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ENVIRONMENTAL EFFECTS ON SPACECRAFT MATERIALS

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This is a summary of some results of Phase I work on an AFGL* contract to study the effects on the natural space environments on materials which may be used for SDI† applications. Phase I was a study of the current state-of-the-art knowledge of those effects, and was carried out by a literature search, a questionnaire mailing, and some visits to NASA and Air Force research facilities. Phase II will be a study of what materials may be used for SDI applications and to what natural space environments they may be vulnerable. Deficiencies in knowledge of the effects of the natural space environments on these materials are to be identified and recommendations are to be made to eliminate these knowledge deficiencies.

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† Strategic Defense Initiative

ENVIRONMENTAL EFFECTS ON SPACECRAFT MATERIALS

PHASE I - STUDY EFFECTS

- LITERATURE SEARCH
- QUESTIONNAIRE MAILING
- FACILITY VISITS

PHASE II - STUDY APPLICATIONS

- ISSUE IDENTIFICATION
- DEFICIENCY DETERMINATION
- RECOMMENDATIONS

Permanent Material Effects Due To Environments

The space environment includes several components - vacuum, residual gasses, solar ultraviolet light, energetic charged (Van Allen, solar flare, and cosmic ray) particles, hot and/or cold electrical plasma and solid objects (micrometeoroids and space debris). The results of the Phase I work showed that these environments produce various effects on different types of material. For example, the space vacuum permits materials to outgass, the residual atomic oxygen erodes ram-facing exposed organics, ionizing radiation decreases mechanical strength (in most materials) and electrical conductivity (in non-insulators), etc. Other effects are surface electrical charging (due to hot plasma) electrical charge neutralization (due to ionosphere), and surface erosion and punctures (due to micrometeoroids and debris objects). While effects due to the space vacuum, solar photon radiation, and micrometeoroids are not greatly dependent on spacecraft altitude, atomic oxygen and ionospheric effects are significant only at low altitudes; hot plasma and solar flare particle effects are high altitude/latitude phenomena, while Van Allen and space debris effects have their own altitude dependences.

PERMANENT MATERIAL EFFECTS DUE TO ENVIRONMENTS

ENVIRONMENT	MATERIAL	EFFECTS
VACUUM	ALL, ESP. ORGANICS	OFFGASSING, OUTGASSING
RESIDUAL GASSES (ATOMIC OXYGEN)	ORGANICS	SURFACE EROSION, GLOW
RESIDUAL GASSES (ATOMIC OXYGEN)	SOME METALS	EMBRITTLEMENT
SOLAR U.V.	ORGANICS	SURFACE DISCOLORATION
VAN ALLEN BELTS	ALL, ESP. ORGANICS	DISCOLORATION, WEAKENING
SOLAR FLARE PARTICLES	CONDUCTORS, SEMICONDUCTORS	THERMAL, ELECTRICAL RESISTIVITY
IONOSPHERE	INSULATORS	CHARGE NEUTRALIZAITON
HOT PLASMA	INSULATORS	HIGH VOLTAGES, DISCHARGES
HOT PLASMA	CONDUCTORS	ELECTRIC CURRENT, HEATING
MICROMETEOROIDS & DEBRIS	ALL, ESP. OPTICS	SURFACE EROSION, PITS. PUNCTURES

Synergistic Effects Involving Sunlight (Including UV)

Based upon the Phase I work, a summary has been compiled of the synergistic effects on materials due to combinations of two environments. This is a summary of those effects which involve sunlight.

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 gasses) can produce unusual spacecraft rotations and/or require special attitude control measures. Sunlight plus vacuum increases organic outgassing and cross-linking (a major effect) while sunlight heating helps anneal out the damage caused by nuclear 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 α_s and/or reflectivity of radiators and mirrors. For exposed coatings, the thermal cycling due to sunlight poses the threat of coating damage/decoloration especially for substrates vulnerable to any of the other environments.

SYNERGISTIC EFFECTS INVOLVING SUNLIGHT (INC UV)

ENVIRONMENTS	EFFECTS	MATERIALS/PARTS
SUNLIGHT + G. FIELD	TORQUES MODIFIED	ENTIRE SPACECRAFT
SUNLIGHT + B. FIELD	TORQUES, DRAG MODIFIED	ENTIRE SPACECRAFT
SUNLIGHT + VACUUM	INCREASED OUTGASSING, CROSS-LINKING	EXPOSED ORGANICS
SUNLIGHT + NUCLEAR RADIATION	INCREASED ANNEALING	EXPOSED SEMICONDUCTORS
SUNLIGHT + SOLID OBJECTS	DECREASED REFLECTIVITY	EXPOSED RADIATORS, MIRRORS
SUNLIGHT + IONOSPHERE	LOWER VOLTAGE, INCREASED DISCHARGES	EXPOSED CONDUCTORS
SUNLIGHT + HOT PLASMA	DECREASED CHARGING	EXPOSED INSULATORS
SUNLIGHT + NEUTRAL GASSES	INCREASED EROSION, TORQUES	RAM-EXPOSED ORGANICS

Synergistic Effects Involving The Gravity Field

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 gasses) can combine with the gravity field to modify the stable orientation. The space vacuum permits orientation changes to persist since it provides no damping. The gravity-modified spacecraft orientation affects the drag due to the inosphere and the residual gasses, 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 nuclear radiation, since the ambient nuclear radiations in space (Van Allen belts, solar flare particles) are quasi-isotropic and produce essentially zero torques on spacecraft. Conversely, the nuclear radiation effects on materials and parts are not affected by the presence or absence of the Earth's gravity field.

SYNERGISTIC EFFECTS INVOLVING THE GRAVITY FIELD

ENVIRONMENTS	EFFECTS	MATERIALS/PARTS
G. FIELD + B. FIELD	TORQUES MODIFIED	ENTIRE SPACECRAFT
G. FIELD + VACUUM	NO TORQUE DAMPING	ENTIRE SPACECRAFT
G. FIELD + NUCLEAR RADIATION	NO OBVIOUS EFFECT	
G. FIELD + SOLID OBJECTS	PROJECTED AREA/ VELOCITY MODIFIED	EXPOSED MIRRORS, RADIATORS
G. FIELD + IONOSPHERE	IONOSPHERIC DRAG MODIFIED	ENTIRE SPACECRAFT
G. FIELD + HOT PLASMA	SUNLIGHT EXPOSURE MODIFIED	EXPOSED INSULATORS
G. FIELD + NEUTRAL GASSES	TORQUES, RAM EXPOSURE MODIFIED	EXPOSED ORGANICS

Synergistic Effects Involving The Magnetic 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 gasses). 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 impacts rates due to stream meteoroids and orbiting debris particles will be modified. Finally, the presence of the geomagnetic field will modify the ionospheric drag.

SYNERGISTIC EFFECTS INVOLVING THE MAGNETIC FIELD

ENVIRONMENTS	EFFECTS	MATERIALS/PARTS
B. FIELD + VACUUM	NO TORQUE DAMPING	ENTIRE SPACECRAFT
B. FIELD + NUCLEAR RADIATION	SOLAR, GALACTIC CUTOFF MODIFIED	SEMICONDUCTOR ELECTRONICS
B. FIELD + SOLID OJBECTS	PROJECTED AREA/ VELOCITY MODIFIED	EXPOSED MIRRORS, RADIATORS
B. FIELD + IONOSPHERE	IONOSPHERIC DRAG MODIFIED	ENTIRE SPACECRAFT
B. FIELD + HOT PLASMA	SUNLIGHT EXPOSURE MODIFIED	EXPOSED INSULATORS
B. FIELD + NEUTRAL GASSES	TORQUES, RAM EXPOSURE MODIFIED	EXPOSED ORGANICS

Synergistc Effects Involving Space Vacuum

In addition to facilitating outgassing, the vacuum of space does not limit many environmental parameters (speed, temperature, voltage, 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. 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 outgass 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.

SYNERGISTIC EFFECTS INVOLVING SPACE VACUUM

ENVIRONMENTS	EFFECTS	MATERIALS PARTS
VACUUM + NUCLEAR RAD.	INCREASED RADIATION RESISTANCE	EXPOSED ORGANICS, TEFLON
VACUUM + SOLID OBJECTS	INCREASED IMPACT DAMAGE	EXPOSED SURFACES
VACUUM + IONOSPHERE	INCREASED DISCHARGING (MORE ELECTRONS)	EXPOSED VOLTAGES, INSULATORS
VACUUM + HOT PLASMA	INCREASED CONTAMINATION	EXPOSED INSULATORS
VACUUM + NEUTRAL GASSES	IONS, RADICALS LIVE LONGER	EXPOSED ORGANICS, SENSORS

Synergistic Effects Involving Nuclear Radiation

The major effect of nuclear radiation is to randomize the structure of materials, 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. Fluid containers are more easily punctured by solid objects if they have been weakened by nuclear radiation. The presence of residual gasses (atomic oxygen) at low altitudes increases the surface damage produced by ionizing nuclear radiation, especially in organic materials on the front (ram) side of the spacecraft.

SYNERGISTIC EFFECTS INVOLVING NUCLEAR RADIATION

ENVIRONMENTS	EFFECTS	MATERIALS/PARTS
NUCLEAR RAD. + SOLID OBJECTS	DECREASED PUNCTURE RESISTANCE	FLUID CONTAINERS (ORGANICS)
NUCLEAR RAD. + IONOSPHERE	DECREASED DISCHARGE RATE	EXPOSED INSULATORS
NUCLEAR RAD. + HOT PLASMA	DECREASED DISCHARGE RATE	EXPOSED INSULATORS
NUCLEAR RAD. + NEUTRAL GASSES	DECREASED RADIATION RESISTANCE	RAM-EXPOSED ORGANICS

Synergistic Effects Involving Solid Objects

Solid objects (micrometeroids 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. 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.

SYNERGISTIC EFFECTS INVOLVING SOLID OBJECTS

ENVIRONMENTS	EFFECTS	MATERIALS/PARTS
SOLID OBJECTS + IONOSPHERE	IMPACT VOLTAGES DECREASED	EXPOSED SURFACES
SOLID OBJECTS + HOT PLASMA	EXPOSE SUBSTRATES	INSULATING SUBSTRATES
SOLID OBJECTS + NEUTRAL GASSES	EXPOSE SUBSTRATES	ORGANIC SUBSTRATES

Synergistic Effects Involving The Ionosphere

Since the ionosphere is a cold plasma, it acts to limit the effects of electric or magnetic fields produced by spacecraft. 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 gasses (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.

SYNERGISTIC EFFECTS INVOLVING THE IONOSPHERE

ENVIRONMENTS	EFFECTS	MATERIALS/PARTS
IONOSPHERE + HOT PLASMA	DECREASED CHARGING RATE	EXPOSED INSULATORS
IONOSPHERE + NEUTRAL GASSES	MORE IONS, RADICALS PRODUCED	EXPOSED ORGANICS

Synergistic Effects Involving Hot Plasma

Since all other combinations of two environments have been discussed, the only combination left is that of hot plasma and neutral gasses. The presence of the neutral gasses (principally atomic oxygen) will increase the electrical discharge rate, due to the hot plasma, by providing additional atoms and ions. 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 gasses occur primarily at low altitudes, this effect will be small.

SYNERGISTIC EFFECTS INVOLVING HOT PLASMA

ENVIRONMENTS	EFFECTS	MATERIALS/PARTS
HOT PLASMA + NEUTRAL GASSES	INCREASED DISCHARGE	RAM-FACING ORGANIC INSULATORS

Summary Of Synergistic Effects On Materials

This matrix lists each environment along both the vertical (left side) and the horizontal (top) axis. The spacecraft (s/c), the types of surfaces (e.g. exposed, high voltage, etc.) and the types of materials (e.g. 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 gasses 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 nuclear radiation indicates the absence of any obvious synergistic effect.

SUMMARY OF SYNERGISTIC EFFECTS ON MATERIALS

	SUNLIGHT (UV)	GRAVITY FIELD	MAGNETIC FIELD	SPACE VACUUM	NUCLEAR RADIATION	SOLID OBJECTS	IONOSPHERE	HOT PLASMA	NEUTRAL GASSES
SUNLIGHT (INC UV)	---	S/C	S/C	ORG	SEMI	OPTICS	COND	INS	ORG
GRAVITY FIELD		---	S/C	S/C	0	OPTICS	S/C	INS	ORG
MAGNETIC FIELD			---	S/C	SEMI	OPTICS	S/C	INS	ORG
SPACE VACUUM				---	ORG	EXP	HV	INS	ORG
NUCLEAR RADIATION					---	ORG	INS	INS	ORG
SOLID OBJECTS						---	EXP	INS	ORG
IONOSPHERE							---	INS	ORG
HOT PLASMA								---	ORG
NEUTRAL GASSES									---

S/C = SPACECRAFT ORG = ORGANICS SEMI = SEMICONDUCTORS
COND = CONDUCTORS INS = INSULATORS EXP = EXPOSED SURFACES
HV = HIGH VOLTAGES

Summary - Conclusions

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 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. Nuclear 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. This paper was an attempt to indicate some of these effects of multiple space environments and a call for more attention to them.

SUMMARY - CONCLUSIONS

EFFECTS DUE TO SINGLE ENVIRONMENTS
(EITHER UNDERSTOOD OR BEING STUDIED)

- SUNLIGHT (INC UV) - EFFECTS BEING STUDIED
- FIELDS (GRAVITY, MAGNETIC) - ENVIRONMENT, EFFECTS KNOWN
- VACUUM (INC CONTAMINATION) - EFFECTS BEING STUDIED
- NUCLEAR RADIATION
  (VAN ALLEN, S. FLARE, GALACTIC) - EFFECTS BEING STUDIED
- SOLID OBJECTS (MICROMETEOROIDS, DEBRIS) - DON'T KNOW
  ENVIRONMENT YET
- PLASMA (IONOSPHERE, HOT) - ENVIRONMENT QUITE VARIABLE
- NEUTRAL GASSES (ESP ATOMIC O) - DON'T KNOW EFFECTS YET

EFFECTS DUE TO MULTIPLE ENVIRONMENTS (MANY NOT UNDERSTOOD (FEW BEING STUDIED

ORGANICS)
INSULATORS) ESPECIALLY VULNERABLE IF EXPOSED
OPTICS)