surface population of NO on the DE (Dynamics Explorer) mass spectrometer source surfaces in orbit.

In addition to visible glows, infrared instrumentation (IRT experiment, Spacelab 2 mission) and UV instrumentation (ISO experiment, Spacelab 1 mission) on the Space Shuttle have detected bright glows. In the UV, glows have also been reported on the S3-4 satellite by NRL and AFGL scientists in Lyman-Birge-Hopfield emission bands of molecular nitrogen. A popular theory for this mechanism involves the surface recombination of atomic nitrogen (see figure 10-b., upper portion of the illustration). It is suggested

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that available "atmospheric N" is swept out by the spacecraft to recombine on the surface. At low altitudes, the plow cloud in front of the moving spacecraft can be sufficiently dense to cause atom exchange between atmospheric N_2 and oxygen atoms reflected off forward-facing surfaces. This atom exchange process yields another source of N, which can also recombine on the surface.

Figure 9.- Glow photograph of the Orbiter, the OMS pods, and the vertical stabilizer during the STS-8 mission. The orange glow appears above the OMS pods, which are in ram. Note that the stars are streaked in the direction of the velocity vector.

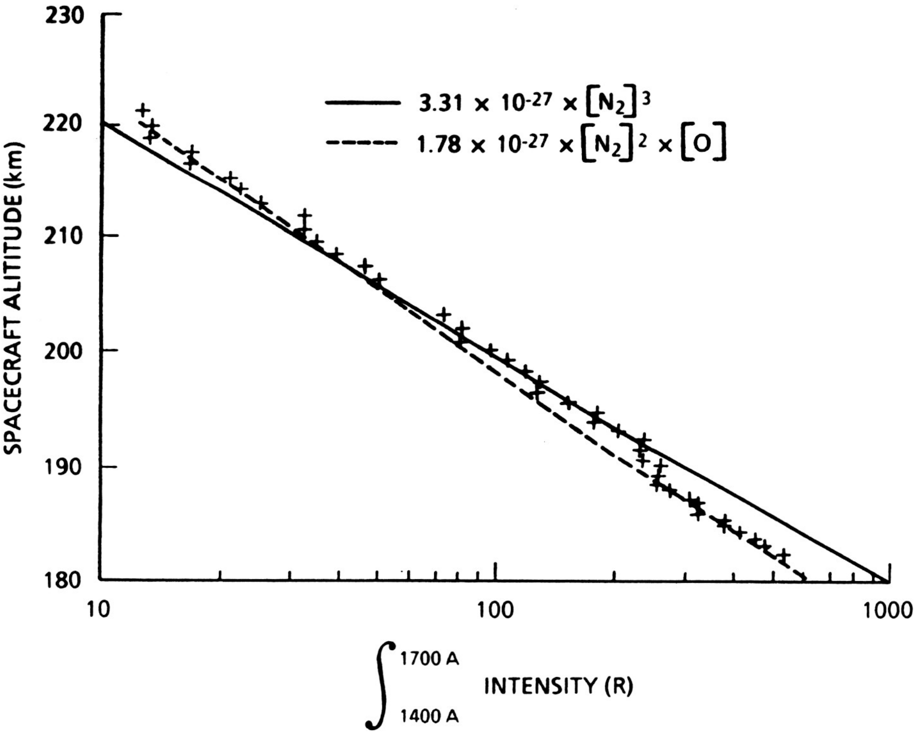


Figure 10-a.- Intensity of nitrogen LBH emissions (1400-1700A) versus altitude for the S3-4 satellite. Note the glow intensity scales as the density of molecular nitrogen to the third power for altitudes between 192 and 205 km, and as the product of oxygen density and the density of nitrogen squared above 205 km. (After Conway, et al., Geophys. Res. Lett., 14, p.628, 1987)

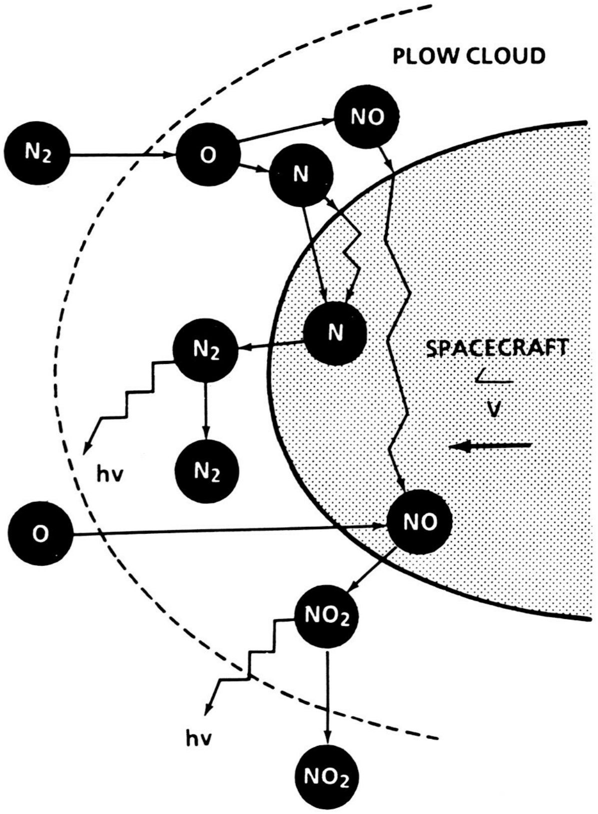
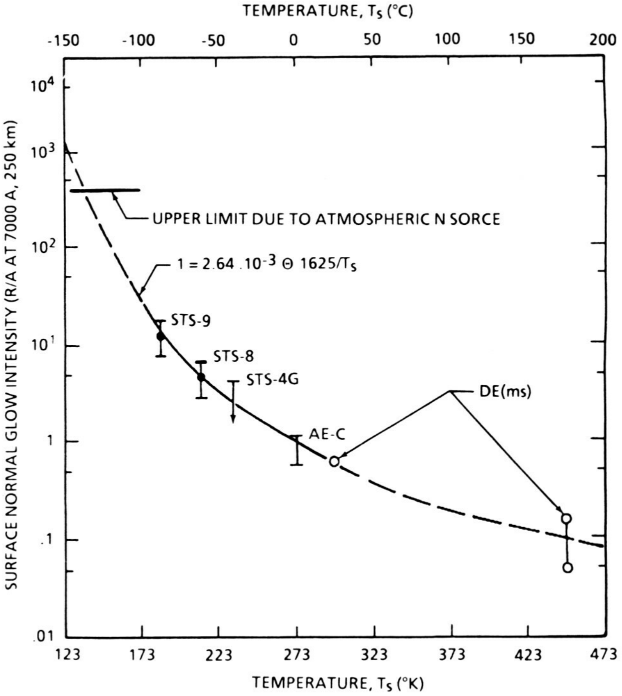


Figure 10-b.- This figure illustrates some insight into the physical processes of spacecraft-atmosphere interaction emission studies. The upper portion of the illustration shows atmospheric N_2 interacting with rebounding O and exchanging atoms to form N and NO. The N is shown to contact surface-bound N and to recombine to form excited N_2. This excited state leads to N_2 LBH emission, which is suspected as being responsible for the low altitude glow (see fig. 10-a.) on the S3-4 satellite. The lower portion of the illustration shows atmospheric O impinging on NO, which is weakly bound to the surface. Surface recombination of O and NO will lead to NO_2. Emission of this excited molecule is proposed as being responsible for the "red" Shuttle glow.

Figure 11.- A plot of surface normal intensity (normalized to 250 km) for the STS-8, STS-9, and STS 41-G glow observations. Units on the x-axis are R [Rayleighs, or 10^6 photons/S-cm^2 (column)] per Å at a wavelength of 7000 Å. The solid curve through the data is a best-fit curve, exponential, with an equivalent bond energy of 0.14 eV. The dashed portion of the curve is an extension of the same formulation. The DE (ms) points on the plot show the inferred slope of the temperature effect from the Dynamics Explorer (mass spectrometer) measurements.



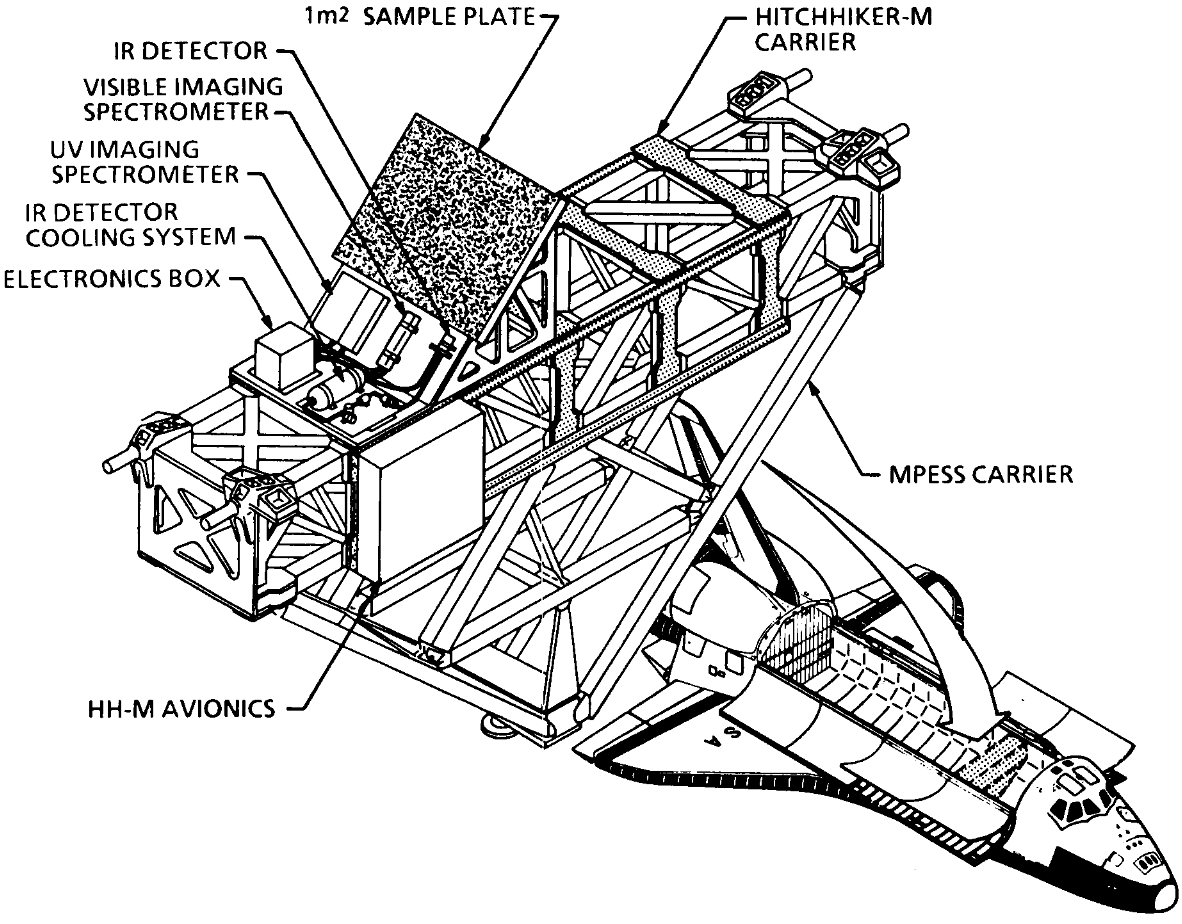


Figure 12.- A schematic of the OAST spacecraft glow flight experiment on a pallet structure. A sample plate is viewed by three detectors, which examine the far-UV to IR wavelength regions. The payload is to be activated from ground commands and will be operated while the sample plate is in a ram attitude, in low Earth orbit.

Observations of glow have provided a number of insights into the phenomenology of these events; however, many aspects still require clarification. For example:

- What are the spectrum and intensity in the IR and UV wavelength ranges?
- Is direct collisional excitation responsible for the IR glows, or does it include other mechanisms as well?
- Does glow intensity change in a predictable way with surface temperature, as our limited flight data seem to suggest?

A scientific payload to address these concepts is evolving as an important element of the newly-initiated OAST Industry/University Technology Experiments Program. This experiment, which is now in its concept development phase, will consist of a temperature-controlled sample plate that is observed by visible, UV, and IR sensors within the Orbiter cargo bay. The experimental hardware (see figure 12) will include scientific instruments operated by ground commands to observe ram glow on the surface of a temperature controlled sample plate.

To satisfy mission objectives, the payload will be operated, ideally, for four orbits near the end of an STS satellite deployment mission. The last two orbits will be elliptical and will be staged as part of the Orbiter reentry sequence, with perigees near 170 km and positioned near the sunset terminator. The sample plate will be thermally conditioned prior to the ram attitude observations by allowing it to radiatively cool to deep space. Results obtained from this experiment will provide the scientific community with more insight into the underlying mechanisms producing space glow and will enable engineers to develop new materials and coatings for future spacecraft such as SDI (Space Defense Initiative) that will supress these unwanted emissions.

ORBITAL DEBRIS EFFECTS: DISTINCTIONS BETWEEN NATURAL AND MANMADE SPACE DEBRIS

The natural meteoroid environment has historically been a design consideration for spacecraft. Meteoroids are part of the interplanetary environment and sweep through Earth orbital space at an average speed of 20 km/sec. At any one instant, a total of about 200 kg of meteoroid mass is within 2,000 km of the Earth's surface. Most of this mass is concentrated in meteoroids of 0.01 cm or less in diameter.

Manmade space debris ("orbital debris") differs from natural meteoroids because it is in Earth orbit during its lifetime and is not transient through regions of space surrounding the Earth. The number of debris objects and the relative velocities of objects in geosynchronous orbit (GEO) are small, so debris is not considered to be a problem in GEO. However, the situation is different in low Earth orbit (LEO), since the flux of debris particles and their relative velocities are highest there. The probability of damaging impacts from orbital debris peaks in this region and exceeds the probability of impacts from the natural meteoroid environment.

THE ORBITAL DEBRIS ENVIRONMENT

There are approximately 3,000,000 kg of manmade orbiting objects within 2,000 km of the Earth's surface (15,000 times more mass than the meteoroid mass). These objects are mostly in high-inclination orbits, sweeping past one another at high relative velocities at an average of 10 km/sec. About 7,000 of these objects are currently being tracked by the U. S. Space Command. Nearly all of the mass in orbit is centered in about 3,000 spent rocket stages, inactive payloads, and a few active satellites. A smaller amount of mass, about 40,000 kg, is in the remaining 4,000 tracked objects. Most of these smaller objects are the result of the 130 satellite fragmentations that have occurred since the beginning of the space program. The population of objects too small to be tracked by the Space Command has been sampled by NASA from ground telescope measurements for objects down to 5 to 7 cm in diameter, and from analysis of hypervelocity impact pits on the returned surfaces of the Solar Max satellite for micro-sized debris. These data indicate a total mass of about 1,000 kg for orbital debris sizes of 1 cm or smaller and about 300 kg for orbital debris smaller than 0.1 cm. This distribution of mass and relative velocity is sufficient to render the orbital debris environment more hazardous than the meteoroid environment to most spacecraft operating in Earth orbit below 2,000 km altitude.

The flux of debris as a function of object size is compared with the meteoroid flux in figure 13. As noted above, actual measurements of the debris flux have been done only for large (greater than 5 to 7 cm diameter) and for very small (smaller than 100 micron) particles. The flux of debris shown in figure 1 for intermediate sizes is an interpolation between these sets of measured values. However, the interpolated values are consistent with those estimated from the size distribution of fragments from explosions. In order to obtain additional data, NASA has initiated a measurement program in collaboration with U. S. Space Command to use their existing optical telescopes and radars. However, these sensors are limited to sizes above 5 to 7 cm. Consequently, NASA is actively considering the construction of a specialized radar capable of detecting 1 cm or smaller objects in orbit at 500 km.

A typical altitude distribution of objects tracked in LEO up to 2,000 km is shown in figure 14, where the number of objects in a 10-km band is plotted against altitude. The peak density is near 800 km, where the density is about 200 objects in a 10-km band. At the Space Station altitude of about 500 km, the density is less, about 80 objects per 10-km band.

The debris population illustrated in figures 13 and 14 represents the current situation. Space activity is placing debris in orbit faster than drag removes it, resulting in an increase in the population of orbital debris by an average of 300 objects per year, at a time when launch rates are about 120 per year. This rate of increase includes only trackable objects; i.e., those having sizes of 10 cm or larger. The increase in

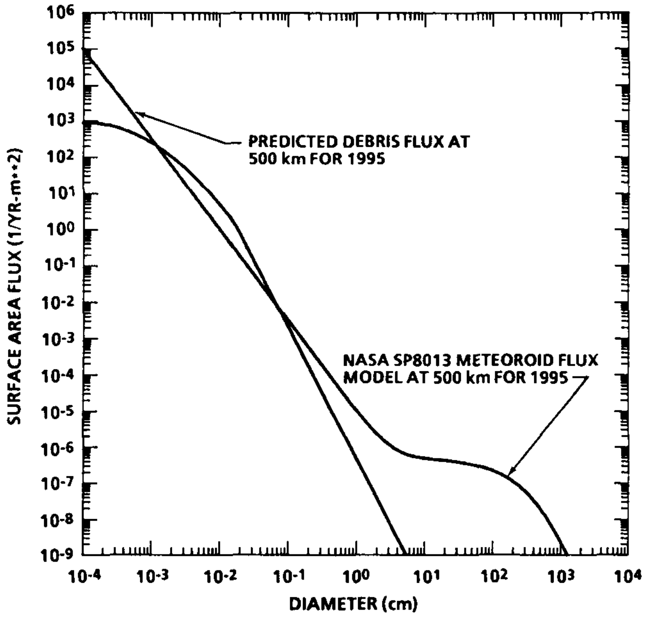


Figure 13.- Flux of orbital debris in the region near 500 km as a function of debris size. The meteoroid flux is also shown for comparison.

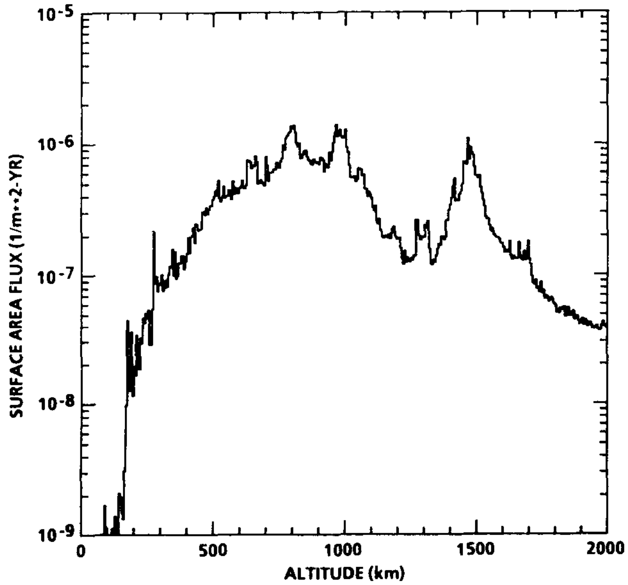


Figure 14.- The altitude distribution of objects tracked by the U. S. Space Command.

number of small objects may be much larger. As a consequence, the design of large spacecraft intended to operate in the future (as for example, the Space Station) must take into account the expected future increases in the debris population. The NASA has an intensive modeling effort underway to make the best possible predictions of the future debris environment.[7,8,9,10] The work has resulted in publication of the "Spacecraft Design Environment," which includes both the current debris environment and current best predictions of the future environment.

EFFECTS OF ORBITAL DEBRIS

The effects of orbital debris and meteoroid impacts can be divided into two broad regions:

(a) *Erosion and pitting:* Small particles (less than 100 microns) are numerous. Impacts from these generally do not lead to penetration of surfaces but cause pitting and erosion. The Solar Max surfaces were peppered with thousands of tiny impact pits.

(b) *Catastrophic impacts:* Large debris objects are few in number relative to small debris, so the probability of impact is low. However, the impact effects of a large object at 10 km/sec could be devastating. It is estimated that a spacecraft in LEO with 40 m^2 of surface area would suffer one impact from a 1-cm particle every 1,000 years. Viewed from another perspective, 1 out of 100 spacecraft in orbit would be impacted by a 1-cm particle every 10 years. While the frequency of this event is small, an impact of this kind would destroy most spacecraft since, at an impact velocity of 10 km/sec, a 1-cm aluminum sphere has kinetic energy approximately equivalent to a hand grenade. There is, of course, an intermediate region where either effect can predominate, depending on the system being impacted. Although the estimated probability is quite low (less than 0.05 percent), the impact of a 1 mm particle on a space suit could cause a catastrophic puncture of the astronaut's life support system. In comparison, the impact of a 1 mm particle on the Space Shuttle Orbiter tiles would produce some pitting damage, but nothing of great significance.

All types of materials can be pitted or penetrated by hypervelocity impacts from meteoroids or orbital debris. Whether or not these impacts are important depends on the function of the material. For example, a mirror could be affected by pitting and erosion caused by the impact of very small particles, yet that would not be a problem for structural materials. A pressure vessel could be damaged catastrophically by the impact of a particle large enough to penetrate its wall, while some other systems could tolerate similar penetrations without difficulty.

Materials retrieved from the Solar Max satellite, the Palapa and Westar satellites, and the Space Shuttle

Orbiter windows are the only available samples which show the actual effect of the meteoroid/debris environment. These materials show impact pits from both micrometeoroids and very small orbital debris particles, the latter identified as mostly paint flakes and aluminum oxide (AlO) particles. Figure 15 shows an impact penetration of one of the aluminum louvers recovered from the Solar Max satellite. Microscopic examination of these pits shows shapes and fracture patterns identical to those observed in laboratory hypervelocity impact tests. By analysis of these shapes, patterns, and remnant chemistry, it has been possible in some cases to deduce the size, velocity, and chemical composition of the impacting particles. Additional information on the characteristics of microparticle orbital debris has been obtained from a stratospheric dust collection program.

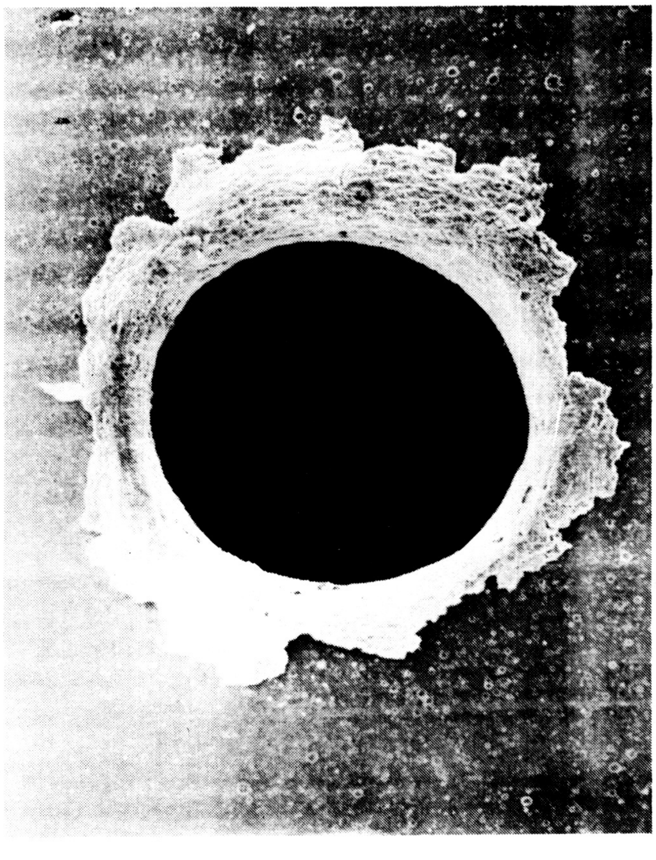


Figure 15.- Penetration of an aluminum louver from the Solar Max satellite by a hypervelocity impact of orbital debris.

LABORATORY EVALUATION OF ORBITAL DEBRIS IMPACTS

The effects of orbital debris impacts can be simulated in the laboratory by firing solid projectiles at test targets. The destructive effect of hypervelocity impact is illustrated in figure 16, which shows a cross-section of the result of an impact on aluminum at 7 km/sec. Light-gas guns can accelerate particles up to a centimeter or more in diameter to velocities of about 7 km/sec. The NASA has an active experimental hypervelocity impact research program using light-gas guns. Figure 17 shows the small light-gas gun at NASA/JSC. This gun is capable of firing 1-mm particles at velocities up to 7 km/sec. The primary objectives of the work have been to study new materials and new designs for spacecraft shielding and to evaluate the effects of hypervelocity impact on subsystems and components of spacecraft.

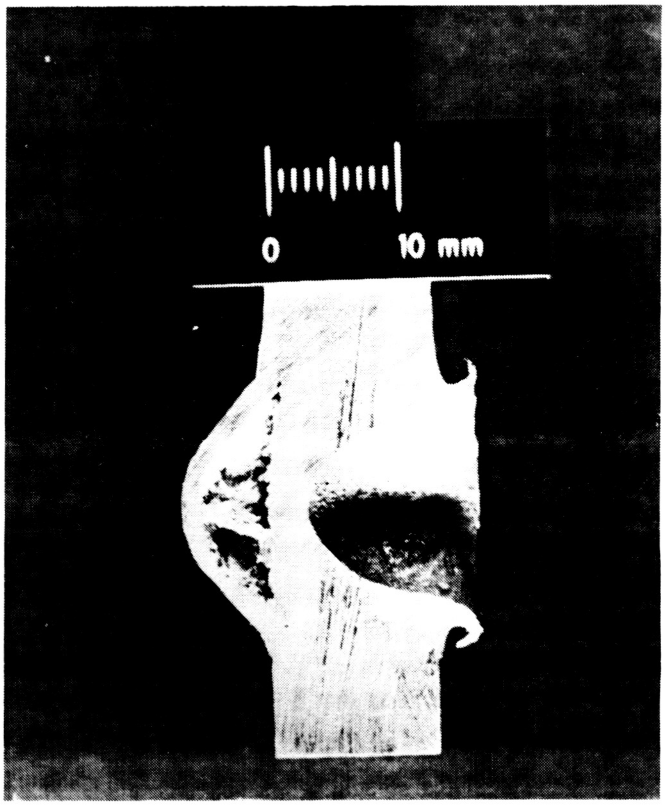


Figure 16.- Hypervelocity impact crater in aluminum.

ORIGINAL PAGE
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Figure 17.- Light-gas gun at the NASA/Johnson Space Center.

New types of materials have been investigated for use in shielding. Materials are needed that can undergo hypervelocity impact, destroy, or stop the impacting object, while producing a minimum amount of secondary particles and impose a minimum weight penalty. Ceramic foam materials and composite materials, such as graphite epoxy, have been tested and show promise. Hypervelocity impacts on complex materials like these produce different effects than impacts on metals such as aluminum. This is illustrated in figure 18, which shows the effect of a hypervelocity impact on a graphite epoxy composite material. In addition to the obvious penetration damage, extensive delamination occurs below the surface around the impact area. During the past year, significant progress has been made in developing new shielding geometries and combining these geometries with new materials to produce a significant improvement in shielding design. A patent disclosure has been filed to cover these new developments.

NYLON PROJECTILE (L/D = 1)
DIAMETER: 1.75 mm
DENSITY: 1.14 gm/cc
VELOCITY: 6 km/sec

Figure 18.- Hypervelocity impact crater in graphite-epoxy composite material.

Tests of space suit materials and truss structures for the Space Station have been conducted. In testing the space suit materials, it was found that the addition of a thermal-meteoroid garment (TMG) layup to the basic suit design contributed significantly to the overall protection against high-velocity particle impacts.[11] Results of these tests now indicate the EVA suits proposed for the Space Station should provide the astronauts with a necessary probability of better than 99.95 percent that no lethal hits by micrometeoroids or space debris will occur over an exposure time of 936 EVA hours during a 1-year period on orbit. It should be noted, however, that these safety figures take into account the debris environment as it is known today and shielding factors provided by the Portable Life Support System (PLSS) and the Space Station structural elements.

Tests of pressurized vessels have provided new insight into possible causes of breakups of spent upper stages in orbit. With only modest internal pressure, the propagation of damage from a single debris impact can lead to destruction of the entire pressure vessel. Impact by only a very small debris object can initiate a catastrophic breakup.

The velocity achievable with such guns falls short of the average impact velocity of 10 km/sec expected for debris impacts. In order to accelerate moderate size projectiles to velocities greater than 7 km/sec, the only proven method is the shaped-charge gun, which generates velocities up to about 11 km/sec by detonating a charge of high-explosive. This method has not found wide application because of cost and experimental difficulties, but recent work sponsored by NASA/JSC has shown promising results. Small particles, a few microns in size, can be accelerated to velocities of 10 km/sec or greater by spark-discharge accelerators, and this technique has proved useful for studying the erosive effects of small orbital debris.

The laboratory results for the impacts of large particles at 7 km/sec can be extrapolated to higher velocities by the use of models whose empirical constants are adjusted to fit the low-velocity results. Currently, this method fails or works poorly with complex materials such as foams or composites. It is also difficult to deal with complex geometries. However, NASA is continuing to pursue an active materials and shielding research program, and, as more data become available, our ability to understand impact processes under realistic conditions will continue to improve.

ORBITAL DEBRIS COLLISION WARNING

As the population of debris in LEO increases, new concepts for protecting spacecraft must be developed. Onboard detection will probably play a key role in warning against orbital debris collision. In order to develop methods for onboard detection of debris in the critical size range (1 mm to 10 cm), significant advances in technology and techniques are required. A flight experiment is planned by NASA to obtain the data required to design a debris collision warning system. The objective of this experiment, which will also be funded under the OAST Industry/University Technology Experiment Program, is to characterize statistically the LEO debris environment for sizes down to 1 mm diameter using visible photometry and infrared radiometry. The data acquired will be used to define the optimal sensors for detecting debris from an orbiting platform and to model the expected performance of a debris warning system based on these sensors. The experiment hardware will consist of a 60-inch telescope fitted with detectors for both visible light and infrared radiation. The telescope and detectors will be flown in the Space Shuttle payload bay to observe the debris environment. The experiment concept is illustrated in figure 19, which shows the telescope mounted in the Space Shuttle payload bay.

CONCLUSIONS

The oxidative and debris effects of the orbital flight environment will require new protective coatings and significant improvements in shielding geometries for future spacecraft. The results of earlier flight experiments have shown that forward-facing surfaces of LEO spacecraft are subject to an atomic oxygen flux of about 1 monolayer/sec. This can produce surface recessions as high as 0.1 monolayer/orbit for unprotected, highly-reactive materials, such as Kapton and epoxy-based composites commonly used in spacecraft applications. In addition, it is anticipated that these surfaces will also encounter a significant

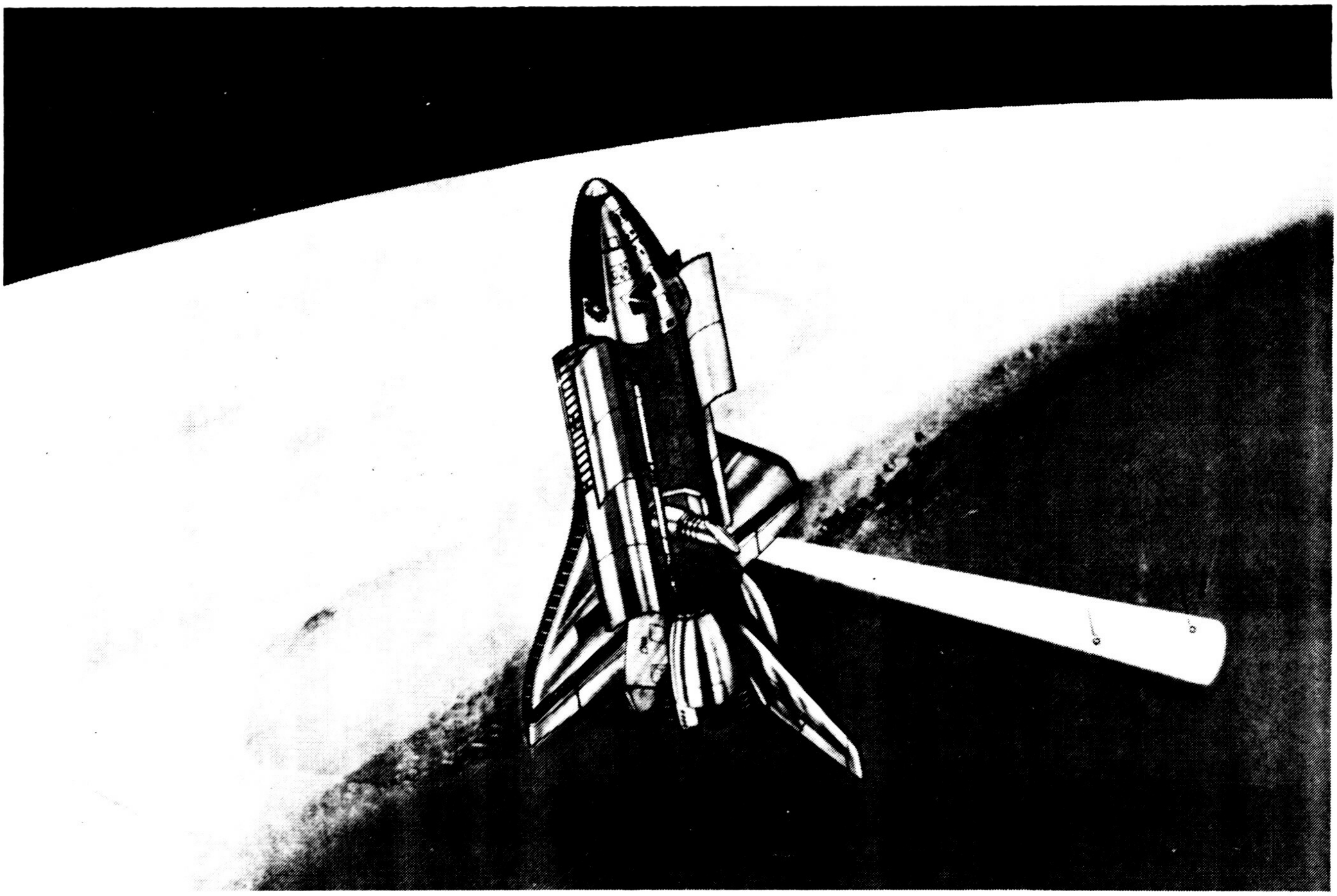

Figure 19.- Detection of orbital debris with a telescope mounted in the Space Shuttle payload bay.

debris flux ($10^5 - 10^3$ particles/year-m^2) of high-energy particles, ranging in size from 1 to 10 microns in diameter, respectively.

It has not been determined to what degree the effects of this combined environment will have on protective coatings now under development for sensitive spacecraft systems. For example, one coating concept now under consideration for large-area, flexible solar arrays consists of a thin film of silicon dioxide (SiO_2) co-deposited with a small percentage of polytetrafluoroethlene (PTFE) to improve flexibility. Aluminized Kapton, which is more pliable than SiO_2 Kapton, would be used for substrate elements, such as stiffener sleeves and hinge reinforcements, where bends and folds may cause cracks or other surface defects to appear in the protective coating. Suitable thicknesses of SiO2/PTFE and Al that are free of defects have been shown from laboratory exposures to provide effectively unlimited atomic oxygen (AO) lifetimes.[12] However, space debris impacts would undoubtedly damage these coatings, and atomic oxygen could then react with exposed regions of the substrate to produce significant undercutting below the protective surface. As the number of particle impacts increases, these damaged areas will coalesce and may eventually result in total failure of the protective coating.

In addition to these anticipated effects, bombardment by larger diameter (0.1 – 1.0 cm), high-velocity particles may produce catastrophic failure of such spacecraft components as onboard propellant tanks, pressurized modules, composite structures, and large-area optical reflectors. Thus, additional studies must be conducted by the aerospace community to devise and develop new shielding concepts for these components and evaluate the synergistic aspects of long-term exposure of future spacecraft to the atomic oxygen/orbital debris LEO flight environment. Such studies will provide a better understanding of the combined effects of this exposure and will increase confidence in the design of Space Station Freedom, satellites, and future space-based platforms.

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APPENDIX A

Follow-On Studies

NASA IN-SPACE TEST BED USER SURVEY

1.0 Experiment Name

EOIM-4 (Evaluation of Oxygen Interactions with Materials, Fourth Series)

2.0 Experiment Description

Describe the experiment in terms of its overall function, hardware, and scope.

EOIM-4 represents a follow-on to EOIM-3 which is now assigned to STS-44 (January 1991). This new experiment will expose Space Station and SDI materials and coatings to the polar or equatorial LEO environments for extended periods to expand our limited data base for atomic oxygen (AO), ionizing radiation, and solar UV interactions with materials. EOIM-4 will consist of both active and passive experiments provided by the NASA centers and SDIO aerospace contractors.

3.0 Experiment Objective

Describe the experiment's objective in terms of its most critical parameters that must be demonstrated.

The objectives of this experiment are to expand our NASA SDIO materials interaction data base for LEO spacecraft in polar and equatorial orbits and develop a fundamental understanding of the chemical mechanisms leading to mass loss, optical and mechanical property changes, and surface recession. This data base will enable selection and use of spacecraft materials that retain their essential properties during extended exposure (15-30 years) to the LEO flight environment.

4.0 Experiment Category

Indicate the category(s) for which the experiment could be classified. (Note: EOIM-4 will include many participants)

US Commercial	x	US Govt Lab	x
DOD	x	University	x
NASA	x	Foreign	
Other			

5.0 Point of Contact

Name James T. Visentine
Organization NASA Johnson Space Center
Address Structures and Mechanics Division
Houston, TX 77058

Phone (713) 483-8923
Facsimile (713) 483-2162

6.0 Level of Technological Maturity

Indicate the experiment's level of technological maturity.
Level 1: ____ Basic Principles Observed And Reported
Level 2: ____ Conceptual Design Formulated
Level 3: ____ Breadboard Demonstrated
Level 4: ____ Tested in Relative Environment
Level 5: x Tested in Space (Aboard the Shuttle)

7.0 Benefits

7.1 Applications

List expected range of applications (missions).

- Space Station
- SDI Space-Based Platforms
- Earth Observation Satellites
- Polar-Orbiting Platforms

7.2 Performance Improvements/Cost Reductions

Describe the expected performance improvements or cost reduction per application.

- Spacecraft mission operation time will be significantly extended.
- Requirements for STS on-orbit maintenance will be minimized.
- Program development costs for replacement spacecraft will be significantly reduced.

8.0 Need for Space Testing

Define the need for space testing as opposed to merely ground testing. Also, describe the advantage or necessity for this experiment to be flown on a free-flying test bed versus on the STS or Space Station.

- Accurate, reliable long-term space exposure data are needed to support development of reliable ground-based materials screening tests and full-life certification programs using accelerated testing techniques. Space testing is required to later verify the results of these ground-based laboratory studies.

9.0 Orbital Parameters

Indicate the experiment orbital parameters.

LEO	x	Equatorial	x
GEO		Polar	x
Duration		4-6 mos	

Critical x Desirable ____
Unimportant ____

10.0 Physical Limits

10.1 Mass

Dry Mass	795	kg
Consumables	795	kg

10.2 Dimensions

	Stowed	Deployed
X-Axis	1.25 m	1.25 m
Y-Axis	2.20 m	2.20 m
Z-Axis	0.75 m	0.75 m

10.3 Volume

Stowed	Deployed
2.1 m^3	2.1 m^3

11.0 Attitude Control And Determination

Pointing Accuracy	± 7.2×10^3	arcsec (±2 degrees)
Pointing Knowledge	± 7.2×10^3	arcsec (±2 degrees)
Pointing Control Rate	________	arcsec/sec
Jitter	________	arcsec/sec

Critical x Desirable ___

Unimportant ___

12.0 Navigation

Position Error	± 100	m
Velocity Error	± 250	m/s

Critical x Desirable ___

Unimportant ___

13.0 Communication

For each communication link, indicate the link path source and destination as well as the data rate.

Source	Destination	Data Rate *kbps*
Payload Carrier	JSC POCC	8

Critical ___ Desirable _x_
Unimportant ___

14.0 Data Processing

Processing Rate ____ mops
Storage 103 mbytes

Critical ___ Desirable _x_
Unimportant ___

15.0 Power

For each device, module, assembly, etc., indicate the power requirements.

Device	Average		Peak	
	kw	hrs/orbit	kw	hrs/orbit
Electronics*	0.75	1.5	1.0	1.5

Critical _x_ Desirable ___
Unimportant ___

*NOTE: Including a flight mass spectrometer and temperature controlled heated trays.

16.0 Thermal Management & Control

16.1 Device Temperature/Heat Rejected

For each device, component, module, assembly, etc., indicate its operating temperature (at some cold plate, or cavity/enclosure) and the heat rejected at that temperature.

Device	Heat Rejected kw	Temperature Range ℃
Electronics	1.0 kw (peak)	±5°C
Optics	– –	– –
Detectors	– –	±2°C
Others	– –	– –

Critical ___ Desirable _x_
Unimportant ___

16.2 Fluids (EOIM-4 requires no fluids.)

Fluid Name	Function

Critical ___ Desirable ___
Unimportant ___

17.0 Orientation

Any	____	Anti-Earth	____
Solar	____	Earth	____
Lunar	____	Inertial	____

Other (described) +ZVV (exposure trays into velocity vector)

17.1 Field Of View ±90 deg (ram exposure)

Critical x Desirable ___

Unimportant ___

18.0 On Orbit Servicing (experiment only)

18.1 Orbit Replacement Units

List any ORU

ORU 1: Passive Exposure Trays
ORU 2: Quartz Crystal Microbalance Sensors
ORU 3: Heated Trays
ORU 4: Mass Spectrometer Ionizer and Detector

For each ORU:

Describe purpose and function of each ORU and proposed method of replacement.

- For high-inclination orbits, each ORU would be replaced using telerobotics controlled from the Shuttle or Space Station.
- For low-inclination orbits, ORU's would be replaced by EVA crewmen from the Space Shuttle.
- Satellite could also be captured and retrieved by the Shuttle and re-deployed on a subsequent mission.

18.2 Resupply Substances

List any substances (gas, liquid, fuel, etc.) to be resupplied.

Substance 1: Attitude Propellant (payload carrier)
Substance 2: Flight-rated Batteries (payload carrier)
Substance 3: ____
Substance 4: ____

For each substance listed above, describe proposed method of resupply.

- Telerobotics or Shuttle capture and service within Orbiter payload bay.

19.0 Environment Contamination

Describe any on-orbit planned activities or potential contingencies which might contaminate the local environment.

- Orbiter primary RCS thruster firings must be inhibited during satellite deployment.
- Orbiter waste water dumps must occur in retrograde directions to avoid re-contact of effluents with material specimens prior to deployment.

20.0 Cost Estimates (Experiment Only)

Indicate estimated costs in thousands.

Flight hardware development	$500K
Integration and launch	$1.1M
Operational	$150K
Recovery	$250K

21.0 Safety and Reliability

Describe any unique or special safety and reliability issues associated with this experiment.

- Payload attitude thrusters must not inadvertently fire during Orbiter RMS capture.
- Experiment power must be remotely shut-down from Orbiter aft flight deck.

22.0 Logistics

Describe any logistics issues and concerns associated with this experiment.

None.

23.0 Other Requirements

Describe any unique or special experiment requirements not asked previously.
This experiment will provide a unique opportunity for NASA and SDIO to share costs and implement future programs proposed by the NASA /SDIO technology insertion working group on space environmental effects.

NASA IN-SPACE TEST BED USER SURVEY

1.0 Experiment Name

SPACECRAFT GLOW SPECTRAL SURVEY (SGSS)

2.0 Experiment Description

Describe the experiment in terms of its overall function, hardware, and scope.

Function: To measure atmosphere effects on spacecraft surface-induced chemiluminescence, or "glow."
Hardware: Visible, IR, and UV detectors

3.0 Experiment Objective

Describe the experiment's objective in terms of its most critical parameters that must be demonstrated.

Experiment objective includes low Earth orbit exposure of ram-oriented spacecraft surfaces to atmospheric gases (atomic oxygen and molecular nitrogen) responsible for the glow emissions. Both uninsulated and insulated surfaces would be studied. Variable altitudes and surface temperatures will enable correlations to be made between glow intensity and these parameters for application to future NASA and SDIO space programs.

4.0 Experiment Category

Indicate the category(s) for which the experiment could be classified.

US Commercial		US Govt Lab	x
DOD	x	University	x
NASA	x	Foreign	
Other			

5.0 Point of Contact

Name	Dr. Gary Swenson
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Address	D91-20 B255 3251 Hanover Street Palo Alto, CA 94304
Phone	415-424-3297
Facsimile	415-424-3333

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6.0 Level of Technological Maturity

Indicate the experiment's level of technological maturity.

Level 1: ______ Basic Principles Observed And Reported
Level 2: ______ Conceptual Design Formulated
Level 3: ______ Breadboard Demonstrated
Level 4: ______ Tested in Relative Environment
Level 5: __x__ Tested in Space

7.0 Benefits

7.1 Applications

List expected range of applications (missions).

Low Earth orbit, preferably elliptical, with instrumentation oriented in ram direction.

7.2 Performance Improvements/Cost Reductions

Describe the expected performance improvements or cost reduction per application.

Understanding of physical processes related to atmospheric population densities and glow spectral intensity. Predictive models of glow interactions would result.

8.0 Need for Space Testing

Define the need for space testing as opposed to merely ground testing. Also, describe the advantage or necessity for this experiment to be flown on a free-flying test bed versus on the STS or Space Station.

The 8 km/sec is necessary. Combined fast O and N_2 environments are not available in laboratories. Low Earth orbits (220 km) are needed for high O-atom fluxes.

9.0 Orbital Parameters

Indicate the experiment orbital parameters.

LEO __x__
GEO _____
Duration _____

Equatorial __x__
Polar _____

Critical __x__ Desirable ____
Unimportant ____

10.0 Physical Limits

10.1 Mass

Dry Mass	30 kg
Consumables	____ kg

10.2 Dimensions

	Stowed	Deployed
X-Axis	20 cm	____ m
Y-Axis	20 cm	____ m
Z-Axis	20 cm	____ m

10.3 Volume

Stowed	Deployed
.008 m^3	____ m^3

11.0 Attitude Control And Determination

Pointing Accuracy	N/A arcsec *
Pointing Knowledge	300 arcsec
Pointing Control Rate	N/A arcsec/sec
Jitter	N/A arcsec

Critical ____ Desirable x
Unimportant ____

12.0 Navigation

Position Error	1000 m
Velocity Error	____ m/s

Critical ____ Desirable ____
Unimportant x

*Note: Ram attitudes required for scientific measurements.

13.0 Communication

For each communication link, indicate the link path source and destination as well as the data rate.

Source	Destination	Data Rate kbps
Orbit	Ground	20

Critical ___ Desirable _x_

Unimportant ___

14.0 Data Processing

Processing Rate _0_ mops

Storage _3_ mbytes

Critical ___ Desirable _x_

Unimportant ___

15.0 Power

For each device, module, assembly, etc., indicate the power requirements.

Device	Average		Peak	
	kw	hrs/orbit	kw	hrs/orbit
Detectors	.040	Continuous	.040	

Critical _x_ Desirable ___

Unimportant ___

16.0 Thermal Management & Control

16.1 Device Temperature/Heat Rejected

For each device, component, module, assembly, etc., indicate its operating temperature (at some cold plate, or cavity/enclosure) and the heat rejected at that temperature.

Device	Heat Rejected kw	Temperature Range °C
Electronics	.025	30-50
Optics		
Detectors	.015	−20
Others		

Critical ___ Desirable _x_
Unimportant ___

16.2 Fluids

Fluid Name	Function
Argon	Joule-Thompson cryostat gas for cooling infrared detectors
Nitrogen	Controlled N_2 release to verify glow production mechanisms

Critical _x_ Desirable ___
Unimportant ___

17.0 Orientation

Any ______ Anti-Earth ______
Solar ______ Earth ______
Lunar ______ Inertial ______
Other (described) Instruments into Ram, (+ZVV)

17.1 Field Of View ± 90 deg (ram exposure)

Critical ____ Desirable x
Unimportant ___

18.0 On Orbit Servicing

18.1 Orbit Replacement Units

List any ORU
ORU 1: ____________________
ORU 2: ____________________
ORU 3: ____________________
ORU 4: ____________________

For each ORU:
Describe purpose and function of each ORU and proposed method of replacement.

18.2 Resupply Substances

List any substances (gas, liquid, fuel, etc.) to be resupplied.
Substance 1: ____________________
Substance 2: ____________________
Substance 3: ____________________
Substance 4: ____________________

For each substance listed above, describe proposed method of resupply.

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16. Abstract
Earlier Shuttle flight experiments have shown atomic oxygen within the orbital environment can interact with many materials to produce surface recession and mass loss and combine catalytically with other constituents to generate visible and infrared glows. In addition to these effects, examinations of returned satellite hardware have shown many spacecraft materials are also susceptible to damage from high velocity impacts with orbital space debris. These effects are of particular concern for large, multi-mission spacecraft, such as Space Station and SDI operational satellites, that will operate in low-Earth orbit (LEO) during the late 1990's. Not only must these spacecraft include new materials and exterior coatings that are resistant to atomic oxygen surface interactions, but these materials must also provide adequate protection against erosion and pitting that could result from numerous impacts with small particles (less than 100 microns) of orbital space debris. This report will present an overview of these concerns and outline activities now underway to develop materials and coatings that will provide adequate atomic protection for future spacecraft. It will also discuss atomic oxygen and orbital debris flight experiments now under development to expand our limited data base, correlate ground-based measurements with flight results, and develop an orbital debris collision warning system for use by future spacecraft.

17. Key Words (Suggested by Author(s))
Atomic Oxygen, Space Environmental Effects, Space Debris, Hypervelocity Impact, Shielding Techniques

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19.0 Environment Contamination

Describe any on-orbit planned activities or potential contingencies which might contaminate the local environment.
Venting and release of gases could temporarily contaminate data.

20.0 Cost Estimates (Experiment Only)

Indicate estimated costs in thousands.

Flight hardware development	$ 800
Integration and launch	$ 400
Operational	$ 100
Recovery	$ 200

21.0 Safety and Reliability

Describe any unique or special safety and reliability issues associated with this experiment.

NONE

22.0 Logistics

Describe any logistics issues and concerns associated with this experiment.

Downlinked data would need to be relayed to investigation team.

23.0 Other Requirements

Describe any unique or special experiment requirements not asked previously.

NONE

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15. Supplementary Notes

16. Abstract

Earlier Shuttle flight experiments have shown atomic oxygen within the orbital environment can interact with many materials to produce surface recession and mass loss and combine catalytically with other constituents to generate visible and infrared glows. In addition to these effects, examinations of returned satellite hardware have shown many spacecraft materials are also susceptible to damage from high velocity impacts with orbital space debris. These effects are of particular concern for large, multi-mission spacecraft, such as Space Station and SDI operational satellites, that will operate in low-Earth orbit (LEO) during the late 1990's. Not only must these spacecraft include ~~new~~ materials and exterior coatings that are resistant to atomic oxygen surface interactions, but these materials must also provide adequate protection against erosion and pitting that could result from numerous impacts with small particles (less than 100 microns) of orbital space debris. T~~his report will present~~ an overview of these concerns is presented and ~~outline~~ activities now underway to develop materials and coatings are outlined that will provide adequate atomic protection for future spacecraft. ~~It will also discuss~~ The report also discusses atomic oxygen and orbital debris flight experiments ~~now~~ under development ~~to expand our limited data base,~~ STET correlate ground-based measurements with flight results, and develop an orbital debris collision warning system for use by future spacecraft.

17. Key Words (Suggested by Author(s))
Atomic Oxygen, Space Environmental Effects, Space Debris, Hypervelocity Impact, Shielding Techniques

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