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Environmental Effects on Spacecraft Material

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A study of the present state-of-knowledge concerning the effects of the natural environments on spacecraft materials has been carried out. The study consisted of a literature review, a questionnaire mailing, and some follow-up facility visits. This is the report describing that study and the conclusions reached.

At the present time, the effects due to single components of the space environment (radiations, plasmas, gases, particles, fields, etc) are either well understood or are actively being investigated. Among the most active areas are atomic oxygen effects (erosion and glow), hot plasma charging, space debris object punctures, and nuclear radiation degradation of exposed materials. Some synergistic effects are also being studied.

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Abstract

A study of the present state-of-knowledge concerning the effects of the natural environments on spacecraft materials has been carried out. The study consisted of a literature review, a questionnaire mailing, and some follow up facility visits. This is the report describing that study and the conclusions reached.

At the present time, the effects due to single components of the space environment (radiations, plasmas, gases, particles, fields, etc.) are either well understood or are actively being investigated. Among the most active areas are atomic oxygen effects (erosion and glow), hot plasma charging, space debris object punctures, and nuclear radiation degradation of exposed materials. Some synergistic effects are also being studied.

The second phase of this study will be concerned with the effects of the natural space environments on materials which are expected to find SDI applications because of their weapon survivability (laser and nuclear hardness). That work has just been initiated; a report dealing with that phase will be issued after the work has been completed.

I. Introduction

A contract (F19628-88-C-0008) was awarded to the Satellite and Space Electronics Division (S&SED) of Rockwell International by the Air Force Geophysics Laboratory (AFGL) to review work dealing with the effects of the natural environments on spacecraft materials and to assess the role of such effects on future Air Force Satellites. The object of this study is to identify the natural space environmental effects on materials that may be used for SDI (Space Defense Initiative) applications and to evaluate the timely availability of the relevant environmental effects information. The concern is that some of the materials which appear attractive because of their mechanical, thermal, electrical properties may be vulnerable to some natural environmental effects. For example, strong, high temperature materials are able to withstand launch and on-orbit operational requirements but may be vulnerable to erosion by atomic oxygen, charging by hot plasma, outgassing in vacuum, discoloration in sunlight, and/or shattering by meteoroid/debris object impacts.

In order to identify these materials and their natural environment vulnerabilities a two-phase program has been planned. The first phase, Phase I, involved reviewing the past, present, and planned future work at several Air Force and NASA facilities dealing with the effects of the natural space environment on materials. This report is a summary of work carried out during Phase I.

The second phase of this study will involve identifying the natural environmental effects which will be significant to future military spacecraft. This includes consideration of the materials which may be required for such spacecraft and the identification of when the materials data for such technologies will be required. The objective is to identify deficiencies in the natural environmental effects knowledge of such materials so that the deficiencies can be remedied in time.

The review of the environmental effects on spacecraft materials (Phase I) included the following three (3) specific activities:

(1) a literature search and review;

(2) a questionnaire mailing; and

(3) facility visits.

The literature search and review involved the usual tools of such activities - examining library compilations such as STAR (Scientific & Technical Aerospace Reports) and IAA (International Aerospace Abstracts), as well as searching relevant computer data bases. This activity uncovered various conference proceedings of relevant subjects such as spacecraft charging, atomic oxygen effects, and debris/micrometeroid effects. These conference proceedings not only indicated the level of activity in relevant areas but also identified the individuals and organizations/facilities involved in those activities. The literature search is discussed in more detail in Section II of this report.

Based in part upon the information obtained from the literature survey, a 20 question questionnaire was prepared and sent to over 200 individuals at over 50 organizations and facilities. The bulk of these questionnaires were sent to Air Force and NASA facilities for two reasons:

a) Individuals at these facilities were prominent in attending relevant conferences and publishing relevant papers; and

b) It was felt that individuals from Air Force and NASA facilities would be less inhibited in revealing their present activities and future plans than individuals from other organizations. However, researchers from several universities and private companies were among the 54 who not only returned the questionnaire, but generally sent copies of their relevant publications. The questionnaire and the information they conveyed are discussed in more detail in Section III of this report.

The literature search and the questionnaires both showed that atomic oxygen effects are the subject of almost universal interest and attention, with spacecraft charging continuing to command the attention of many researchers. Space debris is beginning to attract more interest, especially since recent data indicates a worse problem than expected. The degradation of material properties due to solar ultraviolet and Van Allen particle radiation continue to be significant research areas. Finally, synergistic effects which are due to various combinations of individual environments are worrisome, since these effects are more difficult to understand or simulate in the laboratory.

Following up the literature search, telephone calls were placed to some of the questionnaire respondents asking for additional information. Based upon the information obtained, as well as the analysis of the literature search, certain facilities were selected for follow-up visits. The facilities selected for these visits were the following:

NASA - Jet Propulsion Laboratory

NASA - Lewis Research Center

Air Force - Materials Laboratory

Air Force - Geophysics Laboratory

NASA - Johnson Spacecraft Center

Air Force - Weapons Laboratory

Air Force - Aerospace Corporation.

These facilities were selected because of their prominence in the research of material effects, the individuals engaged in that research, and the convenience with which the visits could be accommodated within the time and budget constraints. This meant that many other individuals doing fine work at other facilities could not be visited.

The facility visits confirmed the conclusions obtained from the literature search and the questionnaires - that atomic oxygen is the current "hot" space environmental research field. Spacecraft charging, solar, and Van Allen radiation effects continue to be active, and space debris rapidly gaining attention. The facility visits are discussed in more detail in Section IV of this report.

The consistency of the results from each of the three activities undertaken as part of Phase I of this study is reassuring -- if the results had been greatly different, the adequacy of the effort would have been suspect. With the Space Shuttle currently scheduled to fly sometime in 1988, hopefully new information (especially from recovered spacecraft and objects from space) will become available on the effects of the space environments on materials.

II. Literature Search

The subject of space environmental effects on materials was sufficiently broad that it was necessary to find or develop a frame of reference to permit organization of the relevant material. Fortunately, the Air Force Geophysics Laboratory (AFGL) had just issued its updated Handbook of Geophysics and the Space Environment (Jursa et al.).(1) With each chapter written by one or more experts in the field addressed, the handbook represents several man-years of effort. The scope and depth of this handbook was considerably greater than could be duplicated by the resources of this contract. In addition, its recent issuance meant that it contained much up-to-date material. Therefore, the relevant material in this book was adopted as the basis for the literature search. Even though the Handbook emphasizes the space environments, there were several references dealing with the effects of these environments on materials.

In order to expand on these references, the literature search began with two abstract report series in the Rockwell S&SED Technical Information Center (TIC) at Seal Beach. These are: The NASA STAR (Scientific and Technical Aerospace Reports) and the NASA IAA (International Aerospace Abstracts). The STAR series lists the following categories relevant to the present contract:

23 Chemistry and Materials

24 Composite Materials

26 Metallic Materials

27 Non-Metallic Materials

In contrast to the STAR series, the IAA series (also issued by NASA) emphasizes foreign publications in the field and has the same categories listed above as the STAR.

The initial procedure was to start with the most recent issues of STAR (Primarily) and IAA (Secondarily) and make a list of what appeared to be relevant articles. The problem with this approach was that the time required to survey even a few years was excessive and the relevancy of the articles (based on their one paragraph abstracts) to the contract was sometimes difficult to evaluate.

In order to better evaluate the literature, full length copies of some of the more promising articles were ordered. Some of the articles were readily obtained, others required more time. By March 15, 1988, a total of 101 relevant articles had been obtained, reviewed, and categorized. The results are displayed in Table 1 which shows not only the subject matter of these articles, but also the Air Force, NASA, and other facilities responsible for the work. This table, which is illustrative rather than exhaustive, shows that

Table 1. Literature Reviewed as of March 15, 1988

	NASA Marshall	NASA Johnson	NASA Goddard	NASA Lewis	NASA Langley	NASA Ames	AF Geophysics Laboratory	AF Materials Laboratory	AF Astronautics Laboratory	AF Rome	AF Arnold	Aerospace Corporation	Jet Propulsion Laboratory	Naval Research Laboratory	Universities	Companies	Totals
Shuttle glow	2	2				3	2								5	4	18
Particle radiation effects		1	2		1								1	2		3	10
Outgassing/contamination	1	1	1					1	1	1	2				1	4	13
Spacecraft charging				9			3			1		1	2		5	2	23
Atomic oxygen effects	3	4		8	1							3	1		6		26
Meteoroid effects		3													1	1	5
Solar UV effects			1			1						1					3
Other															2	1	3
Totals	6	11	4	17	2	4	5	1	1	2	2	5	4	2	20	15	101

atomic oxygen and spacecraft charging effects were the most popular topics and also that NASA-Lewis Research Center and NASA-Johnson (JSC) were responsible for more of the collected papers than any of the other facilities.

While the size of this initial sample was too small to be conclusive, analysis did indicate which technical fields had been the most active in the available time frame and where a large part of the published materials effects work was being done.

As the library work continued, six conference reports on atomic oxygen effects, spacecraft charging, and meteoroid/space debris effects were unearthed. Each of these conference reports contained several very valuable papers. These papers were not only reviewed for their technical content, but also categorized by facility. This categorization is shown in Tables 2 through 6 of this report.

Table 2 shows the facility of origin for the 17 papers and 19 abstracts included in the November 10 - 11, 1986, Jet Propulsion Laboratory workshop on Atomic Oxygen Effects.(2) The Table shows that NASA-Johnson, NASA-Ames, and JPL were the only facilities to present more than two papers at that workshop. The large number (25) of facilities represented indicates the breadth of interest in this subject. The large number of universities (9) represented is also noteworthy.

There were four conferences in Colorado Springs in 1976,(3) 1978,(4) 1980,(5) and 1983(6) dealing with spacecraft charging effects. Even the 1983 conference which included some papers on low earth orbit plasma interactions was dominated by papers addressing spacecraft charging phenomena. These four

Table 2. Atomic Oxygen Papers (1986 Workshop), JPL Publication 87-14 (1987)

	NASA Marshall	NASA Johnson	NASA Goddard	NASA Lewis	NASA Langley	NASA Ames	Air Force Geophysics Laboratory	Air Force Materials Laboratory	Other Air Force	Aerospace Corporation	Jet Propulsion Laboratory	Los Alamos Laboratory	Argonne National Laboratory	Universities*	Companies**	Others†	Totals
Papers		4		1		1	1				2	1	1	3	1	2	17
Abstracts	1			1		2				1	1			8	5		19
Totals	1	4	0	2	0	3	1	0	0	1	3	1	1	11	6	2	36

*University of Alabama P, Yale University P, Vanderbilt University P, A, University of Chicago A, California Institute of Technology A, University of Texas P, A, Auburn University A, Princeton University A, Case University A

**Physical Sciences, Inc., P, A, Aerodyne Research Corp. A, Martin Marietta Corp. A, Lockheed Corp. A, Boeing Corp. A

†Bureau of Standards P, Brookhaven National Laboratory P (P - Paper, A - Abstract)

conference proceedings contain a total of 240 papers. Such a large number of papers on a relatively specific subject indicates an important and active research area.

Table 3 contains a summary of the number of spacecraft charging papers coming from NASA and Air Force research laboratories. Table 4 is the summary of university publications in the area which includes 22 from foreign universities. Table 5 shows the extent of company publications presented at these spacecraft charging technology conferences. The 71 university and 74 company papers are included in the 240 papers categorized in Table 3.

Based on this information, it is obvious that the Air Force Geophysics Laboratory and NASA-Lewis have been in a class by themselves in this critical area. Among universities, the University of California, Stanford, Stanford Research Institute, and Boston College have been especially active, while TRW, S-Cubed, and General Electric have produced the largest number of corporate spacecraft charging papers.

The 1987 orbital debris workshop held at NASA-Johnson (JSC)(7) consisted of 35 papers of which 24 were technical and 11 dealt with management and policy aspects (see Table 6). Half of the technical papers originated at JSC, reflecting the dominant role that institution plays in micrometeoroid and space debris research. With the data from the Solar Maximum Satellite (recovered after 50 months in low altitude earth orbit) revealing more punctures than expected, the subject of space debris promises to be a topic of even more research.

While these library searches and conference report reviews were going on, an alternative effort was underway via the computerized data base route. Since a large number of such data bases are available for use (The Cuadra/Elsevier

Table 3. Spacecraft Charging Conference Papers, 1 (Laboratories)

Conference (year)	NASA Marshall	NASA Johnson	NASA Goddard	NASA Lewis	NASA Langley	NASA Ames	Air Force Geophysics Laboratory	Air Force Materials Laboratory	Air Force Astronautics Laboratory	Air Force Rome	Other Air Force	Aerospace Corporation	Jet Propulsion Laboratory	Naval Research Laboratory	DNA (Defense Nuclear Agency)	Companies (Table 5)	Universities (Table 4)	Totals
1976*	1		2	6			4	1				2	3			18	18	55
1978**	1	2	1	10			6			1		2	1			22	15	61
1980***		2	1	6			4			1	1	7	2		1	23	21	69
1983****	1					10	10			1	1	2	2			11	17	55
Totals	3	4	4	22	0	10	24	1	0	3	2	13	8	0	1	74	71	240

*AFGL-TR-77-0051 (NASA TMX-73537) (1977)

**NASA Conference Publication 2071 (AFGL-TR-79-0082) (1979)

***NASA Conference Publication 2182 (AFGL-TR-87-270) (1981)

****NASA Conference Publication 2359 (AFGL-TR-85-0018) (1985)

Table 4. Spacecraft Charging Conference Papers, 2 (Universities)

Conference (year)	University of California	Northeastern University	University of Houston	Penn State University	Stanford University	York University	Rice University	Colorado State University	Case/Western Reserve University	Boston College	University of Kansas	University of Iowa	Utah State University	University of Michigan	SRI (Stanford Research Institute)	IIT (Illinois Institute of Technology)	Foreign	Totals
1976*	2	1	1	1	4											1	8	18
1978**	2	1		2	1	2	1	1									5	15
1980***	2			1					1	3	2				3		9	21
1983****	2			1	1	1	1		1	3	1	1	1	1	3			17
Total	8	2	1	5	6	3	2	1	2	6	3	1	1	1	6	1	22	71

*AFGL-TR-77-0051 (NASA TMX–73537) (1977)

**NASA Conference Publication 2071 (AFGL-TR-79-0082) (1979)

***NASA Conference Publication 2182 (AFGL-TR-81-0270) (1981)

****NASA Conference Publication 2359 (AFGL-TR-85-0018) (1985)

Table 5. Spacecraft Charging Conference, 3 (Companies)

Conference (year)	Lockheed	General Electric	Rockwell	Hughes	L. W. Parker	TRW	R. Lewis	RCA	S^3	Jaycor	Batelle	SAI	Grumman	Boeing	Mission Research	Beers Associates	Spire Corporation	Total
1976	2	6	1	1	1	3	1	1	1		1							18
1978	1	2	1		2	3			2	1		4	2	2	1		1	22
1980	4	1		2	2	3			4	2		1			1	2	1	23
1983				3	2	1			3	1						1		11
Total	7	9	2	6	7	10	1	1	10	4	1	5	2	2	2	3	2	74

Table 6. Orbital Debris Conference Papers
(NASA Conference Publication 2360, 1985)

	NORAD Headquarters	NASA Johnson	NASA Langley	Aerospace Corporation	Batelle	Companies	Universities	Planck Institute	Pentagon	Teledyne Brown	JPL (Jet Propulsion Laboratory)	USAF Space Division	NASA Goddard	NASA Headquarters	Rand Corporation	Totals
Large particles measurements (real/proposed)	2	2	1			1	1									7
Large particles modeling		2		1	1				1							5
Small particles		4						1	1	1						7
Shielding against particles		3									1	1				5
Debris management, policy factors		1		1	1	2	1		1			1	1	1	1	11
Total	2	12	1	2	2	3	2	1	3	1	1	2	1	1	1	35

directory of on-line data bases, January 1987, identifies 3369 data bases on subjects ranging from Strategic Defense to Rock Music) several of the most relevant ones could be identified. The following data bases thus were accessed as part of the literature search on this contract:

ENVIRONET
(Space Shuttle/Space Station Environmental Information Service)

ITIS
(Integrated Technical Information System)

NASA/RECON

DIALOG

DTIC
(Defense Technical Information Center)

RTIS
(Rockwell Technical Information System)

ENVIRONET:

The NASA ENVIRONET environments data base is a continuously updated on-line information system for users of the space shuttle. It was designed to be a single repository for shuttle payload environment information. The ENVIRONET system operates on the NASA SPAN (Space Physics Analysis Network) based at the NASA Goddard Spaceflight Center (GSFC) in Greenbelt, Maryland. Access is also available through dial-up modems. In this case, the ENVIRONET data base was accessed over the telephone through an IBM A/T with a 1200 baud modem. A list of the topics addressed by ENVIRONET is given in Table 7. It was decided that the sections addressing surface interactions and the particulate environment were of primary importance and were downloaded to floppy disks from which hard copies were made. It is from these files that many of the technical contacts included in the mailing list were chosen. A chart indicating the organization and personnel comprising the shuttle environment working group, which is responsible for the conception and maintenance of the ENVIRONET, is presented in Figure 1. The various panels are made up of recognized experts throughout the government and private aerospace community.

ITIS:

ITIS (Integrated Technical Information System) was developed by the Office of Scientific and Technical Information (OSTI-DOD) and provides access to OSTI on-line systems. ITIS serves as a gateway to other government and on-line systems such as those of the Department of Energy (DOE).

NASA/Recon:

The NASA/Recon on-line system provides NASA Research Centers, Contractors, and Universities access to a family of files with a primary focus on citations

Table 7. Environet-Surface Interactions

Topics		Experts
11.3	Surface Charging	Al Rubin, William Denig (AFGL); Carolyn Purvis (Lewis); Nobie Stone (MSFC)
11.4	V × B effects	P.M. Banks, P.R. Williamson (Stanford); M. Grossi (Harvard); W.J. Raitt (Utah State)
11.5	High Voltage Effects	Al Rubin, William Denig (AFGL); Henry Garrett (JPL)
11.6	Ram/Wake Effects	William Burke, Mike Heinnemann (AFGL); U. Samir (MSFC); M. Smiddy (AFGL)
11.7	Glow Phenomena	William Swider, Ed Murad (AFGL); Jack Barengoltz, Robert Hall (JPL)
11.8	Surface Erosion (Atomic Oxygen)	L. Leger, J. Visentine (JSC); J. Park (GSFC); A. Whitaker (MSFC); W. Slemp (Langley); and others

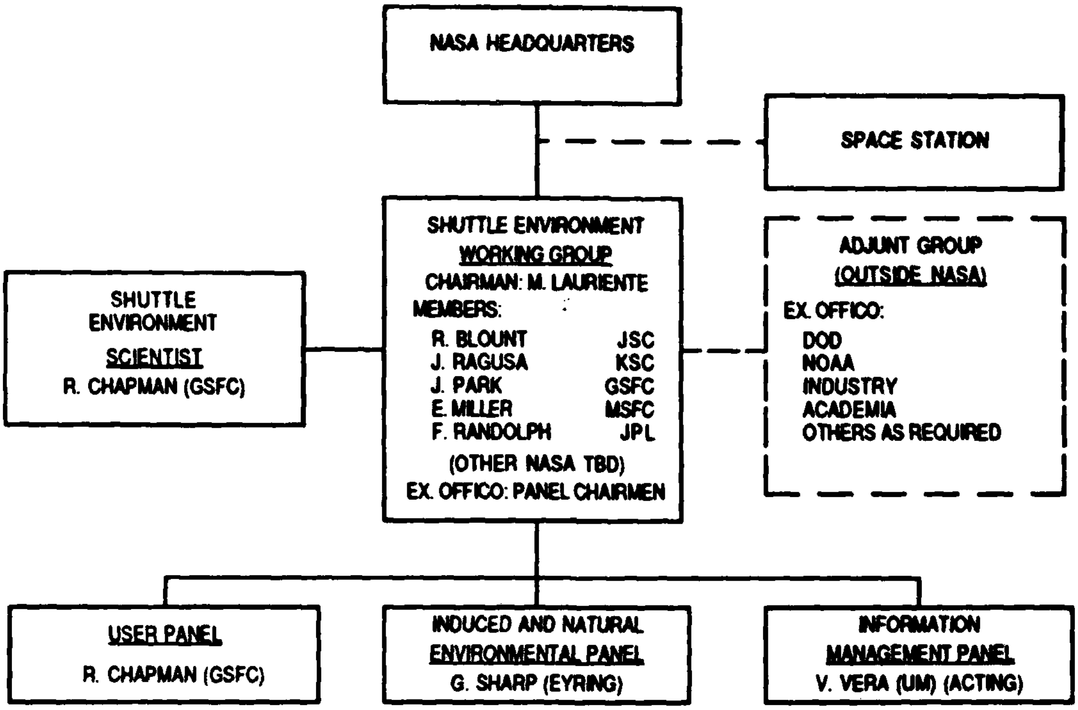

Figure 1. Charter of Shuttle Environment Working Group

and abstracts to the worldwide journal and report literature on Aeronautics and Astronautics. These files include STAR (Scientific and Technical Aerospace Reports), IAA (International Aerospace Abstracts), older reports not found in STAR, R&D Contract Search File (which contains references to NASA Contract and Grant Awards), and Research and Technology Objectives and Plans (over 8,000 descriptions of NASA-sponsored research in progress, 1971-present).

DIALOG:

DIALOG is a huge commercial database which provides access to the 1.5 million citations (with abstracts) of the Aerospace Database. The data sources include books, conference proceedings, patents, and theses, in addition to reports, journals and published papers. The 75 subjects included in the Aerospace Database correspond to the STAR and IAA categories.

DTIC:

The Defense Technical Information Center (DTIC) is a component of the DOD STIP (Scientific and Technical Information Program) that provides a wide range of both demand and subscription services from data bases of planned, on-going, and completed defense research activities. DTIC's interactive on-line system, the defense research, development, test, and evaluation (RDT&E) on-line system (DROLS) enables on-line access to the data base for both retrieval and input. Selected DOD Information Analysis Centers (IACs) use the DROLS input mode to catalog their collections. Registered DTIC users can use DROLS to search DTIC's data base and to order bibliographies and technical reports. Access to classified information requires registration of individual contracts. This process requires approximately one month.

The IACs collect, review, analyze, appraise, summarize, and store available information on technical subjects of interest to DOD. The computerized collections are expanded on a continuing basis to incorporate the most recent international research information. There are currently 11 contractor operated IACs administratively managed and funded by the Defense Logistics Agency (DLA) and the DTIC (a primary level field activity of the DLA). Another 10 are managed by other DOD activities.

RTIS:

RTIS (Rockwell Technical Information Service) is an automated technical information processing system that will incorporate all 17 Rockwell TICs to form one of the largest on-line corporate library information systems in the nation, providing access to both unclassified and classified information. This service is available through each individual TIC.

In a contract of this sort, it was necessary to use data bases (usually via telephone modems) carefully to avoid being overwhelmed by the quantity of technical material obtained. It took some trial and error to select the optimum key words. Finally, the following list of key words proved to be satisfactory, yielding 100 additional references dealing with the effects of the natural environment on spacecraft materials:

SEARCH TERMS USED FOR DATABASE QUERY

DTIC (DEFENSE TECHNICAL INFORMATION CENTER):

(1) PRIMARY TERM - SPACECRAFT
SECONDARY - ELECTRIC CHARGE
- SPALLATION

(2) PRIMARY TERM - SPACECRAFT DEBRIS

(3) PRIMARY TERM - SPACE SIMULATION CHAMBERS

(4) PRIMARY TERM - SPACECRAFT
SECONDARY - AEROSPACE ENVIRONMENTS
- SPACE ENVIRONMENTS

NASA/RECON

(1) PRIMARY TERM - AEROSPACE ENVIRONMENTS
SECONDARY - IONOSPHERE
- MATERIALS

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2. D.E. Brinza, "Proceedings of the NASA Workshop on Atomic Oxygen Effects", Jet Propulsion Laboratory Publication 87-14 (June 1, 1987).

3. C.P. Pike and R.R. Lovell, "Proceedings of the Spacecraft Charging Technology Conference", Air Force Report AFGL-TR-77-0051 (NASA TMX-73537) (February 24, 1977). ADA045459

4. R.C. Finke and C.P. Pike, "Spacecraft Charging Technology-1978", NASA Conference Publication 2071 (AFGL-TR-79-0082) (1979). ADA084626

5. N.J. Stevens and C.P. Pike, "Spacecraft Charging Technology-1980", NASA Conference Publication 2182 (AFGL-TR-81-0270) (1981). ADA114426

6. C.K. Purvis and C.P. Pike, "Spacecraft Environmental Interactions Technology 1983", NASA Conference Publication 2359 (AFGL-TR-85-0018) (1985).

7. D.J. Kessler and Shin-Yi Su, "Orbital Debris", NASA Conference Publication 2360 (1985).

III. Questionaires

As a result of the literature search, it was apparent that the subject of space environmental effects on material covered a lot of territory. In an attempt to summarize these effects, Table 8 was prepared. This Table lists the environments, the types of material primarily affected by the environment, and the major effects produced. To attempt to discuss this table in any depth would require a volume equal to the AFGL Handbook in size. Suffice it to say that each environment individually can produce significant effects on certain materials, while combinations of environments can produce many more effects. When it is realized that there are at least 7! (5040) environmental combinations, the size of the list of possible environmental effects on spacecraft materials becomes apparent.

Since it was not practical to develop a questionnaire which included 7! environmental combinations, the alternative was to list the various environments and ask the respondent to check as many as were applicable. In order to allow for the possibility that some environments had been overlooked, the category of "other" was included.

The types of materials constitute as least as large a group as the combinations of environments, but they generally can be divided into bulk and fiber reinforced categories. Following the lead of many handbooks and abstract services, bulk materials were divided into organics, ceramics, and metals. In addition, there are certain specialized materials designed for special applications--solar cells, paints, windows, adhesives, etc.

The effects categories in the questionnaire were taken from Table 8, with a further subdivision into transient and permanent classes. An "other" category was provided for both surface and bulk property effects.

Following questions designed to obtain information concerning the environments, the materials, and the interaction effects being studied, there were questions asking about the nature of the work, analytical laboratory

Table 8. Permanent Material Effects Due to Environments

Environment	Material	Effects
Vacuum	All, especially organics	Offgassing, outgassing
Residual gases (atomic oxygen)	Organics, some metals	Surface erosion, glow, embrittlement
Solar UV	Organics	Surface discoloration
Van Allen belts	All, especially organics	Discoloration, weakening
Solar flare particles	Conductors, semiconductors	Thermal, electrical resistivity
Ionosphere	Insulators	Charge neutralization
Hot plasma	Insulators; conductors	High voltages, discharges; electric current, heating
Micrometeroids and debris	All, especially optics	Surface erosion, pits, punctures

experiments, or space experiments. For each type of activity, additional questions asked for more details, such as the computer codes used, the laboratory test parameters used, and the orbit and exposure durations in space.

The laboratory experiment parameters were of special interest since data from space experiments is limited and analytical calculations depend upon the input numbers for their relevancy. The two problems with laboratory experiments are the difficulty of simulating the space environmental parameters and the difficulty of doing valid accelerated experiments (measuring the effect of 5 or 10 years in space in a few months). The respondents were well aware of these problems. It is true that the experimental researcher is the person most skeptical of his own results while everyone else is taking these results as gospel.

The final few questions asked about plans for future work of all three types--analytical, laboratory experiments, and space experiments. Understandably, there was hesitation to be too committal here, given the uncertainty of future funding and launch opportunities.

After a couple of iterations the questionnaire and its cover letter (kindly provided by Lt. Col. John Gaudet) were finalized as shown in Appendix I.

The questionnaire was sent to 203 individuals whose names were obtained from the literature search plus some personal contacts. The authors of the AFGL Handbook of Geophysics chapters, the experts listed in the ENVIRONET users manual, and authors of relevant technical papers were all considered to be fair game. The more often a person's name was encountered, the greater the probability that he or she would be sent a questionnaire. However, in order to include as many facilities as reasonable in the survey, several individuals whose names appeared only once in the literature survey were sent questionnaires. Table 9 and 10 show the facilities to which questionnaires were sent and when the replies were received.

The major results of the questionnaire survey are listed in Tables 11 and 12. It is apparent that almost every facility either has, is, or is planning to investigate the effects of atomic oxygen. Since opportunities for space experiments are limited, most of these investigations involve laboratory experiments with 5 eV atomic oxygen beams. Some of the facilities have or will have the capability of simultaneously exposing material samples to atomic oxygen, ultraviolet light, and/or nuclear radiation.

The atomic oxygen effect of interest is primarily the erosion of exposed organic material and its prevention by using a suitable paint or coating. The effects of atomic oxygen on metals did not appear to be especially popular, with the exception of silver (used for solar cell interconnects) since silver turns to silver oxide (an insulator) under atomic oxygen bombardment.

Another effect of some interest was the shuttle glow effect. The effects of the exposed material on the intensity vs. wavelength dependence of this glow is of interest, especially at infrared wavelengths. This glow may limit

Table 9. Questionnaires Sent and Returned, 1

	NASA Marshall	NASA Johnson	NASA Goddard	NASA Lewis	NASA Langley	NASA Ames	AF Geophysics Laboratory	AF Materials Laboratory	AF Astronautics Laboratory	AF Rome	AF Arnold	Aerospace Corporation	Jet Propulsion Laboratory	Naval Research Laboratory	Universities	Companies	Total*
Questionnaires sent	11	5	7	3	3	4	11	7	3	3	4	13	18	8	24	34	158 + 45 = 203
Questionnaires returned as of 3-15-88		1		1	1						1	3	1		4	6	18 + 2 = 20
Questionnaires returned as of 4-1-88	2		2				1	1					3	2		3	14 + 4 = 18
Questionnaires returned after 4-1-88		2							2			2			2	4	12 + 4 = 16
Total number questionnaires returned	2	3	2	1	1		1	1	2		1	5	4	2	6	13	54

*Includes totals from Table 10

Table 10. Questionnaires Sent and Returned, 2

	Harry Diamond Laboratories	National Bureau of Standards	Other Laboratories	Air Force Weapons Laboratory	Office of Scientific Research	Air Force Armament Laboratory	Air Force Space Technology Center	Air Force Academy	Air Force Space Command	Department of Defense	Department of Energy	DARPA	DNA	Army	NASA Headquarters	Navy Centers	White Sands	Total
Questionnaires sent	3	1	8	4	1	2	2	1	1	3	1	1	1	3	5	6	2	45
Questionnaires returned as of 3-15-88			1													1		2
Questionnaires returned as of 4-1-88			1		1									2				4
Questionnaires returned after 4-1-88			3	1														4
Total returned			5	1	1									2				10

Table 11. Results of Questionnaires, 1

Facility	Environment	Material	Application
NASA Johnson	Atomic oxygen, debris	Organics, metals, composites	Space Station
NASA Lewis	Atomic oxygen, hot plasma	Organics, silver, films	Space Station
NASA Langley	Atomic oxygen, nuclear radiation	Organic, metal matrix	Space Station
NASA JPL	Atomic oxygen, nuclear radiation	Organic films, paints	Galileo, Mars, TOPEX
NASA Goddard	Atomic oxygen, contamination	Reinforced organics, ceramics	Space Shuttle, Space Station
NASA Marshall	Atomic oxygen, UV	Glass fiber organics, silicones	Space Shuttle
Army Aberdeen	Particle dose, dose rate	Semiconductors	Sensors
Lockheed Co.	Atomic oxygen, plasma, UV	Paints, windows, solar cells	Various (classified)
Brookhaven Laboratory	Atomic oxygen, nuclear radiation	Organic films	?
S^3 Co.	Hot plasma, atomic oxygen	Solar cells, paints	Various
Los Alamos Laboratory	Atomic oxygen, debris	Organics, metals, Teflon	Space Station, SDI

Table 12. Results of Questionnaires, 2

Facility	Environment	Material	Application
3M Co.	Atomic oxygen	Bulk, reinforced organics	Solar concentrators
Martin Co.	Atomic oxygen, plumes	Organics, paints, windows	SDI
Physical Science, Inc.	Atomic oxygen	Organics, metals, solar cells	Various
W.J. Schafer Co.	Atomic oxygen, nuclear radiation	Organics, ceramics, metals	Optics, Be mirrors
University of Chicago	Atomic oxygen, UV	Metals, semiconductors	Basic research
Calspan Co.	Outgassing, UV	Composites, paints, solar cells	Cold optics
AFOSR	Atomic oxygen, UV	Organics, ceramics, metals	Optics (halides)
AFWAL	UV, particle radiation, atomic oxygen	Graphite, ceramics, metals	Laser shields (SDI)
Aerospace Co.	Particle radiation, atomic oxygen, UV	Coatings, composites, ceramics	Space Shuttle, SDI
Vanderbilt University	Atomic oxygen, UV	Glasses, films, alloys	Various
Auburn University	Atomic oxygen, ozone	Graphite, organics, metals	Research

the sensitivity of certain types of optical sensors used at low earth orbit altitudes.

One of the synergistic effects mentioned in a few of the returned questionnaires is that of solid objects (micrometeroids or space debris) and atomic oxygen. The effect of a protective coating over organic substrates can be defeated by the holes punched through the coating by the high velocity objects. The atomic oxygen atoms can thus reach the organic substrate via the holes through the protective coating. For this reason, bulk oxides (which would presumably not be attacked by atomic oxygen) may be in favor for certain exposed spacecraft surfaces.

Among the other environmental effects mentioned on the returned questionnaire were the particle radiation degradation of semiconductive electronic components, as well as exposed surfaces, hot plasma charging of electrical insulators, and degradation of the α/ϵ ratio of thermal control surfaces due to ultraviolet light. The necessity of accelerated laboratory testing continues to be a problem for solar ultraviolet irradiations, and may be the source of small errors for particle irradiations and atomic oxygen erosion. Among the other problems mentioned are the difficulty of simulating micrometeoroid impact parameters (mass, density, charge, and velocity) and measuring long term room temperature outgassing.

Most of the research indicated in the questionnaire replies (or the reprints which many respondents kindly sent with the questionnaires) had Space Station and/or Space Shuttle applications as the beneficiaries. Some of the research was directed to improving various optical sensors while a few projects were clearly due to classified program needs. Obviously, the SDI platforms at low altitude will be exposed to atomic oxygen and space debris while those at geosynchronous altitude will encounter sporadic hot plasmas. Thus, the direct applicability of much of this research to military, as well as civilian spacecraft, is obvious.

IV. Facility Visits

By March 21, 1988, when many of the returned questionnaires had been received, planning for the facility visits was initialized. The Jet Propulsion Laboratory in Pasadena, California, was chosen for the first such visit because of its proximity and the large number of environment-related activities being carried out there. Telephone calls to a number of researchers, those who had responded to the questionnaire, led to the selection of Friday, April 8, 1988, as the date for the visit. Dr. Ara Chutjian kindly offered to set up an itinerary and act as host for the visit.

The notes of the visit are contained in Appendix II of this report. The major work concerned with the natural space environments around the earth dealt with atomic oxygen and particle radiation effects. The JPL facility for producing atomic oxygen beams is relatively new, and materials testing has only recently been initiated. The ability to produce fluxes of 10^{14} to 10^{15} atomic oxygen atoms/cm^2-sec (which corresponds to a density of 10^8 to 10^9 atoms/cm^3) suggests that simulating the effects of 1 year in LEO (low altitude earth orbit) would be 1 day for a normal atmosphere at an altitude of 1000 km, longer for lower altitudes. They do not anticipate problems due to this degree of time acceleration. Their work to date indicates that ITO (the indium oxide/tin oxide coating developed to prevent surface spacecraft charging) is unaffected by atomic oxygen. This could be useful for spacecraft in polar low altitude orbits.

Several other materials (kapton, teflon, graphite, shuttle tiles, etc.) were also scheduled for testing in the atomic oxygen (AO) facility.

There is a fair amount of interest at JPL in black (carbon filled) kapton film. The electrical conductivity is sufficient to leak off electrical charges. However, it must be protected from atomic oxygen. The nuclear radiation tolerance of the black kapton was also of interest. The radiation tolerances of various paints (S13 GLO, ZOT, black Chemglaze) have been or are being measured.

An "around-the-country" trip to visit several other NASA and Air Force facilities was carried out during the last week in April and the first week in May, 1988. At each facility one or more individuals were kind enough not only to make time for these visits, but to take the lead in making appointments with relevant researchers. A summary of the facility visits to date is listed in Table 13. The notes Mr. R. J. Dempsey made during these visits are contained in Appendix II of this report.

The first stop on the "around-the-country" trip was NASA-Lewis, a pioneer in spacecraft charging studies. Bruce Banks, who coordinated the visit to NASA-Lewis, is studying spacecraft in low altitude polar earth orbits. He is interested in the indium/tin oxide (ITO) coating for its ability to leak off accumulated charges, limiting the high electric fields which can cause electrical discharges. His work shows that while ITO stands up to atomic

Table 13. Facility Visits Carried Out to Date

Facility	Date	Environmental Effects	Contacts
NASA JPL (Haffner, Dempsey)	4-8-88	Atomic oxygen effects; spacecraft charging; particle radiation effects	A. Chutjian, H. Garrett; J. Barengoltz, T. O'Donnell; F. Bouquet
NASA Lewis (Dempsey)	4-26-88	Atomic oxygen effects; spacecraft charging	B. Banks, S. Rutledge; C. Purvis, N. Grier, F. Berkopec
AF Material Laboratory (Dempsey)	4-27-88	Laser beam hardness; particle radiation effects	P. Falco, W. Lehn, R. Craig; A. Gunderson
AF Geophysics Laboratory (Dempsey)	4-29-88	Atomic oxygen effects; spacecraft charging	D. Hunton, E. Murad, M. Giger; A. Rubin, W. Hall, C. Pike
NASA Johnson (Dempsey)	5-2-88	Atomic oxygen effects; micrometeroid, debris	J. Visentine, J. McCoy; B. Kessler, B. Cour-Palais
AF Weapons Laboratory (Dempsey)	5-3-88	Particle radiation effects	K. Hunt, D. Doryland, D. Spreen

oxygen, it loses its optical transparency. This effect is attributed to the loss of oxygen from the tin oxide.

A related study deals with liquid drop radiators. These are promising for large spacecraft power systems but are vulnerable at low altitudes because the electric charges on the drops (used to ensure collection efficiency) leak off in the earth's ionosphere.

In addition to spacecraft charging work, NASA-Lewis has mounted a considerable effort dealing with atomic oxygen (AO) effects. Solar cell arrays and solar concentrators are being studied, and both show AO degradation. The solar cell panels and adhesives used are vulnerable, as are various metal mirrors. Overcoats of SiO_2 limit the erosion due to atomic oxygen if they are at least 1000 Å thick.

One of the significant items mentioned was the effects of man-made activity on the natural environments. It is well known that the trapped (Van Allen) radiation belts and the ionosphere can temporarily be enhanced by at least three orders of magnitude. It is also known that related effects can enhance the atomic oxygen density at low altitudes for non-negligible periods of time. Less obvious are other probable effects (more space debris, for example). Somebody should be concerned about these non-natural natural environments.

The next stop on the trip was at AFWAL (Air Force Wright Aeronautical Laboratories), home of the Air Force Material Laboratories. Here the visit was facilitated by Lt. P. Falco, who arranged discussions with two groups of researchers--a non-structural/non-metallic materials group and a structural materials group.

The researchers in the first group are investigating radiator coatings for two temperature regions (100K through 300K and temperatures < 1200K). The lower temperature radiators have infrared sensor applications while the higher temperature radiators will be used for nuclear power systems. Some of the work deals with high temperature (600C) solar cell adhesives (Dow Corning DC-500, the current adhesive is unsatisfactory at temperatures above 300C). Another project deals with contamination effects produced by combinations of vacuum, solar ultraviolet, and hot plasma (electron) irradiation. A materials selection criteria document dealing with these effects is being prepared. Finally, work is being carried out on solid lubricants and bearings for space applications.

The structural materials group is engaged in research dealing with thermoplastics reinforced with graphite fibers. PEEK (Polyether Ether Ketone) reinforced by AS-4 graphite is of particular interest. Carbon-carbon is another material they are working on. Both materials are vulnerable to atomic oxygen erosion but with coatings should be serviceable in low altitude earth orbit. Finally, metal matrix materials, which offer some structural advantages, are also being developed for some classified applications.

Lt. M. Giger arranged the schedule at the Air Force Geophysics Laboratory, where a spectrum of material environmental effects are being studied. The effect of the material involved in producing the shuttle glow is of interest, as are the infrared emissions produced. They have a facility for simulating atomic oxygen glow. Planned shuttle experiments will make more atomic oxygen glow and erosion information available.

Spacecraft charging phenoma is another area of interest. Various computer codes (NASCAP, POLAR) are used to calculate electrostatic charging parameters for spacecraft in various earth orbits. Much of this work is applied to high voltage solar arrays, for which the effects of contamination and corrosion on electrical properties (surface conductivity, secondary electron emission) are difficult to calculate.

A third area of activity is contamination analysis. The SOCRATES (Spacecraft Orbiter Contamination Representation Accounting for Transient Emitting Species) computer code will be used in the analysis of the planned contamination experiments.

J. Visentine helped arrange the meetings for the visit to NASA-Johnson (JSC) where atomic oxygen (AO) effects are a major field of research. Their work to date has shown that most metals protect themselves against AO by forming oxide coatings (silver and osmium are exceptions). The wavelength spectrum of the shuttle glow due to atomic oxygen is also being investigated, and correlations between erosion and glow phenomena are being sought. The effects of atomic oxygen on many materials and spacecraft components (insulation, seals, lubricants, mirrors, etc.) are being studied.

The Johnson Spaceflight Center is also the center of research on micrometeoroids and space debris. In addition to cataloging and modeling debris object fluxes in space (which are much higher than predicted a few years ago), they have a hypervelocity impact research laboratory for studying the effects of debris objects on spacecraft components. The growth of the debris flux as objects collide with each other is of special interest, since a Saturn-like ring around the earth would make future launches very hazardous.

A novel utilization of a space environment effect is the use of tethers to generate electrical power by cutting the earth's magnetic field lines due to spacecraft motion. Tethers up to 10 km long could theoretically generate several kilowatts of power in low altitude earth orbit. Space testing of the concept in the 1990's is planned.

At AFWL (Air Force Weapons Laboratory) Capt. D. Doryland coordinated plans for the visit as well as providing helpful insight into the SDIO (Space Defense Initiative Office) material concerns. Optical coatings which reflect laser beam radiation are a special area of interest. Quarter wavelength stacks of low atomic number, high temperature dielectric materials (oxides, nitrides) are being investigated for this purpose. PUFF codes are being used to calculate the mechanical shock waves produced in thin films due to pulses of laser or nuclear energy. An electron beam facility is used to simulate the effects of laser beam radiation on optical materials and components, including beryllium, silicon carbide, fused silica, ULE (Ultra Low Expansion) and a glass ceramic, Zerodur.

The results of the facility visits confirmed the results of the questionnaire - atomic oxygen effects (erosion and glow) are on everybody's agenda, spacecraft charging phenomena continue to be investigated (even at low altitude), while debris environments and effects promise to complicate coping with any environmental effect which requires a specialized coating. Appendix II contains R. Dempsey's notes from these visits, while Appendix III is a list of the literature collected during these visits (additional material is being sent by mail by various researchers).

V. Analysis and Discussion

Based upon the work to date (literature search, questionnaires, and facility visits) it is possible to conclude that the material effects due to the individual space environments are either fairly well understood or are being studied. This statement can be supported by a condensed review of our current knowledge and on-going research for each environment. The following discussion is keyed to Table 14.

The effects of sunlight on exposed materials are to heat them (thermal cycling for those not continually in sunlight), produce forces and torques (radiation pressure), and to induce photo-reactions (electron emission, chemical bond rupture, etc.). Qualification models of spacecraft are routinely thermally cycled, the forces and torques on spacecraft are readily calculated, and the effects of solar ultraviolet (UV) light are being studied. While the long term effects of solar UV are not well understood because of the difficulties of matching the wavelength spectrum in the laboratory and of maintaining reasonable temperatures during accelerated testing, researchers are well aware of these difficulties and are working on them.

The effects of the earth's gravity field are to control the spacecraft orbit/trajectory (weightlessness is a consequence of this) and to produce torques (a spacecraft left alone will align its principal moment of inerta along the local gravity gradient). These effects are well known, and the mass properties of each spacecraft are carefully analyzed and measured prior to launch.

A similar situation exists with regard to the earth's magnetic field. The major effects of this magnetic field are to produce v x B electrical potentials on conductors and u x B torques on current loops (or permanent magnetic dipoles). The v x B voltages are usually small, but studies to generate power by kilometers--long tethers are being carried out. Solar cell

Table 14. Effects of Space Environments on Materials

Environment	Material	Effect
Sunlight (including UV)	Organics, spacecraft	Surface heating, discoloration, torques
Gravity field	Entire spacecraft	Gradient torques
Magnetic field	Conductors, magnetic materials	$V \times B$ voltages, $\mu \times B$ torques
Vacuum	All, especially organics	Offgassing, outgassing
Natural particle radiation	Semiconductors; organics	Decreased electronics performance, upsets; weakening, discoloration
Solid objects	Mirrors, pipes, spacecraft	Abrasion, punctures, impulses
Ionosphere	High-voltage conductors	Leakage currents
Hot plasma	Insulators	High voltages, discharges, rf noise
Neutral gases	Organics, spacecraft	Erosion, glow, drag, torques

panels are routinely designed to minimize their net magnetic dipole moments and coaxial cables will be used for the same reason to transmit power on some future spacecraft which use large electric currents. As for the gravitational field, multiterm mathematical expansions are used to accurately describe the geomagnetic field, leading to accurate calculations of these effects.

Space vacuum is so common that it is easy to forget it in listing the natural environments. The main effects of space vacuum are to permit many phenomena which are either prevented or inhibited in the earth's atmosphere. Perhaps the major material effects are the offgassing and outgassing of volatile components. This evolution of molecules (often water) from spacecraft materials constitutes a source of contamination, especially for cold sensitive surfaces (optics, radiators). The molecular contamination due to thousands of materials has been studied and compiled, and every new material is tested almost as soon as it becomes available.

Natural particle radiation (Van Allen belt particles, solar flare particles, and galactic cosmic rays) have been extensively studied so they are fairly well known (in spite of their variability). These radiations produce their most obvious effects on semiconductive electronic components (gain decreases, increased leakage currents, single event upsets, etc.), but surface (exposed) materials, especially organics are also vulnerable. Fortunately, accelerated testing in the laboratory is feasible (annealing effects can be compensated for) and the particle radiation effects on materials are generally well known. Much of the activity here deals with semiconductor electronic components where the evolution toward smaller, lower power devices has necessitated new technologies to prevent decreases in particle radiation hardness.

The effects of solid objects in space (micrometeoroid debris) are well known - the small objects abrade/erode surfaces, while the large ones produce holes, impart linear/angular momentum changes, etc. The problem here is that while the micrometeroid environment is fairly well known, it is being overtaken by the much-less-well-known space debris. The particle size distribution in the 10^{-6} to 10^{+3} gram region is of particular concern. However, recovery of the LDEF (Long Duration Exposure Facility) and the construction of a special ground based radar will help define the environment. Its increase with time, as debris objects collide with spacecraft and with each other, poses a problem which is currently being analytically studied.

The ionosphere is a cold (< 1 eV) plasma which acts to limit exposed high voltages in space. At low altitude it thus produces large leakage current to non-insulators which are not close to ambient potential. It also reflects, refracts, and delays rf signals. These effects are well known. Thus, for spacecraft materials the main effect is to preclude the use of exposed high voltage conductors, especially at low altitudes where the ionospheric density is high.

At high altitudes/latitudes hot (keV) plasma can appear due to solar activity. This hot plasma produces spacecraft charging (high voltages and high electric fields) on exposed insulators. While these voltages are not usually a problem, the high fields can lead to electric discharges. If some of this discharge energy (via conduction and/or radiation) reaches electronic circuits, upsets and damage can result. These phenomena have been studied for over a decade and their material effects are fairly well known.

The residual neutral gases (especially atomic oxygen) which are present at low spacecraft altitudes produce several effects. The forces/pressures (spacecraft drag) and torques have been known for decades. Most recently the material erosion, embrittlement, and visual light glow effects have become known. The erosion/glow phenomena are the subject of a large amount of research, with over a dozen laboratory simulators either under construction or in use.

While the individual natural environments and their effects are either well known or are currently being studied, the synergistic effects due to combinations of two or more of these environments may not be equally known. As a result of the questionnaire and facility visits, several researchers suggested that more attention be given to these synergistic effects. Tables 15 through 22 are a brief summary of the expected effects of combinations of

Table 15. Synergistic Effects Involving Sunlight (Including UV)

Environment	Effect	Material/Part
Sunlight and G field	Torques modified	Entire spacecraft
Sunlight and B field	Torques, drag modified	Entire spacecraft
Sunlight and vacuum	Increased outgassing, Cross-linking	Exposed organics
Sunlight and particle radiation	Increased annealing	Exposed semiconductors
Sunlight and solid objects	Decreased α_s, reflectivity	Exposed radiators, mirrors
Sunlight and ionosphere	Lower voltage, including discharges	Exposed conductors
Sunlight and hot plasma	Decreased charging	Exposed insulators
Sunlight and neutral gases	Increased erosion, torques	Ram-exposed organics

Table 16. Synergistic Effects Involving the Gravity Field

Environment	Effect	Material/Part
G field and B field	Torques modified	Entire spacecraft
G field and vacuum	No torque damping	Entire spacecraft
G field and particle radiation	No obvious effect	
G field and solid objects	Projected area/velocity modified	Exposed optics, radiators
G field and ionosphere	Ionospheric drag modified	Entire spacecraft
G field and hot plasma	Sunlight exposure modified	Exposed insulators
G field and neutral gases	Torques, ram exposure modified	Exposed organics

Table 17. Synergistic Effects Involving the Magnetic (B) Field

Environment	Effect	Material/Part
B field and vacuum	No torque damping	Entire spacecraft
B field and particle radiation	Solar, galactic cutoff modified	Semiconductor electronics
B field and solid objects	Projected area/velocity modified	Exposed optics, radiators
B field and ionosphere	Ionospheric drag modified	Entire spacecraft
B field and hot plasma	Sunlight exposure modified	Exposed insulators
B field and neutral gases	Torques, ram exposure modified	Exposed organics

Table 18. Synergistic Effects Involving Space Vacuum

Environment	Effect	Material/Part
Vacuum and particle radiation	Increased radiation resistance	Exposed organics, Teflon
Vacuum and solid objects	Increased impact damage	Exposed surfaces
Vacuum and ionosphere	Increased discharging (more e^-)	Exposed voltages, insulators
Vacuum and hot plasma	Increased contamination	Exposed insulators
Vacuum and neutral gases	Ions, radicals live longer	Exposed organics, sensors

Table 19. Synergistic Effects Involving Particle Radiation

Environment	Effect	Material/Part
Particle radiation and solid objects	Decreased puncture resistance	Fluid containers (organics)
Particle radiation and ionosphere	Decreased discharge rate	Exposed insulators
Particle radiation and hot plasma	Decreased discharge rate	Exposed insulators
Particle radiation and neutral gases	Decreased radiation resistance	Ram-exposed organics

Table 20. Synergistic Effects Involving Solid Objects (Micrometeoroids, Debris)

Environment	Effect	Material/Part
Solid objects and ionosphere	Impact voltages decreased	Exposed surfaces
Solid objects and hot plasma	Expose substrates	Insulating substrates
Solid objects and neutral gases	Expose substrates	Organic substrates

Table 21. Synergistic Effects Involving the Ionosphere

Environment	Effect	Material/Part
Ionosphere and hot plasma	Decreased charging rate	Exposed insulators
Ionosophere and neutral gases	More ions, radicals produced	Exposed organics

Table 22. Synergistic Effects Involving Hot Plasma

Environment	Effect	Material/Part
Hot plasma and neutral gases	Increased discharge rate	Ram-facing organic insulators

these natural space environments, taken two at a time. The following paragraphs delineate the material in these charts.

Sunlight effects include thermal cycling (for many spacecraft surfaces) as well as discoloration and mechanical damage in many organics. Sunlight pressure can also produce torques on a spacecraft if the center of pressure is not in line with the center of mass. The combination of sunlight with other torque-producing environments (the gravitational and magnetic fields of the earth, the residual atmospheric gases) can produce unusual spacecraft rotations and/or require special attitude control measures (see Table 15). Sunlight plus vacuum increases organic outgassing and cross-linking (a major effect) while sunlight heating helps anneal out the damage caused by particle radiation (especially in semiconductors). Photoelectric currents due to sunlight decrease the voltages and currents due to hot plasma charging, while both sunlight and solid objects can act to change the solar absorptance and/or reflectivity of radiators and mirrors. For exposed coatings, the thermal cycling due to sunlight poses the threat of coating damage/discloration especially for substrates vulnerable to any of the other environments.

The earth's gravity field not only controls the orbit parameters of a spacecraft (position and velocity as functions of time) but also affects the orientation (spacecraft like to have their principal axis aligned with local vertical). Thus, the other torque-producing environments (magnetic field, residual gases) can combine with the gravity field to modify the stable orientation (see Table 16). The space vacuum permits orientation changes and oscillations to persist since it provides no damping. The gravity-modified spacecraft orientation affects the drag due to the inosphere and the residual gases, while the impact of a solid object can change the velocity and the orientation/spin of a spacecraft. There does not appear to be any obvious synergistic effect due to the combination of the gravity field and particle radiation, since the ambient particle radiations in space (Van Allen belts, solar flare particles) are quasi-isotropic and produce essentially zero torques on spacecraft. Conversely, the particle radiation effects on materials and parts are not affected by the presence or absence of the earth's gravity field.

The major effects of the geomagnetic field will be to produce potentials and torques on current loops. Thus, the voltages produced will have a modification (small) on the voltages produced by other space environments (hot plasma, ionosphere) and will modify the torques produced by other environments (sunlight, gravity gradient, residual neutral gases) (See Table 17). In addition, the geomagnetic field limits the energies as a function of direction which solar flare and galactic particles can reach a given spacecraft orbit. If the torques modify the orientation of the spacecraft, the impact rates due to stream meteoroids and orbiting debris particles will be modified. Finally, the presence of the geomagnetic field will modify the ionospheric drag.

In addition to facilitating outgassing, the vacuum of space does not limit many environmental parameters (speed, temperature, voltages, etc.) as the earth's atmosphere does. Thus, solid objects hit at higher velocities, the temperatures produced by sunlight (or its absence) are more extreme (no convective cooling), and the electron densities in hot or cold plasmas are greater than would be the case in air (see Table 18). Many materials exhibit increased tolerance for ionizing radiation in vacuum (broken chemical bonds have time to reform) but some atomic oxygen effects are enhanced (ions and radicals live longer). Since organic materials outgas more and have weaker chemical bonds than most inorganic materials, they tend to be the most vulnerable to these effects. Finally, space vacuum and hot plasma can combine to produce more surface contamination than the vacuum would produce alone.

The major effect of particle radiation is to randomize the structure of material, decreasing their ability to transmit stress (some materials become brittle), electrical current, and thermal energy. However, electrical insulators become more conductive, decreasing the discharge rate in hot plasma (see Table 19). Fluid containers are more easily punctured by solid objects if they have been weakened by particle radiation. The presence of residual gases (atomic oxygen) at low altitudes increases the surface damage produced by ionizing particle radiation, especially in organic materials on the front (ram) side of the spacecraft.

Solid objects (micrometeoroids and space debris) not only erode and puncture surfaces (affecting mirrors, radiators fluid containers, etc.), but also can produce changes in spacecraft orientations and orbit. If the erosion, punctures, or reorientations expose surfaces or substrates to environments for which they were not designed, additional effects can follow (see Table 20). Thus, a hole in an insulating coating can expose a high voltage substrate to the ionosphere with considerable consequent current leakage, while a hole in an oxide coating can expose a non-oxide substrate to atomic oxygen attacks, and a hole in a conducting coating can increase discharge rates due to hot plasma. On the other hand, the voltages produced by solid object impacts will be reduced by the presence of the ionosphere.

Since the ionosphere is a cold plasma, it acts to limit the effects of electric or magnetic fields produced by spacecraft (see Table 21). At low altitudes the Debye lengths are measured in millimeters so the ionosphere can "see" small spacecraft features. At high altitudes the ionosphere is much less dense and has meter-sized Debye lengths so it can be overwhelmed by hot (keV) plasma. Nevertheless, the ionosphere does act (along with sunlight) to decrease the hot plasma charging rate. The ionosphere also co-exists with the residual gases (at low altitudes) and with the Van Allen belts (at high altitudes) where it acts to produce more ions and radicals than would otherwise be present.

Since all other combinations of two environments have been discussed, the only combination left is that of hot plasma and neutral gases. The presence of neutral gases (principally atomic oxygen) will increase the electrical discharge rate due to the hot plasma by providing additional atoms and ions (see Table 22). This increased discharge rate will be observed on ram-facing organic insulators in the dark. Since hot plasma is primarily a high altitude environment, while neutral gases occur primarily at low altitudes, this effect will be small.

The matrix shown in Table 23 lists each environment along both the vertical (left side) and the horizontal (top) axis. The spacecraft (S/C), the types of surfaces (eg. exposed high voltage, etc.) and the types of materials (eg. organics, conductors, semiconductors, or insulators) most affected by the environmental combinations, are listed in the boxes. Thus the combinations of gravity and magnetic fields will affect the entire spacecraft by producing torques, while the combination of sunlight and solid objects will be especially severe on optical surfaces (mirrors, radiators). Neutral gases plus almost all other environments primarily affect ram-facing organics while hot plasma plus other environments affect insulators. The zero for the combination of gravity field and particle radiation indicates the absence of any obvious synergistic effect.

Based on the work carried out to date, it is possible to conclude that the effects of a single space environment are either currently understood or

Table 23. Summary of Synergistic Effects on Materials

	Sunlight (UV)	Gravity Field	Magnetic Field	Space Vacuum	Particle Radiation	Solid Objects	Ionosphere	Hot Plasma	Neutral Gases
Sunlight (including UV)	—	Spacecraft	Spacecraft	Organics	Semiconductors	Optics	Conductors	Insulators	Organics
Gravity field		—	Spacecraft	Spacecraft	No Obvious Effects	Optics	Spacecraft	Insulators	Organics
Magnetic field			—	Spacecraft	Semiconductors	Optics	Spacecraft	Insulators	Organics
Space vacuum				—	Organics	Exposed surfaces	High Voltages	Insulators	Organics
Particle radiation					—	Organics	Insulators	Insulators	Organics
Solid objects						—	Exposed surfaces	Insulators	Organics
Ionosphere							—	Insulators	Organics
Hot plasma								—	Organics
Neutral gases									—

currently being investigated. Thermal cycling, ultraviolet light degradation and radiation pressure have been studied for over two decades. The torques and v x B effects of the earth's gravity and magnetic fields are studied in freshman college physics courses. Contamination, especially that due to rocket exhaust plumes and organic material outgassing/offgassing/shedding, is an active research field. Particle radiation, which is primarily of interest to semiconductor electrical engineers and thermal control coating specialists, produces generally well known effects. Solid objects (especially debris) environments are under active investigation, as are the effects of neutral atomic oxygen. Plasma effects are a maturing technology after a decade of intense work.

It is the effects of multiple space environments that will probably hold some surprises, since all of the problems of studying single environments in the laboratory (energy, flux, and angular distribution simulation plus accelerated testing) are compounded. It is expected that exposed organics, optical surfaces and insulators will be especially vulnerable.

V. Summary and Conclusions

The object of this study (Phase I of AFGL contract F19628-88-C-0008) was to review the current state-of-knowledge concerning the effects of the natural space environments on materials. This consisted of a literature search, a questionnaire mailing, and visits to some leading Air Force and NASA research facilities. The literature search located many references, 300 of them papers at conferences dealing with spacecraft charging, atomic oxygen effects, and space debris. Nearly all of the references were unclassified. The literature search indicated that spacecraft charging and atomic oxygen effects have been most popular, with interest continuing in the effects due to micrometeoroid/debris, particle radiation, solar ultraviolet radiation, and vacuum-produced outgassing (contamination). Synergistic effects due to combinations of these environments were also popular.

The 20-question questionnaire was mailed to 203 researchers at 79 organizations and facilities including 13 Air Force facilities, 9 NASA facilities, 24 private companies, and 19 universities. A total of 54 of these questionnaires were returned, some accompanied by copies of published articles. The returned questionnaires showed that almost everybody is currently studying atomic oxygen effects (organic material erosion, and shuttle glow phenomena). Much of this work is directed toward the Space Station and/or the Space Shuttle. Other active areas are spacecraft charging, space debris objects, and particle and ultraviolet radiations.

A series of visits to selected Air Force and NASA facilities was planned and carried out. After an initial visit to NASA-JPL (Jet Propulsion Laboratory), other visits were made to NASA-Lewis, Air Force Materials Laboratory, Air Force Geophysics Laboratory, NASA-Johnson, and Air Force Weapons Laboratory. Since the visit to the Aerospace Corporation will involve some Phase II work it has been postponed. The facility visits confirmed that atomic oxygen effects are almost universally being investigated, most of this work consisting of laboratory experiments. Much of the current spacecraft charging work consists of analytical studies, while space debris work involves both hypervelocity impact experiments and analytical modelling. While coatings are being developed to cope with atomic oxygen and spacecraft charging effects, the vulnerability of these coatings to debris object impacts is a current concern.

Low atomic number ceramics would appear to be favored for high temperature space applications while oxides (presumably not vulnerable to atomic oxygen effects) may have advantages for spacecraft in low altitude orbits. The vulnerability of these ceramics to high velocity impacts is a major worry. Meanwhile, high temperature, low atomic number electrical conductors (e.g., carbon-carbon and metal matrix materials) are being developed for high altitude spacecraft applications (where atomic oxygen is not a problem but spacecraft charging is). There are a number of natural space environmental aspects of these material applications which will be considered in Phase II of this study.

Phase II will consist of a delineation of the material needs for SDI spacecraft and the identification of promising candidate materials to fill these needs. The information available and/or being gathered on the effects of the natural space environments on these candidate materials will be reviewed to ascertain that there are not gaps in that information. If there are gaps they are to be identified so timely action to fill them can be taken. Thus, this report is only the first of two volumes dealing with the effects of natural environments on spacecraft materials.

Appendix I. Cover Letter and Questionnaire

This Appendix contains copies of the cover letter and the questionnaire mailed out in this study (see Section II of the report for more details).

DEPARTMENT OF THE AIR FORCE
AIR FORCE GEOPHYSICS LABORATORY (AFSC)
HANSCOM AIR FORCE BASE, MASSACHUSETTS 01731-5000

REPLY TO ATTN OF PHE (Lt Giger, 617-377-3991)

SUBJECT Impact of the Space Environment on Spacecraft Materials

TO Spacecraft Materials Researchers

1. The Air Force Geophysics Laboratory (AFGL) has contracted with Rockwell Satellite & Space Electronics Division to conduct a Spacecraft Materials Interactions Effects study. The study will identify characteristics of spacecraft materials which are affected by the space environment. We would appreciate your assistance in our efforts to gather information on your involvement in space research.

2. In addition to DOD and NASA efforts, many private laboratories have done research on the impact of the space environment on materials used in space, or are starting new projects to study advanced materials subjected to the space environment. In order to improve the transition of this technology to the designers of space systems, Rockwell will assemble this information and correlate it with known spacecraft applications. The information you provide will be of great value to develop specific recommendations for a document which will ultimately be the standard reference in materials interactions for all space system developers within the DOD.

3. The first step in this project is the distribution of the attached survey questionnaire to determine the extent of available data and to identify all primary research groups. Your cooperation in completing and returning the questionnaire in a timely fashion will ensure us the most accurate information possible. We will get the maximum benefit if received by 15 March 1988.

4. Any additional or expanded comments or suggestions will also be greatly appreciated. We hope to distribute the results of the survey in late 1988 or early 1989 to all participants.

5. Any questions or comments may be directed to:

Dr. James Haffner (Rockwell Corp.), 213-594-3582;
Dr. Joseph Kelley (Rockwell Corp.), 213-594-1276; or
1Lt Mike Giger (AFGL), 617-377-3991.

6. Thank you for your cooperation.

JOHN A. GAUDET, Lt Col, USAF
Program Manager
Space Systems Technology
Space Physics Division

2 Atch
1. Questionnaire
2. Return Envelope

NAME:____________________

FACILITY:____________________

ENVIRONMENTAL EFFECTS ON SPACECRAFT MATERIALS

SURVEY QUESTIONNAIRE

I.

With which environments are your investigations primarily concerned (If more than one environment, please indicate priority) ?

___ Vacuum (eg. outgassing)
___ Atomic oxygen
___ Other ambient species
___ Sunlight (including ultraviolet)
___ Cold plasma (eg. ionosphere)
___ Hot plasma
___ Electric fields
___ Magnetic fields
___ Nuclear radiation
___ Solid objects (micrometeoroids, space debris)
___ Other
___ Other

Are there any environments not listed above that you believe to be significant (please describe them) ?

II.

With what material categories are your investigations concerned ?

___ Bulk organics

___ Fiber reinforced organics (kind of fiber ________________)

___ Bulk ceramics

___ Fiber reinforced ceramics (kind of fiber ________________)

___ Bulk metals

___ Fiber reinforced metals (kind of fiber ________________)

___ Other bulk inorganics (type of material ________________)

___ Fiber reinforced inorganics (type of material ________________)

___ Other (What materials ? ____)

___ Solar cells

___ Paints

___ Other surface treatments

___ Adhesives

___ Transmissive materials

III.

Are there any materials not listed above that you feel to be of importance in future space systems for Strategic Defense Initiative (SDI) applications (please name them) ?

IV.

With what effects are your materials investigations primarily concerned Please indicate if the effects you are investigating are transient or permanent.

transient /	permanent /	
___	___	Surface erosion
___	___	Surface contamination
___	___	Surface puncture
___	___	Surface charging
___	___	Electrostatic discharge
___	___	Surface thermal changes
___	___	Surface electrical changes
___	___	Surface optical changes
___	___	Other surface changes (kind of change: ______________________)
___	___	Bulk mechanical changes
___	___	Bulk thermal changes
___	___	Bulk electrical changes
___	___	Bulk chemical changes
___	___	Bulk optical changes
___	___	Other bulk changes (kind of change: ______________________)

V.

Are there any effects not listed above that you feel to be of importance (please describe them) ?

VI.

Please indicate the nature of your investigations.

____ Analytical

____ Large computer models

____ Laboratory experiments

____ Space experiments

VII.

What work in the area of natural space environmental effects on materials has been carried out at your facility in the last five years ?

VIII.

What publications, reports, papers have resulted from this work ? (Copies would be appreciated if available. A list of references is adequate.)

IX.

What are the major environmental effects on materials programs planned for the next three years at your facility ?

X.

What natural space environments will be involved ?

XI.

What materials/geometries/users will be involved ?

XII.

Will this work involve :

___ Space experiments
___ Laboratory experiments
___ Analysis
___ Large computer models

XIII.

For experiments in space, what will be the:

orbital parameters ?

Exposure duration ?

Temperatures ?

Orientation with repect to the sun ?

Orientation with respect to the velocity vector ?

XIV.

For experiments in the laboratory, what environments will be simulated ?

How will they be simulated ?

What degree of time acceleration ?

What geometries will be used ?

XV.

For analytical work, what computer code(s) will be used ?

What geometries will be simulated ?

What approximations will be made ?

XVI.

What results are expected in these cases ?

Computer simulations:

Geometry variation:

Different approximations:

XVII.

When will these results be available ?

XVIII.

What effects of natural environments do you think should be emphasized in future investigations ?

Why are these effects significant ?

What materials would be affected most ?

XIX.

Do you know of any facility/individual/group that has done, is doing, or will be doing research that should be included in this survey (please provide names, addresses, phone numbers where possible) ?

XX.

Other comments/suggestions ?

Appendix II. Facility Visit Notes

This appendix includes the written notes of the material discussed during the facility visits. A condensed summary is presented in Section IV of this report.

Notes from JPL Visit 4-8-88

Dr. Ara Chutjian told us of his atomic oxygen facility, which involves a four step process. First, electrons bombard NO gas, forming NO ions. These ions decay in 10^{-13} sec to form O^- ions and N neutral atoms. After separating the O^- ions they are accelerated to 5 eV (which is a velocity of 8 km/sec, the orbital velocity of spacecraft in LEO). These accelerated ions are in the doublet P ground state. An argon UV (3800Å) laser beam then removes the electron, leaving oxygen atoms in the 3P ground state. The advantages of this approach is that the beam (10^{14} to 10^{15} atoms/cm^2-sec) is in the ground state, is free of other ions, and has an energy which can be varied from 2 to 50 eV.

Some additional information was also presented. The ions have a spiral motion with a transverse energy of 0.2 eV in addition to the 5 eV of directed motion. The laser beam makes 100 passes through the negative ion beam, converting 15% of the O^- ions to O atoms. A trochoidal plate (which contains an ExB field) removes the O^- ions remaining, leaving the neutral O atomic beam. However, by turning the trochoidal plate voltage off it is possible to carry out experiments using the O^- beam to bombard targets.

The materials they will be testing for atomic oxygen effects are kapton (including the black, carbon filled Kapton), FEP Teflon, Polyethylene, Graphite, and Shuttle Tile Material.

Dr. Chutjian was interested in obtaining samples of composite materials to test, and R. L. Long, telephone number (213) 594-3671, has been asked to talk with him to determine his preferences and requirements (sample geometry, preparation, etc.).

The next visit was with H. B. Garrett and P. Leung concerning their work (the responses of materials to the natural space environments). They were of the opinion that no simulation facility can take the place of actual exposure in space because of the difficulty of approximating the significant parameters and the synergistic effects due to various environmental combinations. Garrett spoke of the surprise when spacecraft and objects have been retrieved from space - lots of holes due to micrometeoroids and space debris, plastic surfaces eroded away, etc. Metal surfaces had been sputtered clean by atomic oxygen, most paints had discolored, and glass windows had darkened. Materials of interest included S13GLO, black Chemglaze paint, ZOT paint (which does not charge up in space) and black Kapton (charges only to 1 KeV).

Garrett referred us to various publications (Vol. 71 and Vol 107 of Progress in Astronautics and Aeronautics, NASA SP-404, Nature 323, p 136, 9-11-86) which contain many more details of his work. He referred us to Fennel and Kuhn (Aerospace Corp.) for work on spacecraft charging, and to Arnold, Tenn for work on atomic oxygen.

Frank Bouquet discussed the particle radiation testing that JPL is doing. Much of it is with high energy protons (eg 138 MeV at Univ. of Indiana) but some of it at low energy (0-3 MeV at Boeing). They are interested in the Galileo mission to Jupiter. While their laboratory-produced total doses are high ($2x10^7$ rads) their dose rates (4050 rads/sec) are low. The effects of these protons on SiO_2, ZOT paints, pyrotechnic squibs, and 500 Å ITO coatings are being studied. There is a coating (deldron) of interest which fails at $2x10^6$ rads. Other missions for which radiation effects data is being sought are Topex and Magellan.

J. Barengoltz is studying the effects of atomic oxygen on composite materials and coatings. He likes ITO because it stands up to atomic oxygen. He is also interested in osmium because of its UV reflectance. His work shows that with time atomic oxygen can work its way through aluminum and silver even if these coatings are a millimeter thick or more. If there is an organic substrate it can be attacked even though the coating is intact. He mentioned the Goddard experiment with a coated QCM (Quartz Crystal Microbalance) which was flown to measure atomic oxygen effects in real time. He referred to the 1986 AIAA meeting in Reno as the source of several good papers.

Among the interesting statements Barengoltz made was that surfaces not on the front (ram) side of a spacecraft can suffer atomic oxygen damage since the atoms can sometimes reach these surfaces by recoil (there is apparently some data to back this up). Another effect is the atomic oxygen erosion of the substrates exposed by micrometeoroid and debris object impacts.

Tim O'Donnell has been studying second surface Kapton layers with an ITO overcoat. They use the carbon-filled Kapton because the Galileo spacecraft has a ± 10 volt tolerance. The ITO will be 350-400 Å thick, since for thickness 500 Å it cracks while for thicknesses 200 Å it isn't conductive enough (also atomic oxygen leaks through). There are plans to study ITO on ZOT paint in the future. They have been studying coating adhesion and using the Auger effect to investigate the profiles of coating. He is interested in conductive white paint.

Minutes of Meeting at NASA - Lewis Research Center

Lewis Research Center (LeRC) is primarily concerned with space propulsion systems and power systems. They are investigating and evaluating materials for such systems. Atomic oxygen (AO) and spacecraft charging are of particular concern. LeRC has material test capabilities (AO and spacecraft glow) and is investigating synergistic effects of AO and temperature (± 80°C) particularly on solar array and solar concentrator materials. Concentrators operate in the 100 sun region and require higher temperature range evaluation. Nuclear power systems such as the 300 kw SP-100 use 700 to 900 K radiators for cooling. Radiators are titanium or beryllium clad. No Dynamics Isotope Power System (DIPS) work has been performed.

Exotic radiators using fluids to provide radiating droplets are being evaluated. They use diffusion pump oil. Silicon-based oils turn to glass in the space environment. The droplets are at approximately 200C and provide light weight radiators.

Dr. Bruce A. Banks said the spacecraft charging could occur at low altitudes (less than 1000 KM) if in polar orbit. Indium Tin Oxide (ITO) is a material of great interest for keeping differential charging minimal. ITO conducts after exposure to AO but becomes metallic and non-transparent. Both LeRC and Lockheed have noted this. Cases which involve AO and charging occur in LEO polar orbits or slow transit from LEO to GEO during launch and separation. The tin oxide in ITO when AO-exposed loses oxygen.

Sharon Rutledge conducted a tour of the test facility. Plasma Ashers are used extensively for AO test. Materials are exposed to normal atmosphere pressure gases. Nitrogen does not significantly affect AO induced degradations. The Asher AO is at an energy of approximately 0.1 eV. Natural AO energies are closer to 4.25 eV. Ultra-violet material testing facilities are available using deuterium lamps.

Dr. Banks was concerned with AO effects on solar array and concentrator materials. Both reflector and refractor materials are of interest. Beryllium has poor reflectance in the visible range requiring larger reflectors, and is toxic. Aluminum and protected silver reflectors have been evaluated. Refractors are more of a problem. AO causes polymer refractors to erode and glasses are heavy.

Solar arrays have AO problems. Kapton coverings erode. Thin layers of SiO_2 or SiO_2/Kapton mixes prevent erosion. Coatings 1000 Angstroms thick ± 200 to 300 Å significantly limit erosion. Coating pinholes allow oxidation to occur behind the pinholes permitting it to spread into sensitive materials. New Kaptons are much clearer and transparent. Some Solar Array (SA) adhesives have AO problems. Silicones are better and fluoropolymers have up to 100 times less erosion.

Composites have been investigated. Graphite/epoxy is AO prone, both the graphite and epoxy eroding. Fiberglass/epoxy has epoxy erosion only.

J. C. Roche, John Staskus, N.T. (Norm) Grier and Dale Ferguson provided additional information providing various papers and documents of interest.

Dr. Banks provided some excellent advanced material data for more exotic solar dynamic power systems. More data was promised.

John Staskus has been performing computer modelling of materials charging and has test experience with Kapton, Tiles, and Paints.

Solar array interconnects are potential problems. Solar arrays usually have negative and positive sections. Negative sections are producing noise, light, and erosion. Positive sections are more sensitive, power-wise. The arcing noise in solar arrays settles down with time.

The natural environments could be changed drastically by man-made activities. Many launches and re-entries can alter the ionosphere. No one appears to have the charter for disturbed natural environmental effects.

Minutes of Meeting at AFWAL/MLB--Materials Lab Branch

Met with Capt. Tim Fotinos, Lt. Pat M. Falco, Dr. Robert D. Craig.

Air Force Wright Aeronautical Laboratory (AFWAL) is involved in the study of high temperature phenomena. Some materials and properties are restricted. Basically, AFWAL is studying Intrinsically Hard Materials (IHM) and has not been doing very much with Optical Surface Reflectors (OSR). Two groups were spoken with, a Non-Structural/Non-Metallic Group and a Structural Group.

The Non-Structural Group is involved with radiator coatings ranging from Cryogenic (Diffuse Black) 100K radiator coatings thru 300K (Plasma Spray Ceramics) using Medium Z metal films and oxides up to 1000 to 1200K radiator materials for nuclear power SP-100 application.

They are working with solar cell adhesives. DC 500 is a 300C present day adhesive. Hughes Aircraft has developed and tested 450 to 500C adhesives. The design goal is to develop 600C adhesives.

They are working with exotic insulations. Atomic oxygen limits applications. Inquiries were made concerning the usage of boron, and beryllium carbides, nitrides, and other ceramics. In general, they think ceramics have problems and carbides are AO damage-prone.Presently they are working on:

(1) Multithreat radiator coatings;

(2) High temperature Multilayer Insulation (MLI) with TRW using metal foil;

(3) Solid and liquid lubrication;

(4) Contamination/Lockheed. A material selection criteria is in preparation and will be provided to Dr. Haffner when completed.

AFWAL is working with contamination, outgassing, reflectance and absorptance changes. In addition, they have a Solar Simulator called SCEPTRE (Space Combined Effects Primary Research Apparatus) that provides up to 3 suns from 0.2 to 2.2 micron and electron beam irradiation up to 20 keV simultaneously if required. Two separate beam energies can be used at the same time.

Dr. Robert D. Craig is a materials engineer in the Structural Materials Branch. He is very interested in thermoplastics, in particular polyether ether ketone (PEEK), with AS 4 graphite fiber. This material is AO-prone but thin coatings are being investigated to prevent erosion.

Thermo-plastics are the most mature technology and carbon-carbon is the least mature, but offers the most possibilities for laser hard materials. It is expensive, requiring high pressure and temperatures while being formed. It is excellent from a total dose - bremsstrahlung viewpoint.

Metal matrix materials using graphite fibers between melted metal powders (Al, Mg) are a medium material technology being investigated.

Bobby McConnell is the expert in solid and fluid lubricants. His specialty is solid lubricants and bearings. Ceramic bearings (silicon carbide and nitride) are of interest. His solid lubricants sputter deposit molybdenum disulfide (MoS_2). AO could be a problem of exposed bearing surfaces but guards are possible. Pointing accuracy makes his job difficult. He is studying surface property modification (hardening, lubing, etc.). Operating temperatures considered go upward from cryogenic but no upper limit has been found.

The two groups spoken with were more involved in testing than computation. AFWAL has materials computational capabilities of some level. Air Force Geophysics Laboratory (AFGL) usually defines environments. AFWAL is providing the funding to AFGL for our present contract.

Past and future AFWAL materials efforts are described in the attachment.

Minutes of AFGL Meeting

Contact was made with Lt. Mike Giger and Lt. Col. Gaudet. Lt. Giger conducted the tour and arranged introductions to scientific staff. AFGL has a test facility for evaluating contamination, spacecraft glow. They have flown experiments in space and are planning various experiments with the Shuttle Orbiter on materials erosion, contamination of Orbiter, and spacecraft glow.

Dr. Don Hunton will be flying a payload in Orbiter in the 1990 time period (Flt. 42) to determine atomic oxygen erosion of materials. This flight is to be in a circular orbit at 250 km. The payload bay will be held in an attitude to get maximum erosion for 40 hours. The required attitude will be very close to the attitude the Orbiter would take without attitude control. Dr. Hunton provided a copy of a paper on the planned experiment he co-authored. A 40-hour AO exposure will only affect very AO- prone materials such as organics and plastics. He has already flown two experiments, the 1990 experiment will be the third.

Dr. David L. Cooke works with environment modelling and computer analyses. He has codes of interest for space charging, such as:

1) NASA Charging Analysis Program (NASCAP) for Geosynchronous Earth Orbit (GEO)

2) NASCAP for Low Altitude Earth Orbit (LEO)

3) Potential of Large Objects in the Auroral Region (POLAR) for polar orbits

4) SOCRATES for contamination studies. He is concerned with charging effects at GEO, polar orbits, especially on high voltage systems. High voltage systems not only attract electrons but can produce x-rays. In addition to the orbit, the time period during which the material is being charged is important as well as secondary emission

characteristics. Outer surfaces are extremely hard to predict; contamination, corrosion, etc., all can affect secondary emission. He mentioned predicted problems with the charging of solar array silver interconnects which discharge at 400 to 500 volts, causing noise and damage.

Defense Meteorological Satellite Program (DMSP) analyses and test of charging was performed with excellent correlation of results. DMSP flew at 1000 KM in polar orbit and charged negatively to 400 volts. The charging voltages scale with satellite size ($S^{2/3}$). Launch and re-entry charging so far has not been a problem with charges leaking off as they are produced.

AFGL can model charging on any configuration spacecraft but they do not have the capability to handle classified modelling. They will provide their codes to us. The beautiful graphics they have will be harder to provide.

Dr. Cooke has NASCAP code write ups. He provided a copy of the NASCAP for LEO and can provide the NASCAP for GEO in the near future.

Dr. Ed Murad is the Contamination Program Manager and is involved with AO and spacecraft glow phenomenon. He is working on glow effects for various types of spacecraft. He is feeding contamination data to Lt. Mike Giger for the Contamination Handbook which is in the planning stages. The SOCRATES code (Spacecraft Orbiter Contamination Representation Accounting for Transient Emitting Species) is being used.

Minutes of Meeting at NASA Johnson Space Center

NASA is doing some extremely useful work in investigating and cataloging space debris and micrometeoroid environments, especially in investigating effects of impacts of pellets in the 5 to 10 KM/sec velocity range. They have test capabilities for pellet and larger impact testing in vacuum. They are doing some spacecraft charging work but it is restricted to keeping a fixed potential on a spacecraft by dragging tethers through plasma clouds generated by the spacecraft. They have noted problems with solar arrays having induced currents when operating at LEO. Their tether concepts are only of value at LEO since the magnetic field intensity decreases with distance from the center of the earth as $1/R^3$. The tether concept can be used for power generation as well as propulsion of spacecraft. Testing is planned of the tether concepts in orbiter flights in the 1990 period. Some of the Get-Away-Special flight experiment hardware was also examined.

Dr. J. E. McCoy is pushing the tether concept. It is quite revolutionary but needs space verification. Tethers up to 10 KM long are proposed. The tethers can be up, down or both (symmetrical). Ball Bros. has a 200 KW power system on the boards. In principle, up to a MW can be generated.

Jeanne Lee Crewes, the manager of the Hypervelocity Impact Research Laboratory (HIRL) was helpful and briefed me on HIRLs test capabilities and showed me the results of the impact testing. Don Kessler does high velocity impact research and is the resident expert on space debris and micrometeroid environments. He provided printed data (NASA Memoranda 4506, 5099, 5402 and 5901), on Cosmic Rays.

Kessler was a valuable source of data. He said gram for gram, pellets at 2 to 3 KM/sec had more energy than explosives. Pellets can be accelerated with:

Light Gas Guns--easily to 7 KM/sec, with difficulty to 10 KM/sec. The USAF has accelerated 8 ounce pellets. Usually pellets are 1/16 to 1/8 of an inch in diameter.

Rail Guns--use electromagnetic fields to accelerate particles, pellets

Van de Graaf--can accelerate charged particles. A 1/10 micron particle can reach 30 KM/sec A 1 micron particle can reach 2-3 KM/sec. The use of these accelerators for hyper-velocity impact work is unusual. TRW had one, but shut it down. The French have one or more.

Andrei Konradi is very involved in the environments definition and space experimental research, particularly cosmic rays, and proton and heavier particle effects, which produce spallation, heavy particles, and biological effects. He suggested our obtaining four Naval Research Laboratories (NRL) documents--NRL Memorandum Reports.

- 5901 12-31-86
- 5402 08-09-84
- 5099 05-26-83- 4506 08-25-81

The titles (abbreviated) are Cosmic Ray Effects on Microelectronics, Part IV.

These documents not only discuss electronic effects, but define in detail cosmic ray environments and other environments. Konradi is the resident expert on auroral production and effects.

Much of the NASA help was in the form of written detailed data which at this time has not been reviewed, and suggestions on where to get more data. The data provided is included as attachments.

Kessler and Cour-Palais provided data on the Orbital Debris Environment and Spacecraft Shielding which they collated, wrote, and will present to interested parties. Kessler provided data on Earth Orbital Pollution which he authored. McCoy provided three papers he wrote on tether concepts and Konradi provided three papers on environments.

Jim Visentine--working with Wright Patterson Air Force Base (WPAFB) on AO is concerned with solar arrays, kapton, polyurethane paints, and AO effects on silver since Silver Oxide is non-conductive.

Shuttle uses Silver--Teflon radiators. Space Station can not use these. It will use special anodized materials for the radiators. (Accurex developed the coating process).

Visentine suggests checking contamination-produced by AO, and high temperatures on optics. He is concerned with synergisms involving AO and UV and UV-electron combinations.

Insulation, seals, lubrication, no metallic standoffs--all non-metallics used on spacecraft are AO prone.

Most metals form oxide coatings which protect them from further oxidation--silver and osmium are exceptions (osmium is good for UV reflectors).

AO causes S/C glow. Glow could be a problem for some space vehicles. Glow seems to be most intense in infrared range - red-orange, but theoretically UV should also be present. Experiments are planned to determine the entire spectrum (0.5 to 14 micron). AO and nitrogen form the coating and more AO produces the glow. New theories keep developing and laboratory testing and space experiments are really needed.

Hopefully, coatings can be developed which will suppress the glow. Kapton glows least, but erodes. Black paint Z-306 glowed most, but eroded least. Niobium also glows. Unburned hydrazine chemical reacts and, through a complex process, glow occurs. Glow is broad-band spectra.

Jim Visentine provided three of his papers on materials interactions due to space environments, mostly geared towards Space Station, and another paper on protective coatings and evaluation techniques.

Minutes of AFWL Meeting

A meeting with Capt. David Doryland of the Optical Components Branch was attended. It was a very fruitful meeting. He is on the Space Defense Initiative Office (SDIO) Optics Coordinating Committee (OCC) with the responsibility of guaranteeing that SDIO optics can withstand the natural environments and also be producible in required amounts.

He is involved with optical coatings to reflect High Energy Laser (HEL) radiation. He is concerned with excimer, free electron and chemical (ALPHA SPICE) lasers. The free electron lasers can be designed to operate at a single wavelength from ultraviolet to infrared. He is mostly concerned with the 1.06 micron region.

The quarter wave stack materials he is interested in are

BN/C (diamond like)

Si_3N_4/SiO_2

SI_3N_4/Al_2O_3

AlN/Al_2O_3

Boron nitride is a low Z material with excellent X-ray and thermal properties. He is not very enthusiastic about rugate filters.

Capt. Doryland is using the TFT-PUFF (Thin Film Transport PUFF) code to evaluate mechanical shocks in thin films. Lt. Rick Engstrom will provide us a copy of this code. His telephone number is (505) 844-7422.

More data is available from K-TECH in Albuquerque - Allan Watts (505) 268-3379.

Capt. Doryland will be testing optical coatings in the very near future on a Delta Star rocket in LEO (Low Earth Orbit) or MEO (Medium Earth Orbit) for about a week. He is interested in beryllium, silicon carbide, fused silica, ultra low expansion (ULE), titanium doped silica, and a glass ceramic Zerodur. He is testing optical materials with NASA-Lewis Research Center (Bob Banks) for AO, UV and electron effects. Most of AFWL's past efforts have concerned survivability. In the near future, endurability (natural effects) will be emphasized.

Rockwell has a facility at AFWL--called OCEL (Optics Component Evaluation Lab). They support AFWL, running tests of reflectance, transmittance, absorptance, and scatter (before, during, and after exposure). Dick House (Rockwell) provides high technology optical support services. Rockwell International operates the equipment and test lab. Capt. Couick is in charge of the high power CO_2 laser facility. Several 30 to 40 KW CO_2 lasers provide continuous wave irradiation.

Rockwell International's Robert McBroom simulates laser irradiation with an electron beam which can be focussed or defocussed, raster swept for large area irradiation, or provide a 2 mm diameter beam. A one amp beam at 20 to 40 KV provides continuous, modulated, or swept irradiation. Much of the testing is of materials used for carbon dioxide lasers. Tests in air, vacuum or space are performed.

Rockwell International's Dave Merriman measures optical distortions when an electron beam is used to simulate a laser. He has some extremely precise distortion measuring equipment. He measures massive high power laser components with electron beams being used to simulate the lasers. The electron beams provide higher power densities and greater flexability of test than AFWL's lasers. OCEL has tested various types of mirrors such as silicon, silicon-carbide, metal, and molybdenum. They have not tested detector optic mirrors.

Capt. Jay Tilley is doing research on phased array optics. Most of his work has been ground or air related although sometimes he used optical phased arrays for space laser radars. His phased array interfaces with the space environments exclusively through mirrors. Capt. Tilley's phased arrays operate in the visible and near infrared (a few microns). He is not involved with endurability, he is developing concepts. Dr. Singaraju and John Mullis are developing localized shielding concepts using complicated shielding of integrated circuits in the package or can. Sandia is developing these shields called RAD PAK. Fabrication is an issue.

In addition, they are concerned with electron charging internally of material for circuit boards. The enhanced electron environments have electrons in the 1 to 3 MeV range which do the internal charging. Some discussion of low energy electron charging and UV induced discharging occurred. Mullis promised to send what available data they have and provide names of Rockwell International people with additional reports. Both support SABIR efforts.

Appendix III. Facility Visit References Collection

This Appendix lists papers, reports, etc., collected during facility visits.

Copies of papers collected by R.J. Dempsey on trip 1988. B.A. Banks, "Advanced Materials for Survivability for Solar Dynamic Power Systems", NASA-Lewis briefing.

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J.B. Cross, E.H. Lan and C.A. Smith, "A Technique to Evaluate Coatings for Atomic Oxygen Resistance", - paper.

Anon, "Non-Structural Materials for Space Systems - Focal Area 6" Briefing on FY 1989, FY 1990.

D.A. Gulino, "The Survivability of Large Space-Borne Reflectors under Atomic Oxygen and Micrometeoroid Impact", 25th AIAA Aerospace Sciences Meeting, Reno, Nevada (January 12-15, 1987).

C.K. Purvis, H.B. Garrett, A.C. Whittlesey, and N.J. Stevens, "Design Guidelines for Assessing and Controlling Spacecraft Charging Effects", NASA Technical Paper 2361 (September 1984).

B.A. Banks, M.J. Mentick, S.K. Rutledge, and H.K. Nara, "Protection of Solar Array Blankets from Attack by Low Earth Orbital Atomic Oxygen" - paper.

D.E. Hunton et al., "Quadruple Mass Spectrometer for Space Shuttle Applications: Flight Capabilities and Ground Calibration", - paper.

E. Murad, "Glow of Spacecraft in Low Earth Orbit", in proceedings of the 1985-1987 MIT Symposia on the Physics of Space Plasma Vol. 6, T. Chang, J. Belcher, J.R. Jasperse and G.B. Crew, eds., Scientific Publishers, Inc.

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