THE UNIVERSITY OF MICHIGAN

INDUSTRY PROGRAM OF THE COLLEGE OF ENGINEERING

WEAR CONSIDERATIONS IN THE DESIGN OF SPACECRAFT

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PREFACE

John Norby, the author of this survey paper, is now working for the Air Force in space vehicle research. The paper was submitted to Professor Charles Lipson in December, 1960, in connection with the course ME 183, "Wear Considerations in Design". Professor Lipson recommended it for Industry Program distribution.

I. INTRODUCTION

Space vehicles and their materials are subjected for long periods of time to an environment radically different from that at and near the earth's surface. The effect of these environmental factors on materials cannot be determined by existing data pertaining to wear. It is therefore, necessary to study the space environment by experimental laboratory techniques, and by rocket and satellite probes deep into space. Present theories on conditions in space, and the effect on material properties must be tested before space vehicles can carry man with assurance of a safe return.

It is the intent of this paper to present a summary of the state of knowledge as it exists today pertaining to the effects of the space environment on material surfaces and structural properties.

II. SUMMARY

The space environment is vastly different from conditions near the earth's surface. Properties such as temperature extremes, high radiation intensities, meteoric bombardment, ionized gas particle bombardment, and high vacuum, all have potential detrimental effects on spacecraft materials.

In near space, problems of lubrication, seizure of contacting surfaces, and re-entry overheating are primary considerations. Space travel to the moon and other planets will result in other problems of concern in which knowledge is scarce and speculative. The effects of solar plasmas and long time exposures to meteoric erosion may become highly destructive to spacecraft surfaces.

It is therefore necessary to identify and develop suitable materials and design criterion that are sufficiently capable to withstand the wear mechanisms of the space environment.

III. PROPERTIES OF THE SPACE ENVIRONMENT

The general characteristics of space are summarized in Table I. The approximate composition is shown in Figure 1. (Ref. 1)

As a space vehicle travels further from the earth's surface, the ambient pressure reduces gradually to high vacuum. At 200 miles altitude the pressure is approximately 10^{-7} mm Hg. and at 1000 miles is 10^{-11} mm Hg. (1)

The radiation is basically the same as that encountered on the earth's surface, but is present in much higher intensities. The atmosphere shields most of the primary cosmic radiation and the short-wavelength end of the solar spectrum. The Van Allen belts that encircle the earth in outer space are high concentrations of protons and other charged particles of high energy.

Approximately 93% of radiant energy arrives as light of wavelengths between 0.3 and 2 microns. Cosmic radiation in space consists mainly of protons, but also includes particles of higher mass. The total flux in a 24 hour period is about 105 particles per square cm.

The Van Allen radiation belts contain electrons of energy greater than 13 MEV, and protons with energy up to 700 MEV. (million electron volts)

Particles of lower energy such as the proton and helium ions that compose the solar wind, and neutral gas atoms (H beyond 600 miles, and H, N, O, at lesser distances) are important and potentially dangerous constituents of the space environment. These ionized gas particles are termed solar plasmas, and can build up to high intensities during solar storms. (2)

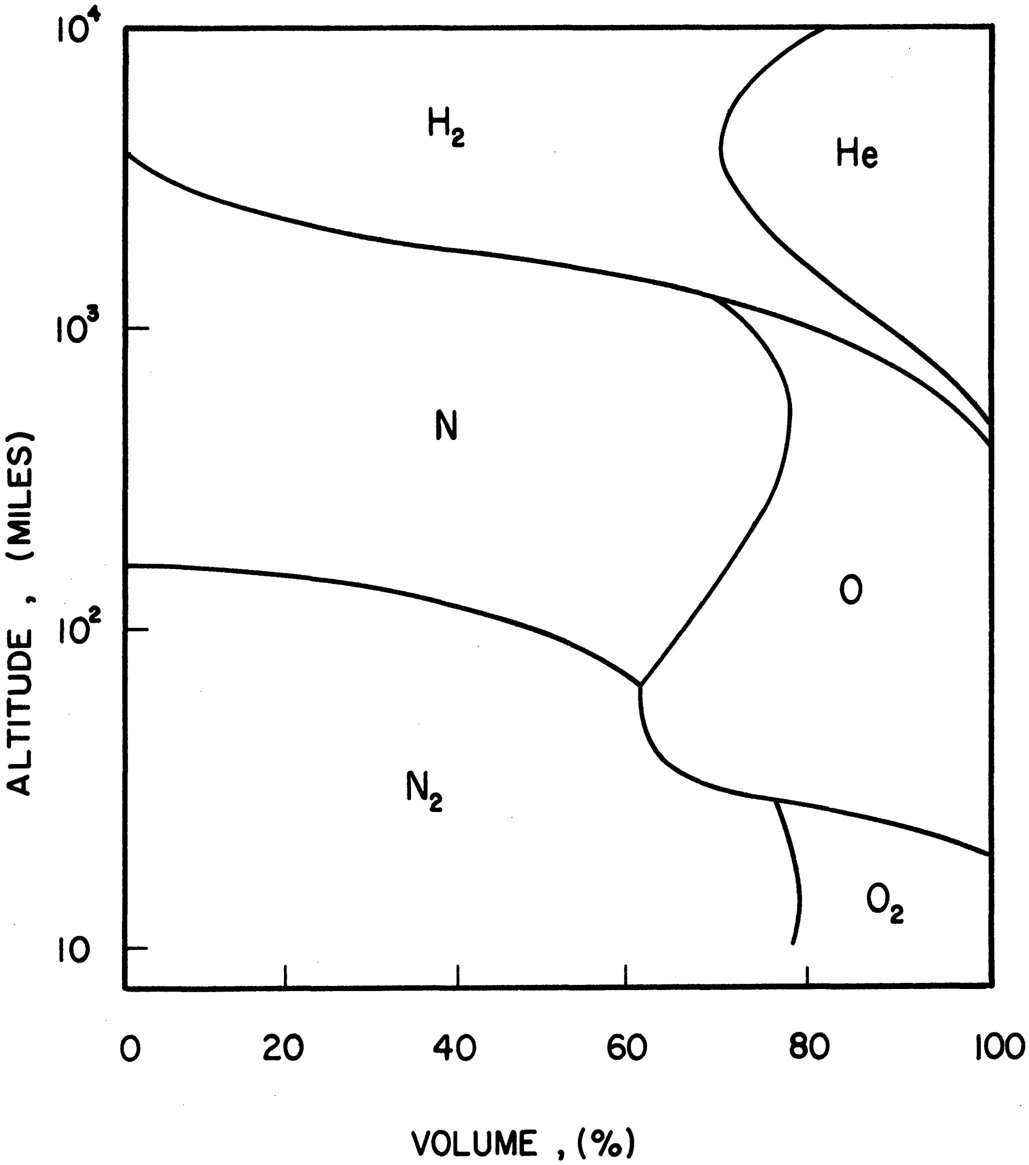

Figure 1. Approximate Composition of the Atmosphere.

TABLE I

CHARACTERISTICS OF THE SPACE ENVIRONMENT

Low pressure and density

Chemical Composition

Ionized layers

Thermal radiation fields, influencing temperature of vehicle

- Infrared solar radiation
- Earth's albedo
- Reflection from earth's atmosphere
- Re-radiation to outer space

Other solar radiation

- X-rays
- Ultraviolet
- Visible

Cosmic radiation

- Electromagnetic (x-rays, gamma radiation)
- Primary particles (protons, alphas, atomic nuclei)
- Secondary particles (electrons, positrons, mesons, neutrons)

Artifically produced radiation

- Nuclear explosions
- Nuclear propulsion
- Other propulsion (ion, photon, etc.)

Electromagnetic fields

- Geomagnetic field
- Interplanetary magnetic fields

Force fields

- Gravitational
- Acceleration
- Vibration

Material fields

- Micrometeorites at high velocity

Meteoroids are distributed throughout the solar system in varying sizes, quantities, and with different physical properties. It has been estimated from observation and satellite probes that there exists a high concentration of extremely minute particles. These particles are termed interplanetary dust or micrometeorites, and the intensity varies from 30-300 impacts/sq. cm/ year, of particles larger than 4 (2)

IV. EFFECTS OF SPACE ENVIRONMENTAL CONDITIONS ON MATERIALS

A. Extreme Temperature Effects

The surface temperature of a space vehicle is determined by the relative emissivity and absorptivity of its surface, the external environment, vehicle and orbit geometries, and internal heat sources. The surface temperature is most sensitive to thermal radiation from the sun at an altitude above 200 miles, it can therefore, be regulated within a wide range by a proper selection of surface finishes. (3)

The surface finish in terms of texture, shade, color, pattern, etc., must be endurable throughout the lifetime of the space vehicle. In the shadow of the sun it is possible to obtain surface temperatures near absolute zero, and in direct sunlight the temperature can reach the vaporzation point of many materials. It may therefore be necessary to provide a spinning exterior surface in order to balance the temperature extremes. Near the earths surface (up to 10,000 miles), an appreciable amount of heat is absorbed by radiation from the earth's surface.

Table II lists the service temperature ranges of some plastic films. (4)

Variations in surface temperature resulting from insufficient balancing can cause high stresses in materials. These stresses can result in failure, cracking etc., if the variations are extreme. Local cold spots should be avoided because the loss in ductility can cause certain brittle fractures and surface cracking. Conventional wear mechanisms can be accellerated by the induced stresses (pitting by contact loading, surface fatigue etc.)

TABLE II

DATA ON SELECTED PLASTIC FILMS
BASED ON CONTINUOUS SERVICE TEMPERATURE

MATERIAL	THICKNESS (IN)	MAX. CONTINUOUS SERVICE TEMP. °F	MIN. CONTINUOUS SERVICE TEMP. °F
NYLON 6	0.0005	380	-100
POLY-PROPYLENE	0.00075	300	-
POLYVINYLIDENE CHLORIDE (SARAN)	0.0005	290	-
POLYTETREFLUORO-ETHYLENE	0.002	565 - 585	-90
POLYTRIFLUORO MONO-CHLORDETHYLENE	0.002	300 - 395	-120
POLYESTER (POLYETHYLENE TEREPHTHELATE)	0.00025	490	-80
ETHYL CELLULOSE	0.003	210 - 275	-75
CELLOPHANE PLAIN	0.0009	375	0
CELLOPHANE COATED	0.0009	300 - 375	0
CELLULOSE ACETATE	0.0005	250 - 300	-25
CELLULOSE TRIACETATE	0.003	300 - 400	-25

B. High Vacuum Effects

1. Loss of Material

Sublimation and evaporation are accellerated by the absence of an atmosphere in that molecules leaving the surface of a material do not make collisions that can return them to the surface.

Table III lists maximum lossed in metal thickness at 50 and 70% of the absolute melting point for a variety of metals. (2) It can be noted that the appropriate choice of materials must be made on the bases of vaporization rate, and not the melting point. A good example is chromium and platinum. The vaporization rates at 50% of their melting points vary by a factor of 10^{10} while their melting points are only 48°F apart.

The maximum possible rate of loss G of a pure material in high vacuum is:

$$G = \sqrt{\frac{M}{T}}\ \frac{p}{17.4} \qquad \text{(ref 5)}$$

where: G = rate loss in g/sec-sq cm of exposed surface
M = molecular WT. of material
T = Temperature in °K
p = vapor pressure in mm hg at temperature T.

Table IV gives the temperature at which the loss from typical low melting point metals will reach 1.0 g/yr of material from 1 sq. cm. of exposed area. (5)

Table V gives vapor pressures and loss rates for typical plasticizers as calculated from the equation above. (5)

Plastics contain a variety of ingredients and are therefore, more complex in structure than metals. The basic polymer of the plastic

TABLE III

MAXIMUM VAPORIZATION LOSSES COMPUTED FROM LANGMUIR EQUATION FOR VARIETY OF METALS AT 50 AND 75% OF THEIR ABSOLUTE MELTING POINT

		50% OF ABSOLUTE MELTING POINT		70% OF ABSOLUTE MELTING POINT	
METAL	MELTING POINT °F	TEMPERATURE °F	LOSS, IN / YR.	TEMPERATURE °F	LOSS IN/YR
C	6700	3120	7.5×10^{-5}	4550	21.7
W	6170	2855	2.9×10^{-9}	4180	4.2×10^{-3}
Ta	5425	2480	3.6×10^{-11}	3660	3.3×10^{-4}
Mo	4760	2150	1.4×10^{-8}	3195	1.1×10^{-2}
Nb	4380	1960	4.6×10^{-15}	2930	1.5×10^{-6}
Cr	3272	1405	2.0×10^{-3}	2150	115
Pt	3224	1380	8.4×10^{-14}	2120	3.5×10^{-6}
Fe	2800	1170	7.7×10^{-9}	1820	1.4×10^{-2}
Co	2723	1130	8.1×10^{-12}	1770	8.7×10^{-5}
Ni	2650	1095	2.1×10^{-11}	1720	2.9×10^{-4}
Be	2340	940	1.6×10^{-9}	1500	6.6×10^{-3}
Al	1220	380	4.8×10^{-23}	715	2.6×10^{-12}
Mg	1200	370	1.0×10^{-3}	700	53

TABLE IV

LOSS OF METAL TO SPACE

MATERIAL	MELTING POINT (°C)	TEMPERATURE FOR LOSS OF 1 g/Sq Cm-Yr (°C)
Cs	29	25
Na	98	130
Mg	651	250
Al	660	690

TABLE V

PLASTICIZER LOSS TO SPACE

	ROOM TEMPERATURE	100°C
VAPOR PRESSURE (mm Hg)	10^{-4} - 10^{-2}	0.1 - 1.0
LOSS (g/Sq Cm-day)	1 - 100	1000 - 10,000

is not likely to have a high vacuum pressure with a corresponding high loss in material, but some of the other ingredients may.

2. Changes in Composition of Material

Exposure to vacuum of alloy materials results in changes of composition. The various components of an alloy will vaporize at different rates. The mechanical properties such as strength, hardness and creep rates may change as a result of composition change.

Most plastics contain a plasticizer with a high volatility. The loss of this plasticizer through material sublimation will result in cracking, and an increase in brittleness.

Ceramics exposed to high vacuum at high temperatures can undergo changes in mechanical and physical properties due to an interdiffusion of components or chemical reactions. (2)

3. Change in Optical Transmissions

Glasses that are exposed to high temperatures in vacuum may devitrify as a result of composition changes. The optical transmission characteristics of plastics can be changed due to crazing by loss of plasticizer. (2)

4. Changes in Emissivity

Changes in emissivity and reflectivity will result from the surface roughening after evaporation. Changes can also be anticipated for metals that under atmospheric conditions are covered with a protective oxide film. (2)

5. Wear and Seizure of Contacting Surfaces

a. The Problem Defined

In the high vacuum of space, lubrication is required not only to reduce friction, but is also essential for preventing seizure of moving surfaces in contact. This problem of seizure is caused by the removal of absorbed surface films of gas, a few molecules thick, which are present on the cleanest surfaces in the atmosphere. When these surface films are stripped off in space, bare metal surfaces are cold-welded together by intimate contact. (4)

b. Oils and Greases as Lubricants

Lubrication with oils and greases in space is difficult unless all moving parts are hermetically sealed. First, the evaporation rate is high for oils, and for greases the more volatile constituents distill away leaving a hard residue. Another problem is the removal of oils and greases by the escaping air stream during launching operations.

Oxide surface films are unable to re-form in a vacuum once they are broken during rubbing of contact surfaces. Besides providing a low shear strength film in most cases, these oxides are also necessary for the formation of a metal soap when lubricating with fatty acid compounds.

The formation of very heavy grease or varnish in bearings is due to the polymerization of some lubricants by the catalytic action of clean oxygen free metal surfaces. (6)

A study of the evaporation rates of oils and greases under simulated space conditions was conducted by the Airborne Instrument

Laboratory. Tables VI, VII, VII give the results of these tests (7). The object was the determination of oils and greases that would not evaporate excessively in vacuum. This would permit use of conventional stock components. Results of the tests showed that lubricants are commercially available which can be usable in high vacuum for a period of at least 1000 hours. The ability of these materials to act efficiently as lubricants under actual load and run conditions must still be investigated.

c. Solid Lubricants

Solid lubricants are a possibility for space use, but, they are generally restricted for use in sleeve bearings which have high torque characteristics. Non-standard motors will also be required with solid lubricants.

Bearings with silver or gold plated balls have been used in vacuum, but they are very difficult to produce. The low shear strength silver film has a relatively low wear life and is therefore restricted to shorter time periods of use. (6)

Graphite cannot be used since its lubricity depends upon absorbed water vapor which is lost in vacuum conditions.

Molybdenum disulfide ($Mo\ S_2$) does provide good lubrication in vacuum since the sulfur atoms that act as low shear strength layers are not lost. (6)

The problems and disadvantages of solid film lubrication can be listed as follows:

1. Problems of good adhesion in thin film coating.
2. Thin films wear through, and are not self-healing. Therefore, life is relatively short.

TABLE VI

EVAPORATION RATE OF OIL AT 10^{-2} mm Hg AND 85° C

	Vapor Pressure mm Hg 25° C	Viscosity Centistokes 25° C	Evaporation Rate 10^{-4} gm/ cm^2/hr 85° C 10 microns	Total Evaporation Rate 10^{-4}/gm/cm^2 85° C at 10 microns
Florocarbons				
Brand A				
Type 1				Completely evaporated
Type 2		Thick	90	
Type 3		Solid		Not tested
Silicones				
Brand B				
Type 1		1		Completely evaporated 20/30 hr
				600/40 hr
Type 2		50	0.5	600/40 hr
Type 3		30	20	
Type 4	5×10^{-9}	60	20	
Brand C				
Type 1	8	30	0.5	10/25 hr
Di-Esters				
Brand D				
Type 1		20	5	300/25 hr
Type 2		15	3	1890/50 hr
Type 3			7	500/40 hr
Type 4		40	0.1	10/80 hr
Other Synthetics				
Brand E				
Type 1	5×10^{-7}	51	5	100/20 hr
Type 2	2×10^{-8}	18	4	100/60 hr
Type 3		30	2	350/100 hr
Brand F				
Type 1		15	8	900/100 hr

TABLE VI (CONT)

Petroleum				
Brand F				
Type 2		45	1	200/100 hr
Brand G				
Type 1			100	
Type 2			100	
Type 3			4	150/30 hr
Brand H				
Type 1	10^{-6}	50	10	500/30 hr
Type 2	$6x10^{-7}$	70	3	80/30 hr
Type 3	10^{-8}	80	1	50/30 hr
Type 4	10^{-9}	Very thick	Zero	Zero
Brand I				
Type 1		100*	0.2	78/60 hr
Type 2		100*	0.3	180/90 hr
Type 3		6	5	450/25 hr
Brand J				
Type 1	10^{-7}		10	230/30 hr
Brand K				
Type 1			10	
Brand L				
Type 1				
Type 2				100/30 hr
				150/30 hr
Unknown				
Brand H				
Type 5			1	50/20 hr
Brand M				
Type 1			2	50/20 hr
Brand N				
Type 1			5	550/80 hr
Brand O				
Type 1			3	100/30 hr
				200/100 hr
Brand P				
Type 1			0.5	75/30 hr
Animal Oils				
Spermoil			1	125/80 hr
				150/30 hr

TABLE VII

EVAPORATION RATE OF GREASE AT 10^{-2} mm Hg

	Thickeners or Additives	Evaporation Rate 10^{-4} gm/cm^2/hr 85° C at 10 microns	Total Evaporation 10^{-4} gm/cm^2 85° C at 10 microns
Di-Esters			
Brand D			
Type 5	Lithium Soap	0.1	180/70 hr
Type 6	Lithium Soap	3	200/40 hr
Type 7	Lithium Soap	2	200/70 hr
Brand F			
Type 3	Lithium Soap	2	150/60 hr
Brand Q			
Type 1	Lithium Soap + Mo S_2	60	500/8 hr
Silicones			
Brand B			
Type 5		0.5	50/46 hr
Type 6	Lithium Soap	1	250/70 hr
Brand C			
Type 2	Lithium Soap	0.1	30/60 hr
Brand H			
Type 6	Indanthrene Dye	0.1	5/30 hr
Type 7	Indanthrene Dye	0.5	10/30 hr
Petroleum			
Brand Q			
Type 2	Silica Thickner	0.5	10/20 hr
Type 3	Lithium Soap + Mo S_2	3	300/70 hr
Other Synthetic			
Brand R			
Type 1	Sodium Soap	0.5	160/70 hr
Unknown			
Brand H			
Type 8		4	400/70 hr
Type 9		2	60/30 hr

Lithium Soap 0.1 180/70 hr
Lithium Soap 3 200/40 hr
Lithium Soap 2 200/70 hr

Lithium Soap 2 150/60 hr

Lithium Soap + Mo S_2 60 500/8 hr

TABLE VIII

DEPENDENCY OF EVAPORATION OF LUBRICANTS ON TEMPERATURE AND VACUUM

	Evaporation Rate in 10^{-4} gm/cm^2/hr*	
	10^{-2} mm Hg	2×10^{-7} mm Hg
OILS	85° C	110° C
Petroleum, Brand H, Type 1	1.0	7.0
Petroleum, Brand I, Type 1	0.2	0.7
Petroleum, Brand F, Type 1	1.0	2.0
Di-Ester, Brand D, Type 4	0.1	0.8
Silicone, Brand C, Type 1	0.5	0.5
Unknown, Brand P, Type 1	0.5	200.0
GREASES		
Petroleum, Brand Q, Type 2	0.5	2.0
Silicone, Brand C, Type 2	0.1	1.0
Silicone, Brand H, Type 6	0.1	1.5
Silicone, Brand B, Type 6	0.1	1.5
Di-Ester, Brand D, Type 5	0.1	2.0
Synthetic, Brand R, Type 1	0.1	100.0

Weight of all samples about 0.5 gm/cm^2

*10^{-4} gm/cm^2/hr $\cong$ 1 mm thickness/1000 hr.

3. The coefficient of friction of solid lubricants is higher than oils and greases, therefore, more heat is produced and more power required.

4. The increase in frictional heat is difficult to remove since no heat is lost by convention to air. Oil and greases can act as coolants.

Despite these disadvantages, solid film lubrication still offers many desirable features. Several plastics such as teflon and nylon have been used in gears and bearings as self-lubrication solids. Sintered nylon powders mixed with molybdenum disulfide offers some good possibilities.

Another group of self-lubrication solids are pourous compacts impregnated with lubricants such as MoS_2 or low-vapor pressure oils and greases. Such materials have good friction and wear properties. (6)

d. Dissimilar Materials

Another method designed to prevent seizure in high vacuum is the use of widely dissimilar materials, such as glass or carbides, in contact with steel or other metal components. These applications however, are restricted to low loads and speeds with virtually no impact loading. Balls of these materials have a tendency to shatter under heavy loads. (6)

C. Micrometeoric Erosion

Any exposed surface in space such as the skin of a space vehicle is subjected to the action of meteoritic particles. The effects can be in the form of surface erosion or can be punctures. Table IX gives data concerning meteoroids and their penetration probabilities. (8)

TABLE IX

DATA CONCERNING METEOROIDS AND THEIR PENETRATING PROBABILITIES

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Meteor visual magnitude	Mass (G)	Radius	Ass. vel.	K.E. (ergs)	(cm) Pen. in Al	No. striking earth per day	No. striking 3m Sphere per day
0	25.0	49,200	28	1.0x10^{11}	21.3	-	-
1	9.95	36,200	28	3.98x10^{13}	15.7	-	-
2	3.96	26,600	28	1.58x10^{13}	11.5	-	-
3	1.58	19,600	28	6.31x10^{12}	8.48	-	-
4	0.628	14,400	28	2.51x10^{12}	6.24	-	-
5	0.250	10,600	28	1.00x10^{12}	4.59	2x10^{8}	2.22x10^{-5}
6	9.95x10^{-2}	7,800	28	3.98x10^{11}	3.38	5.84x10^{8}	6.48x10^{-5}
7	3.96x10^{-2}	5,740	28	1.58x10^{11}	2.48	1.47x10^{9}	1.63x10^{-4}
8	1.58x10^{-3}	4,220	27	5.87x10^{10}	1.79	3.69x10^{9}	4.09x10^{-4}
9	6.28x10^{-3}	3,110	26	2.17x10^{10}	1.28	9.26x10^{9}	1.03x10^{-3}
10	2.50x10^{-3}	2,209	25	7.97x10^{9}	0.917	2.33x10^{10}	2.58x10^{-3}
11	9.95x10^{-4}	1,680	24	2.93x10^{9}	0.656	5.84x10^{10}	6.48x10^{-3}
12	3.96x10^{-4}	1,240	23	1.07x10^{9}	0.469	1.47x10^{11}	1.63x10^{-2}
13	1.58x10^{-4}	910	22	3.89x10^{8}	0.335	3.69x10^{11}	4.09x10^{-2}
14	6.28x10^{-5}	669	21	1.41x10^{8}	0.238	9.26x10^{11}	1.03x10^{-1}
15	2.50x10^{-3}	492	20	5.10x10^{7}	0.170	2.33x10^{11}	2.58x10^{-1}
16	9.95x10^{-6}	362	19	1.83x10^{7}	0.121	5.84x10^{12}	6.48x10^{-1}
17	3.96x10^{-6}	266	18	6.55x10^{6}	0.0859	1.47x10^{13}	1.63
18	1.58x10^{-6}	196	17	2.33x10^{6}	0.0608	3.69x10^{13}	4.09
19	6.28x10^{-7}	144	16	8.20x10^{5}	0.0430	9.26x10^{13}	1.03x10
20	2.50x10^{-7}	106	15	2.87x10^{5}	0.303	2.33x10^{14}	2.58x10
21	9.95x10^{-8}	78.0	15	1.14x10^{5}	0.223	5.84x10^{14}	6.48x10
22	3.96x10^{-8}	57.4	15	4.55x10^{4}	0.064	1.47x10^{15}	1.63x10^{2}
23	1.58x10^{-8}	39.8*	15	1.81x10^{4}	0.0121	3.69x10^{15}	4.09x10^{2}
24	6.28x10^{-9}	25.1*	15	7.21x10^{3}	0.00884	9.26x10^{15}	1.03x10^{3}
25	2.50x10^{-9}	15.8*	15	2.87x10^{3}	0.00653	2.33x10^{16}	2.58x10^{3}
26	9.95x10^{-10}	10.0*	15	1.14x10^{3}	0.00480	5.84x10^{16}	6.48x10^{3}
27	3.96x10^{-10}	6.30*	15	4.55x10^{2}	0.00353	1.47x10^{17}	1.63x10^{4}
28	1.58x10^{-10}	3.98*	15	1.81x10^{2}	0.00260	3.69x10^{17}	4.09x10^{4}
29	6.28x10^{-11}	2.51*	15	7.21x10	0.00191	9.26x10^{17}	1.03x10^{5}
30	2.50x10^{-11}	1.58*	15	2.87x10	0.00141	2.33x10^{18}	2.58x10^{5}
31	9.95x10^{-12}	1.00	15	1.14x10	0.00103	5.84x10^{18}	6.48x10^{5}

* Maximum radius permitted by solar light pressure.

For the larger meteoroids a shielding is required to prevent penetration into critical regions. According to Rodriquez (ref 9) "More comprehensive information on meteoroids will have to be obtained from deep space probes before better estimates of meteoroid shielding requirements can be made available for vehicles on missions to regions of the solar system more remote from the earth."

The effect of the vast amounts of interplanetary dust (micrometeorites) is that of surface erosion. These minute particles do not cause punctures of the skin, but may change the radiation properties of the skin thereby upsetting the temperature controlling mechanisn. (10)

According to Singer (ref 10) "Large meteors, those having a mass of more than a milligram, can penetrate thin skins of satellites or space ships upon contact-a milligram meteor penetrating approximately 3 mm of aluminum skin. On the other hand, the much smaller less energetic micrometeorites will not be able to penetrate a skin of this thickness but instead will gouge out small pieces of the skin, a process very similar to sandblasting. Prolonged exposure above the atmosphere, therefore, will produce a gradual erosion of the skin; this thinning has deleterious effects, since it will eventually damage the integrity of the space ship or satellite." Tables X and XI give data by Singer pertaining to this erosion problem.

Many theories exist predicting negligible to complete erosion. According to the Naval Ordnance Test Station (ref 11), the material is either melted or vaporized, and erosion occurs as a result of droplets or vapor being released from the surface. By equating the heat of fusion of the released material to the kinetic energy of the micrometeorites,

TABLE X

DATA ON MICROMETEORS

Radius (cm)	Mass (g)	N(> r) (cm^{-3})	Penetration Depth (cm)
$2x10^{-2}$	$1.1x10^{-4}$	$1.1x10^{-17}$	$8x10^{-2}$
10^{-2}	$1.4x10^{-5}$	$3.8x10^{-17}$	$4x10^{-2}$
$3x10^{-3}$	$3.8x10^{-7}$	$2.3x10^{-16}$	$1.2x10^{-2}$
10^{-3}	$1.4x10^{-8}$	$1.4x10^{-15}$	$4x10^{-3}$
$3x10^{-4}$	$3.8x10^{-10}$	$9.5x10^{-15}$	$1.2x10^{-3}$
10^{-4}	$1.4x10^{-11}$	$5.5x10^{-14}$	$4x10^{-4}$
$3x10^{-5}$	$3.8x10^{-13}$	$4.7x10^{-13}$	$1.2x10^{-4}$
10^{-5}	$1.4x10^{-14}$	$2.2x10^{-12}$	$4x10^{-5}$

The space concentration N(>r) gives the number having a radius greater than r and is taken from the zodiacal light observations. M_o is the absolute visual magnitude (reduced to an altitude of 100 km). The penetration and erosion is given per particle.

TABLE XI

FLUX, PENETRATION AND EROSION

W_e = 20 km/sec			W_o = 50 km/sec -		
M_o	Flux ($cm^{-2}s^{-1}$)	Erosion (g)	M_o	Flux ($cm^{-2}s^{-1}$)	Erosion (g)
10.6	$2.9x10^{-11}$	$2.5x10^{-2}$	8.9	$5.9x10^{-11}$	$6.3x10^{-2}$
12.8	$1.0x10^{-10}$	$3.2x10^{-3}$	11.1	$2.0x10^{-10}$	$8x10^{-3}$
16.7	$6.0x10^{-10}$	$2.4x10^{-2}$	15.0	$1.2x10^{-9}$	$2.2x10^{-4}$
20.3	$3.6x10^{-9}$	$3.2x10^{-6}$	18.6	$7.4x10^{-9}$	$8x10^{-6}$
24.2	$2.5x10^{-8}$	$8.7x10^{-8}$	22.5	$5.0x10^{-8}$	$2.2x10^{-7}$
27.8	$1.5x10^{-7}$	$3.2x10^{-9}$	26.1	$3.0x10^{-7}$	$8x10^{-9}$
31.7	$1.2x10^{-6}$	$8.7x10^{-11}$	30.0	$2.5x10^{-6}$	$2.2x10^{-10}$
35.3	$5.8x10^{-6}$	$3.2x10^{-12}$	33.6	$1.2x10^{-5}$	$8x10^{-12}$

Flux and erosion (per Particle) are calculated for two assumed velocities; in reality there is not much choice about the geocentric velocity of the interplanetary (zodiacal) dust which is about 12 km/sec. Taking this dust flux, the total erosion of the vehicle's skin is only about 10^{-5} cm per year (if uniformly distributed.)

the erosion is proportional to the cube root of the particle kinetic energy. Erosion by this process is estimated as negligible.

Titvak (ref 11) has suggested that particles traveling faster than the speed of sound within the vehicle skin will cause shock waves, and thereby flake and chip large pieces of material from the surface.

According to another study (ref 11), "the smallest and by far most numerous particles have a projected area of only 10^{-6} sq. cm. A flux of only 10^{-6} of these particles per sq. cm. per second would result in 30 particles per sq. cm. per year, or an eroded area of only 3×10^{-5} of the total satellite surface in a year. It is improbable that this will cause significant erosion to any oxide layer."

Another suggestion by several researchers (ref 11) has been that particle impact speeds exceeding the speeds of lattice vibrations will cause the solid to merely flow around the meteor, producing no noticeable damage.

Steurer (ref 11) suggests by qualitative extrapolation of some observations that, "meteoric particle impact will not produce pitting or damage to the surface but will result in a coating or covering of the surface with meteoric substances, similar to a high-velocity spray coating."

It is obvious that much research is needed in this area to substantiate or disprove existing theories.

D. Atomic and Molecular Sputtering

The surface atoms of a space vehicle can be sputtered (ejected) by collision with high velocity gas atoms. The incident atom transmits

its energy to a surface atom which may become ejected before the lattice can transfer the energy to a large volume. (10)

According to Stein of the Lockheed Missiles and Space Division (ref 12) "In a period of one year, a satellite flying in a circular orbit through an atmosphere containing only 10^8 particles/cu cm. is struck by about 2.5×10^{21} particles on every square centimeter of its frontal area. If we are pessimistic and assume that one atom will be sputtered from the surface for every particle that strikes it, about 0.25 mm of surface material will be removed in the course of the year. Although the removal of this small amount of material will not affect the structural qualities of the satellite, it will affect any passive temperature control system." It might be noted that it will also affect the performance of optical elements and solar cells.

At the University of California an experiment is in progress which is designed to provide detailed information on sputtering from potassium surfaces as a function of the incident angles, and of the incident ion energy and mass (12). A vacuum of better than 10^{-6} mm hq. was used as the surface ambient pressure. The study is performed by beam techniques in which an ion beam is formed from a capillary arc source and focussed along the axis of a pyrex glass cross, through a hole, and onto the target. Figure 2 gives some results of these tests. Since this is a highly simulated case, the results are suggestive rather than directly applicable to space flight. Much more research is needed in this area under actual conditions or under more closely simulated space flight conditions.

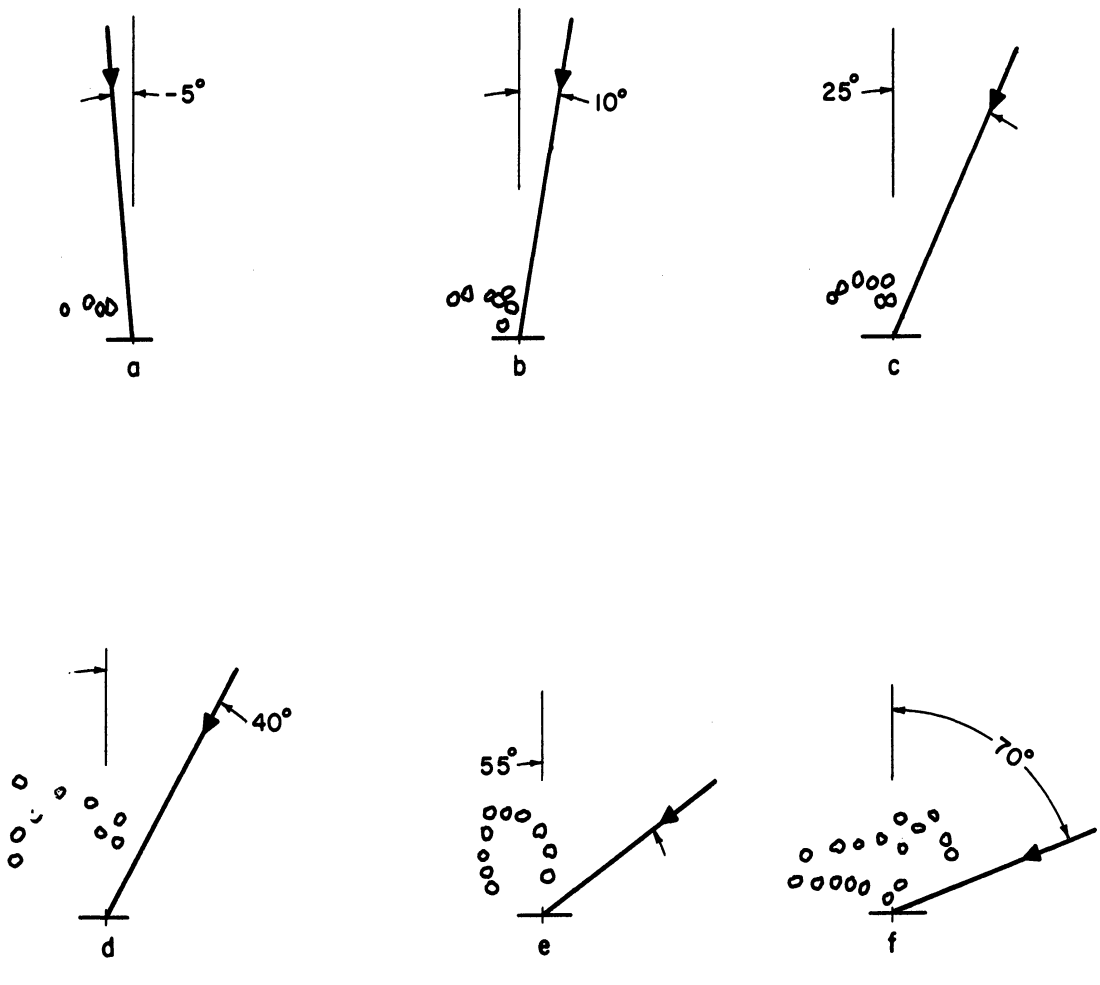

Figure 2. Preliminary Results of the Angular Dependence of the Number of Sputtered Potassium Atoms by 185-ev Argon Ions.

E. Electro-Magnetic Radiation Effects

The effects of ionizing radiation on metals is considered negligible. However, over extremely long exposures (many years) an effect similar to cold working of metals may result, with a corresponding increase in yield strength, and decrease in ductility (13)

Structural plastics are more vulnerable to radiation with possible effects such as depolymerization and internal gas generation. A study was made by the Wright Air Development Center to determine the effects of ultraviolet radiation on typical polymeric coatings (14). The results of the series of tests under atmospheric conditions is shown in Figure 3. The radiation source was a hydrogen discharge lamp with wavelengths approximating that of the sun, and with much higher intensities than that excepted from the sun.

Other tests were conducted under high vacuum conditions. The conclusions drawn from this work are; "The high rate of polymer-film degradation usually associated with the effects of ultraviolet light depends upon the presence of an oxygen-bearing atmosphere. These initial studies point to the probability that, in most instances, polymers will degrade less rapidly in vacuum than in air. However, this is not intended to imply that molecular crosslinking within the film (if such occurs) is desirable. In fact, if excessive crosslinking occurs, the film is likely to become brittle, may shrink, and probably will suffer a decrease in its adhesion to the substrate. These physical properties must be evaluated in subsequent experiments."

The flux level of cosmic radiation is considered too low to cause any material damage. (2)

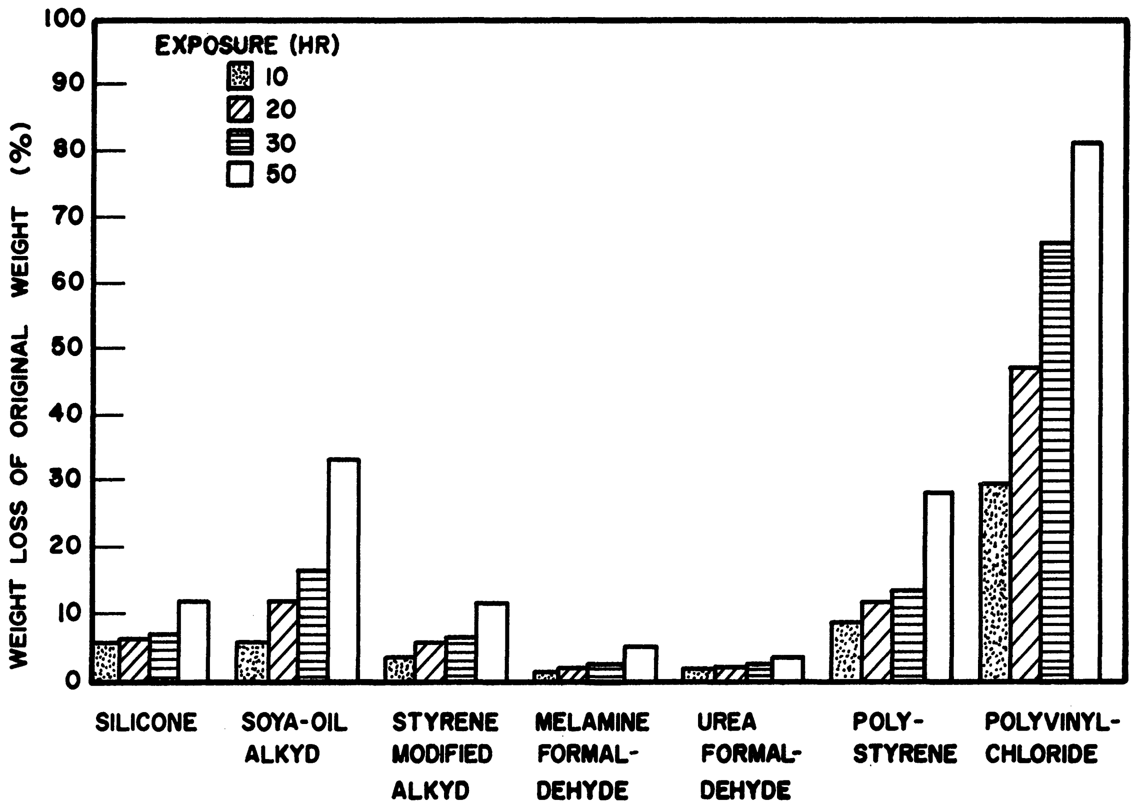

Figure 3. Effects of Near-Ultraviolet Irradiation on Polymer Films Under Normal Atmospheric Conditions.

The great probability of nuclear energy for space vehicle power and propulsion will result in radiation damage to materials. Complete shielding of the reactor is not feasible due to the high weight requirements. Distance between crew members and reactor provided by a cable or other means of design is more likely. The high energy particles that will spread in all directions from the reactor, such as gamma photons and neutrons, can have a detremental effect on some materials. A summary of these possible effects is shown in Figure 4. (ref 4)

F. Solar Plasma Effects

Solar plasma streams that exist outside of planetary magnetic fields can cause serious damaging effects to all materials. (15) This "magnetically unprotected" region exists at more than 22,000 miles from the earths surface.

As mentioned previously, when high velocity ions or atoms strike a solid surface, momentum transfer, or possible chemical processes lead to ejection or sputtering of surface atoms. It has been estimated by calculation that the time required for solar protons to destroy a 300 A plastic coating, on the basis of 600 particles/cm^3, and a velocity of 100 Km/sec, would be less than one month. (15) It might be noted that a reasonable average density for "quiet" conditions might be about 600 particles/cm^3, and about $10^5/cm^3$ during an intense solar storm.

Complete stripping of a coating by sputtering would occur in time t by the following equation: (ref 15)

$$t = NLd/MY\ (nv)$$

10^{14} n cm^2	GERMANIUM TRANSISTOR - Loss of Amplification
	GLASS - Coloring
10^{15}	POLYTETRAFLUORETHYLENE - Loss of Tensile Strength
	POLYMETHYL METHACRYLATE - Loss of Tensile Strength
	WATER AND LEAST STABLE ORGANIC LIQUIDS - Gassing
10^{16}	NATURAL AND BUTYL RUBBER - Loss of Elasticity
	ORGANIC LIQUIDS - Gassing of Most Stable Ones
	BUTYL RUBBER - Extensive Change, Softening
10^{17}	POLYETHYLENE - Loss of Tensile Strength
	MINERAL-FILLED PHENOLIC POLYMER - Loss of Tensile Strength
	NATURAL RUBBER - Extensive Change, Hardening
10^{18}	HYDROCARBON OILS - Increase in Viscosity
	METALS - Most Show Appreciable Increase in Yield Strength
	CARBON STEEL - Reduction of Match-Impact Strength
	POLYSTYRENE - Loss of Tensile Strength
10^{19}	
	CERAMICS - Reduced Thermal Conductivity, Density, Crystallinity
	ALL PLASTICS - Unusable as Structural Materials
10^{20}	CARBON STEELS - Severe Loss of Ductility, Yield Strength Doubled
	CARBON STEELS - Increased Fracture-Transition Temperature
	STAINLESS STEELS - Yield Strength Trebled
	ALLUMINUM ALLOYS - Ductility Reduced but not Greatly Impaired
10^{21}	STAINLESS STEELS - Ductility Reduced but not Greatly Impaired

Figure 4. Effect of Fast Neutrons on Materials

where: N = AvoGadro's No.

L = Coating Thickness

Y = Sputtering yield assumed independent of L but averaged over angle and weighted according to the incident velocity distribution

M = Coating atomic weight

d = density of coating

(nv) = The solar flux averaged over the exposure time.

According to Reiffel (ref 15), "If the surface of the plastic film itself, rather than an overlying metal coating, were exposed to the solar plasma, radiation damage effects over and above those caused by solar ultraviolet and x-ray, emission are to be expected."

If the exposure is at a high enough energy level, hydrogen evolution leading to charring and carbonization should occur.

V. SURFACE EROSION DURING ATMOSPHERIC RE-ENTRY

A space vehicle entering a planetary atmosphere will be subject to extreme aerodynamic heating with a resulting deterioration of the impact surfaces. There are a variety of surface protection or cooling systems which can be used for this purpose. In general these systems involve: (ref 16)

1. The absorption of the heat by a temperature rise, a phase change, or a chemical change.
2. The rejection of most of the heat by a mass efflux from the surface (ablation)
3. The rejection of heat by radiation from the surface.

In the ablation process the aerodynamic heat energy produced by friction is absorbed by the mechanisms of melting and vaporization of the surface material that is ejected into the air boundary layer. Radiation from the high temperature ablation materials (emissivity high) is a contributing heat removal source. An additional mechanism of heat rejection is present when the ablating materials react chemically with the boundary layer of air.

Ablation Materials

From reference (17) the following desirable characteristics of ablation materials for atmospheric re-entry are listed:

1. In general, gasification during ablation is desirable. The large amount of gas generated thickens the boundary layer and reduces the rate of heat transfer. Gasification products of low molecular weight enhance this effect because of their large heat capacity and larger diffusion coefficients.

2. Ablation materials should have good thermal insulation characteristics so that the ablation process, the loss of structural strength resulting from heating beyond the ablation zone, and the effect of local irregularities during ablation, are confined to the surface.
3. Ablation materials should have a high resistance to thermal and mechanical shock and be easy to fabricate in large sizes.

Materials of interest may be grouped as follows:

1. Plastics which depolymerize to a gas but do not liquefy (e.g., Teflon)
2. Materials which sublime and react with the constituents of dissociated air. (e.g., graphite)
3. Materials which first melt and then vaporize (e.g., glass)
4. Composite materials, such as reinforced plastics which pyrolize and char. (e.g. phenolic-nylon)

Based on analysis and experiment (17) the largest amount of ablation will occur with Teflon type materials, but the amount is less than 3 lb per ft^2 during the re-entry heating cycle. Teflon and phenolic-nylon can serve effectively as a thermal insulator, but phenolic-nylon has higher structural strength and is therefore more suitable. Graphite is not limited by high ablation rates, but rather by the heat penetrating aspects, and mechanical limitations such as thermal shock, and fastening problems. Phenolic-glass has some good ablation characteristics but has inferior self-insulation qualities, and therefore conducts more heat to the interior of the re-entry space vehicle.

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