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SPACECRAFT
MATERIALS
GUIDE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SPACECRAFT MATERIALS GUIDE

Edited by

Charles L. Staugaitis

Goddard Space Flight Center

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PREFACE

The Spacecraft Materials Guide is intended primarily for the aerospace engineer responsible for the design and fabrication of spacecraft systems as an aid in the selection of components and the utilization of suitable materials systems and processes. A variety of materials and processes that pertain to aerospace fabrication is discussed, problem areas are noted, and recommended materials are presented.

It has been recognized that consideration of the requirements to be placed on materials in spacecraft design is important, particularly in view of the hazardous nature of space environments. The ultimate success of a system is strongly dependent upon the satisfactory resolution of the various crucial materials problems which can be encountered. The effectiveness of any resolution must necessarily be predicated on the cooperative rapport established between the designer and the materials specialist, with the latter bringing both service experience and laboratory evaluations to the problem-solving process.

As the focal point for many technical matters dealing with materials and processes, the Materials Engineering Branch (MEB) at Goddard Space Flight Center (GSFC) has been directly exposed to numerous spacecraft problems and component failures. As a consequence, a considerable amount of information has been compiled from internal and other sources and, of equal importance, a great deal of specialized experience has been acquired regarding practical design use of engineering data or material properties.

One of the important functions of the MEB at GSFC is the dissemination of this reservoir of knowledge to those responsible for planning, designing, and fabricating flight hardware. For this reason, this Spacecraft Materials Guide is issued to summarize many of the materials which have demonstrated their suitability for space application, and to point out common, recurring problem areas. Recognizing the broad nature of the subject of materials, the text of this document was deliberately limited to the following four topics: "Encapsulants and Conformal Coatings," "Optical Materials," "Lubrication," and "Bonding and Joining." Historically, these applications have incurred a high incidence of problems. It should be noted that this Spacecraft Materials Guide differs from other similar publications in that much of the information contained herein was developed within the Materials Engineering Branch by its technical staff in the course of carrying out their materials support responsibilities to NASA/Goddard flight projects.

The purpose of this document is to instill an awareness of and an appreciation for the dangers inherent in the misapplication of even suitable materials for spacecraft use through the presentation of materials, problem areas, and solutions. Some information may not have been fully covered and some omissions may exist which, if available, would enhance the text. Comments will be most appreciated.

Charles L. Staugaitis
Head, Materials Engineering Branch
Goddard Space Flight Center

CONTENTS

ENCAPSULANTS, CONFORMAL COATINGS

Aaron Fisher

INTRODUCTION

Encapsulant materials are part of a broad spectrum of protective media generally employed in providing a status quo environment for embedded units. Unit in this context refers to a wide application spectrum such as PC boards, high voltage cabling, and connectors. The purpose of encapsulants is to prevent any detrimental change which might alter the optimal function or operation of an embedded or coated unit (1) by vibration cushioning, (2) by providing anticorrosion dry environments which also minimize electrical malfunction, and (3) by providing a firm structure for handling or a cellular structure in cases where weight might be a problem.

Conformal or thick coatings provide combinations of properties which could be considered an extension of those provided by encapsulants. Basically, the encapsulant is a pourable material of a resinous nature. When chemically modified, that is, cured or hardened, it will supplant the medium of comparatively easily ionizable air. The cured material provides a physically protective body of uniform electrical properties and/or other attributes selected to best suit the function of the unit.

CONSIDERATIONS

There are many types of encapsulants and coatings and many formulations within a given type. It is simply not very practicable to note that some form of protection is necessary and then indiscriminately select any system which is pourable and hardens readily. A material must be selected after its properties or characteristics have been sieved, not only through the requirements of the unit to be treated, but also through the requirements of adjacent components and the environment. An encapsulant system with properties that are compatible with the original unit, adjacent complexes, and the environment becomes the system to use. In some cases a resin system may have to be designed to meet all necessary parameters successfully.

However, within the plastics industry there are companies that provide a variety of plastic materials with known properties which can satisfy a host of specialized applications. In the design of a total system, it is imperative that the materials selected be compatibly coupled with the particular hardware design. The choice of an encapsulant must suit the design; however, in some cases it may be necessary to modify the original design concept in order to make it easily adaptable to a readily available formulation system. A cooperative approach between the material and design engineers could prevent a situation where an excellent design, driving rapidly to its ultimate goal of flight hardware, finds that a required specialized type of protection is not available or that existing types are incompatible.

A few examples illustrate the dangers of not only improper material selections but also inadequate coordination between the materials specialist and the design engineer. Production photomultiplier tubes, because of either improper potting materials or technique, developed soft resin spots and possibly incipient cracks in areas of high voltage. The potting material and technique used were incompatible as a "total" tube design package. The tube was electronically excellent. The designer did not completely foresee all the requirements for good potting. High voltage-resistance and easy-fill operability were required of the potting material. The resultant solid potting was essential to the support of the tube during launch vibration and later to contain the high voltages inherent in the systems operation. It had not been foreseen that a viscous resin-glass bead composite would have difficulty flowing through narrow apertures. In addition, catalyst blending had not been uniform. This resulted in potting soft spots, with lowered voltage resistivity.

A unique and immense spacecraft light baffle, which cost several hundred thousand dollars, was nearly scrapped because an epoxy black paint would not adhere well to the aluminum surface. The specks of paint and the exposed aluminum reflecting surface could detrimentally affect the optical data input once in orbital operation. The flat black optical properties of the paint were acceptable, but the paint failed in its adhesion requirements, a potential source of damage to the optical system. Through laboratory testing it was determined that overcoating the old paint on the baffle with flexible, adhering, flat black paint Chemglaze Z-306, a polyurethane type, would be an effective solution. This was undertaken with totally positive results; no paint specks lifted during vibration tests and the baffle was successful.

These examples indicate that encapsulants and coatings must be designed to fulfill very specific functions and be compatible with other critical experiment parameters. The important point is that the design must be approached from the aspect of the total system and is not limited to local materials consideration. That is, the possible impact of a specific material on its total environment, the potential effects or ramifications of using a particular material or encapsulant, cannot be ignored in experiment design.

A more specific example, a connector insulation problem common to all spacecraft systems, required that an insulating resin protect exposed pins which were located between a previously applied support shrink tubing and solder cup of Cannon connectors. In previous applications, the multiheaded harnesses with wire-suspended connectors had been coated with a low-viscosity, modified epoxy resin. Adequate insulation of the pins with that material required that all of the connector pins from a specific cable be first coated on one side and allowed to cure overnight. The connectors were then turned over so that the pins could be coated and cured on the opposite side. This procedure took too much time, wasted manpower, and required considerable accuracy. In addition, the resin could possibly flow into the connector and coat contacts or freeze the desired floating characteristics of the pins when the resin cured. If this occurred, the harness would not meet its specifications.

A new approach to insulation was required which would eliminate the above noted problems inherent with a low-viscosity resin. A flexible, fast curing, very low outgassing, thixotropic, ultraviolet fluorescent resin was developed. A modification allowed this to be extruded as a continuous 2.8×10^{-3} cm (1/8 in.) diameter "grease consistency" rod from a highly pressurized 4.13×10^5 to 4.8×10^5 N/m^2 (60 to 70 psi) trigger-activated, hand-held dispenser. This system allowed for:

- Connectors to be twisted and held at any angle from the cable while the protective insulating resin bead was run around the connector pins;
- A connector to hang at any angle from the cable while the next connector was insulated; and
- The cable to be left untended, at any angle, while the next cable connectors were coated.

The resin system is designed to gel in about one hour, after which rougher handling is allowable. A solid, room-temperature cure occurs within 16 to 18 hours, and very little exotherm is produced. A complete cure requires 7 days at room temperature.

A fluorescent material was incorporated in the resin to provide the capability for the following inspections:

- Inadvertent flow-through onto the pins,
- Presence of voids, and
- Presence of gaps in the coating.

The cured resin fluoresced and emitted a bright green color when exposed to a common, hand-held laboratory ultraviolet source of 3650Å. Imperfections could be observed and recoating performed as required.

The material was excellent from a low outgassing point of view; total weight loss was 0.38 percent and volatile condensable materials were 0.02 percent. Insulation operations on 170 connectors of a previous IMP spacecraft not utilizing this technique required approximately 14 man-days. The new procedure required only 3 man-days (a three-man team completed the entire job in one day) and provided a neater, more reliable package than previously possible. This potting formulation and procedure for insulation of electrical connectors is described in Appendix A. Sources for the required material components are also presented in Appendix A.

The material used was a Cab-o-sil modified, fluorescent thixotropic urethane resin system which has grease-like consistency and is highly viscous when prepared (see formula below). The resin was applied using a pressurized 4.13×10^5 to 4.8×10^5 N/m^2 (60 to 70 psi) gun, with very little subsequent resin flow, no matter what the angle of application or base support.

The formulation, after cure, becomes a flexible, fluorescent, solid polyurethane and has very low outgassing in a vacuum environment at 398 K (125°C).

The following formula is based on quantities of resin needed for several connectors and may be increased proportionately as necessary if many connectors are being prepared.

Solithane C-113	30.00 g
Solithane C-113-300	21.90 g
Cab-o-sil MS-5	3.40 g
Dibutyl Tin Dilaurate	0.05 g
Vyac Luminescer 174	0.05 g

General Types of Encapsulants

Encapsulants have been and can be designed to modify many of the basic properties of the original resin by the incorporation of various additions. There are companies that specialize in providing modified resin systems with various and highly desirable characteristics. In addition, they provide measured physical properties and describe successful areas of application.

The basic resin systems are classified as:

- Rigid,
- Semirigid, or
- Flexible.

The basic resin material may be epoxy, polyurethane, polystyrene, polyester, acrylic, or silicone; the choice of material is governed by the need for some secondary or tertiary property, that is, adhesion, electricals, thermal conductivity, expansion, outgassing, and so forth.

Solid and foam structure materials are included in the above basic resin systems. Foams may be initiated as a pourable liquid or may be heat generated from a compounded solid.

Low Density Foams

Low density foams 0.03 to 0.32 g/cm^3 (2 to 20 lb/ft^3) range from a thin friable condition to a potentially structural form capable of supporting applied loads. The methods of developing cellular structure for different chemical forms are:

- Air whipped, pourable–promotes cellular formations by incorporating air bubbles;
- Chemically, gas generated, pourable–gas evolves from reaction of components;
- Gas added under pressure, moldable–bubbles produced by introducing N_2 gas under pressure in a confined volume and then subsequently releasing pressure;
- Heat breakdown of an incorporated blowing agent, which releases gas to the surrounding polymer matrix.

In many rubbers and elastomers thermal activation releases desired gas because such blowing agents as bicarbonate and celogen have previously been incorporated into the formulations.

Syntactic Foams

Syntactic foams 0.35 to 0.08 g/cm^3 (22 to 50 lb/ft^3) represent two-component, bubble-resin systems. They consist of a polymeric or ceramic hollow sphere included within a polymerizable matrix, either foam or liquid. These foams may be pourable but generally are applied by a trowel.

Electrical Encapsulants

In addition to low density and syntactic foams, highly specialized encapsulant systems can be formulated for electrical applications. The many possible modifications are tailored using specific fillers to meet specific requirements such as:

- Conductivity–RF Shielding,
- Resistivity,
- Dielectric constant, from 1 plus to 10 or 25, and
- Dielectric strength–high-voltage resistance and corona resistance.

Other requirements for specialized encapsulant systems may include:

- Thermal conductivity,
- Thermal expansion to approximate that of metals,
- High density,
- Ultraviolet resistance,
- Particulate radiation resistance,
- Fluorescence,
- Shrinkage,
- Thixotropy.

Some resin systems have high viscosities, some are thixotropic, while others may be fluid. Some need elevated temperatures for cure, others harden at room temperature, yet others require moisture or sometimes ultraviolet light in order to cure. Some systems generate high temperatures and are violently exothermic during cure, while others are only warm to the touch.

The limitless possibilities available to achieve the desired properties required for a particular application of encapsulants and conformal coatings necessitate careful consultation of the parameters of available materials prior to final fixing of design. Potting materials can also be used improperly; some of the more important factors which can be a potential problem if overlooked are presented below.

- *Thermal Expansion.* It is undesirable to have high coefficient mismatches because of the induced stress buildup during thermal cycling. Semirigid potting materials can be useful for minimizing stress at interfaces, and specially filled materials of comparatively low expansion can equalize thermal coefficients. Where an item may require extensive silicone potting, the container should allow freedom for silicone expansion. In addition, high thermal expansion of the silicones is modified by using hollow spheres as fillers.

- *Dielectric Constant.* Dielectric-constant-sensitive breadboard hookups invariably behave differently than conformally coated circuit board prototype hookups. The difference could be in the required circuit board coating whose dielectric constant may range from 2.5 to 5.6, while the breadboard hookup circuitry operates at an air interface dielectric constant of 1.0.

- *Corona.* Some simple, ruggedly designed, solid-state, high-voltage circuits might perform more efficiently without potting, if they could withstand launch vibration effectively. If not, low-outgassing silicones are recommended.

- *Voids.* Most pottings are improved by resin deaeration in a vacuum prior to potting. This is especially important in high-voltage systems.

- *Foams.* Among other considerations, rigid, gas-tight cellular foams can maintain dielectric constants, normally between 1.2 to 1.7, depending on the dielectric constant of the resin matrix and the foam density. However, with flexible unicellular foam systems, dielectric constant changes will occur in vacuum over the long term.

- *Potting Mixing.* Ingredients should contact only glass or stainless equipment during mixing prior to pouring in order to minimize the introduction of organic contaminants, water vapor, and so forth, which occurs by using paper cups, wooden stirrers, or some wax coated containers.

- *Primer Coat.* Some pottings, such as silicones or polyurethanes, may require primers to optimize adhesion.

- *Barrier Coats.* Silicone pottings may require a barrier precoating to prevent substrate poisoning of potting catalyst and corresponding softening in the affected area.

- *Hollow Spheres.* Hollow bodies useful for inclusion in acceptable resin matrices should be tested for potential cracks. These may be immersed in ethyl alcohol and can be pressurized to about 1.7×10^5 N/m^3 (25 psi) while in the alcohol. Those hollow spheres that subsequently float are dried and selected for actual potting.

- *Outgassing.* There are many materials which generate products while in vacuum at various temperatures, and the possibility for affecting other systems by outgassing must be considered. These products, for example, moisture, unreacted constituents, solvents, and low molecular weight polymers, may condense on cool optics or thermal control surfaces. In addition, such vapor state products may create a poor vacuum locally in a high-voltage area, thereby creating an environment conducive to corona discharge as indicated by Paschen's Law. Condensables can also disastrously affect the efficiency of radiant coolers and thereby destroy the discriminatory effect of critical semiconductors.

Therefore, a basic consideration in utilizing all polymer materials is that their outgassing levels be low, and that they meet the combined criteria of no greater than 1-percent total weight loss nor more than 0.1-percent condensables. Test conditions include heating at 398 K (125°C) for 24 hours in a vacuum of at least 1.33×10^{-4} N/m^2 (1×10^{-6} torr) and controlling the condensing plate at 298 K (25°C).

The requirement described eliminates many potentially undesirable material selections. Outgassing information on over 2638 variously preconditioned polymers, available at GSFC*, indicates that there are acceptable polymeric materials suitable for any spacecraft application problem. Potting and conformal coating materials with acceptable outgassing properties are presented in Appendix B.

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* See, "A Compilation of Low Outgassing Polymeric Materials Normally Recommended for GSFC Cognizant Spacecraft" by A. Fisher and B. Mermelstein, NASA TM X-65705, July 1971, and "A Compilation of Outgassing Data for Spacecraft Materials" by W. A. Campbell, Jr., R. S. Marriott, and J. J. Park, NASA TN D-7362, September 1973.

OPTICAL MATERIALS

Alfred G. Eubanks

INTRODUCTION

Those materials and systems which serve primarily to transmit or to reflect electromagnetic radiation in the ultraviolet, visible, and/or infrared wavelength regions are described in this chapter in terms of their use in space. Included are lenses, windows, mirrors, and optical filters. Applications of optical systems in space include still and television camera lenses; windows; selective wavelength filters for detectors used in light-sensing devices such as star trackers and meteorological experiments; and reflective devices such as mirrors to direct light beams and to function as Cassegrainian telescope reflectors.

The application of each space optical system is usually unique and, thus, requires individual selection of the materials to fulfill the design specifications. It is impossible, therefore, to present a list of optical materials that will be suitable for all optical systems. There are, nevertheless, certain characteristics that pertain to most optical materials which can be helpful in their selection and use. First, almost all optical systems contain either crystalline or amorphous ceramics. Ceramics are brittle (which can lead to chipping or cracking), weak in tension, and strong in compression. In addition, many single-crystal optical materials such as potassium bromide (KBr), sodium chloride (NaCl), and lithium fluoride (LiF) are cleavable and may split under relatively low stresses. Secondly, it should be recognized that virtually no optical material, especially when used as a transmitting medium, is completely stable when exposed to space radiation conditions, for example, electrons, protons, and solar cosmic and ultraviolet radiation. Even the most radiation resistant of these materials exhibit some degradation, especially in the ultraviolet region, when exposed to sufficient radiation. Also, all of the optical transmitting materials with which the Materials Engineering Branch has had experience fluoresce to varying degrees during radiation and exhibit phosphorescence for varying periods of time after cessation of the irradiation.

Finally, it is especially important that optical materials intended for space use, since they are, as previously noted, mostly ceramics, be properly prepared to ensure compositional uniformity, absence of foreign materials, freedom from internal stresses, and so on, and that their relatively unusual properties be considered when they are designed into a system.

MATERIALS

The optical materials discussed in this chapter are separated into the following categories.

- Optical Glasses
- Fused Silicas (as utilized in protective windows and solar-cell covers)
- Interference Filters
- Mirror Materials
- Colored-Glass Filters
- Infrared Transmitting Materials

Table 1 lists a number of the above materials that have been used in space applications along with some of their pertinent physical, mechanical, and optical properties.

Optical Glasses

Most optical glasses, with the exception of some of those containing lead (for example, flints), exhibit appreciable degradation of optical properties, primarily transmission, although the refractive index may also change, in some cases, when exposed to simulated space radiation levels. Test data are available for a number of optical glasses including Corning numbers 8362, 8363, and 8365 and general glass types 517:645, 541:599, 573:574, 617:336P, and 649:338P. Except for those glasses with a "P" designation* and Corning 8362, 8363, and 8365, which are lead-containing glasses, the glasses listed show a significant decrease in transmission when exposed to ultraviolet radiation equivalent to 400 to 500 hours of solar exposure or to charged particle radiation on the order of 10^{12} electrons per cm^2 of 1-MeV energy or of 10^{13} protons per cm^2 of 1-MeV energy. These dose levels are usually experienced in relatively short periods in the space environment, depending on the orbit. Our experience shows, however, that optical glass elements can generally be shielded from most of the particle radiation by placing a protective window in front of the optical system. These protective windows are commonly made of fused silica or sapphire. For missions where the glasses will be exposed to appreciable amounts of ultraviolet radiation, a suitable short wavelength cutoff filter may prove satisfactory.

Another approach would be to use a cerium-doped optical glass as the front element in the optical system or as a window material.

Fused Silicas

All of the fused silicas tested by the Materials Engineering Branch degrade when exposed to high levels of ultraviolet radiation (several percent in the ultraviolet region after 2200 hours

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* The "P" designation indicates those glasses that have had cerium oxide added as a means of increasing their resistance to radiation.

Table 1
Some Properties of Selected Optical Materials*

Material	Coefficient of Thermal Expansion cm/cm^{-1} °K^{-1} X 10^{6}	Compressive Strength N/m^{2} X 10^{-7} (psi X 10^{-3})	Modulus of Rupture N/m^{2} X 10^{-7} (psi X 10^{-3})	Tensile Strength N/m^{2} X 10^{-7} (psi X 10^{-3})	Young's† Modulus N/m^{2} X 10^{-10} (psi X 10^{-3})	Refractive‡ Index	Region of Transmission μm
Fused Silica	0.55(248-623 K)	100 (>150)	10.5 (15.5)	4.8 (7)	7.2 (10.5)	1.459	~0.17-4.5
Sapphire	6.7 (323 K, ∥ C-axis) 5.0 (323 K, ⊥ C-axis)	–	44.8 (65)	–	34.4 (50)	1.834-1.586	~0.17-6.5
Optical Glasses§							
Flint	~10	66 (~96)	–	5.5 (~8)	5.1 (7.4)	1.523-1.786	~0.38-3.5
Crown	~ 9 (293-323 K)	21 (~30)	–	6.5 (~9.5)	6.2 (9.0)	1.505-1.671	~0.32-3.5
Cer-Vit	0.0 (273-313 K)	–	5.7 (8.3)	–	9.2 (13.4)	1.540	0.4-4.5
Germanium	5.5-6.4	–	–	–	10.3-15.8 (15-23)	4.1	1.9-23
Silicon	4.2 (283-323 K)	–	–	–	13.1 (19)	3.4	1.2-15
Irtran 1	10.7 (248-373 K)	109 (158)	15.0 (21.8)	–	11.0 (16.0)	1.378-1.227	0.5-8.5
Irtran 2	6.6 (248-373 K)	84 (121.2)	9.7 (14.1)	–	9.6 (14.0)	2.291-2.251	0.4-14.5
Irtran 4	7.7	–	5.2 (7.5)	–	7.1 (10.3)	2.485-2.323	0.5-22
Magnesium Fluoride	18.8 (248-573 K, ∥ to C-axis) 13.1 (248-573 K, ⊥ to C-axis)		6(~9)	–	11.0 (~16)	1.38	0.11-7.5
Lithium Fluoride	37 (273-272 K)	–	–	–	6.5 (9.4)	1.392	0.11-8.0
Calcium Fluoride	24 (293-333 K)	–	–	–	7.6 (11.0)	1.433	0.13-12.0
Cesium Iodide	50 (298-323 K)	–	–	–	0.53 (0.77)	1.987-1.619	0.24->50

* Values given were gathered from various sources, are nominal, and may vary from lot to lot.

† Calculated from flexure measurement data unless otherwise indicated.

‡ Indices given are for 298 K and range from that of the short-wavelength cutoff value to that of the long-wavelength cutoff value.

§ Optical glasses are available with a wide range of refractive index values and those given here are for general information only.

for the best grades); however, this level of ultraviolet radiation is not usually experienced because of mission length, except in cases where long sun-viewing periods are required by experiment objectives. In the case of charged particle radiation, exposure to 1-MeV electrons on the order of 10^{14} electrons per cm^2 or to 1-MeV protons on the order of 10^{15} protons per cm^2 can cause significant transmission degradation in this material. Fused silicas vary, as do most materials, in their ability to resist radiation. Our experience indicates that the higher-purity fused silicas such as Corning 7940 and Suprasil-W are more resistant than others such as Infrasil-I, Infrasil-II, and General Electric 101. Data showing the effect of ultraviolet radiation on the transmission of several fused silicas are shown in Figures 1 and 2. Figure 3 shows the effect of charged particle radiation on one of these materials. With regard to mechanical properties, fused silicas are strong enough to remain intact during pre-flight handling and launch, unless large-sized, relatively thin elements are used.

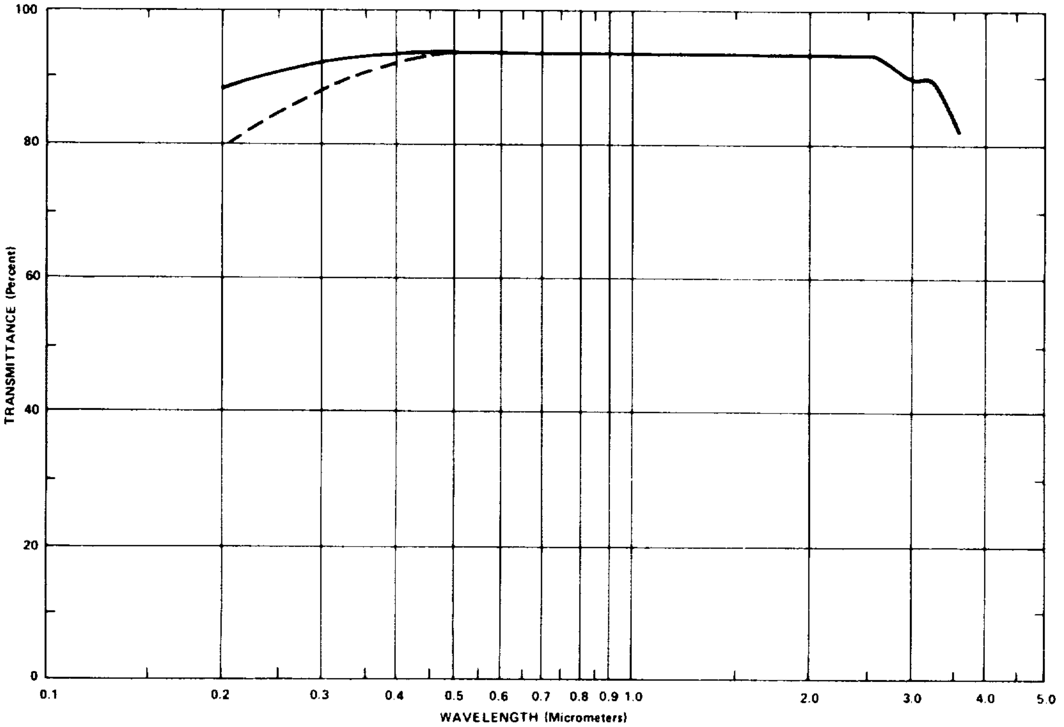

Figure 1. Transmittance of Suprasil-W before and after ultraviolet irradiation at 3.5 ultraviolet solar constants for 1100 equivalent ultraviolet solar hours (4-mm-thick sample).

Interference Filters

The radiation resistance of multilayer interference filters depends on two factors: (1) the substrate material and (2) the materials which constitute the interference layers. In the case of filters transmitting somewhere in the wavelength region between 180 nm and 2.5 μm, our experience has shown that Corning 7940, Suprasil-W, and Linde sapphire are acceptable

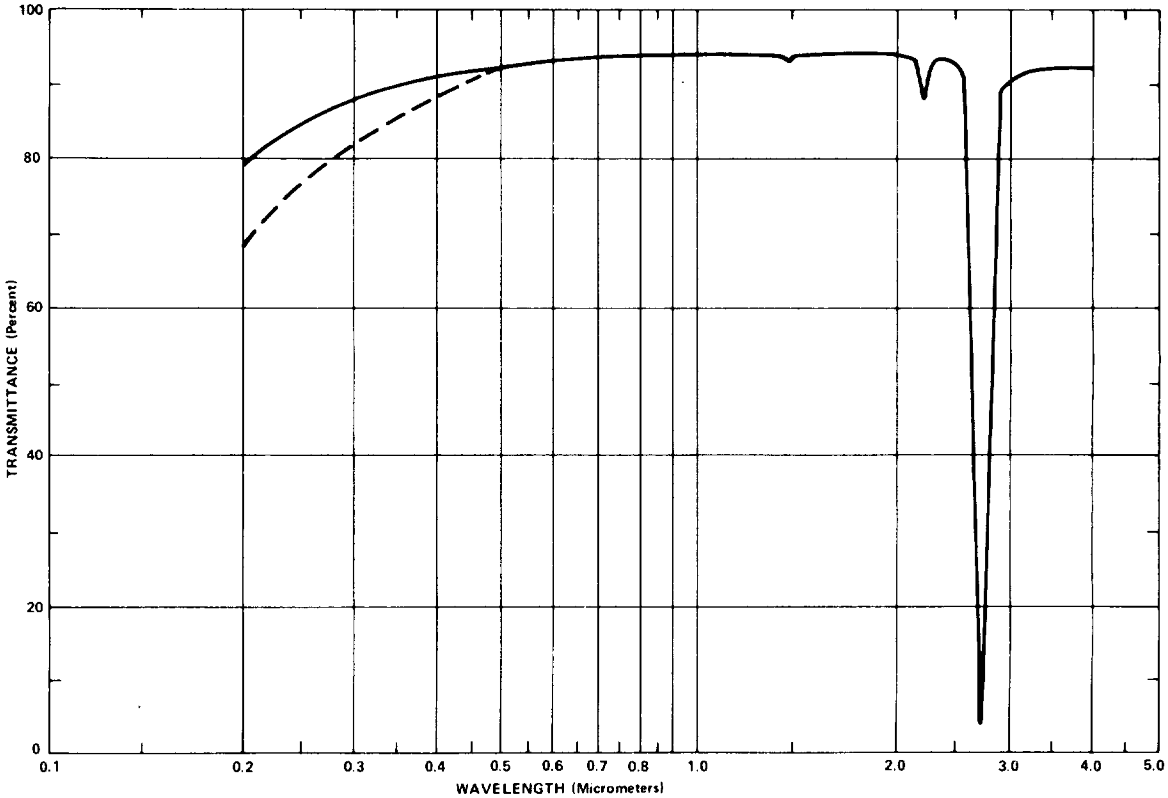

Figure 2. Transmittance of Corning 7940 fused silica before and after ultraviolet irradiation at 3.5 ultraviolet solar constants for 1100 equivalent ultraviolet solar hours (4-mm-thick sample).

as substrate materials, although the user should be aware that sufficient ultraviolet radiation can cause degradation of several percent in the ultraviolet transmitting region. For the interference layers, cryolite (Na_3AlF_6) has been found to be unacceptable from a radiation resistance standpoint; whereas magnesium fluoride (MgF_2), silicon dioxide (SiO_2), thorium fluoride (ThF_4), zinc sulfide (ZnS), and zirconium oxide (ZrO_2) are satisfactory. We have also examined aluminum, silver, and gold as thin-film materials and found them to be acceptable for filter applications.

It should be pointed out that the spectra of many multilayer interference transmission filters begin to change almost immediately after deposition of the thin-film layers and continue to do so for as long as six to eight months before becoming stable. In most cases, an experienced filter manufacturer can allow for this change so that the filter will transmit at the desired wavelength after stability is attained.

If constructed of the thin-film and substrate materials described above, interference filters have satisfactory mechanical properties for withstanding launch environment when properly supported.

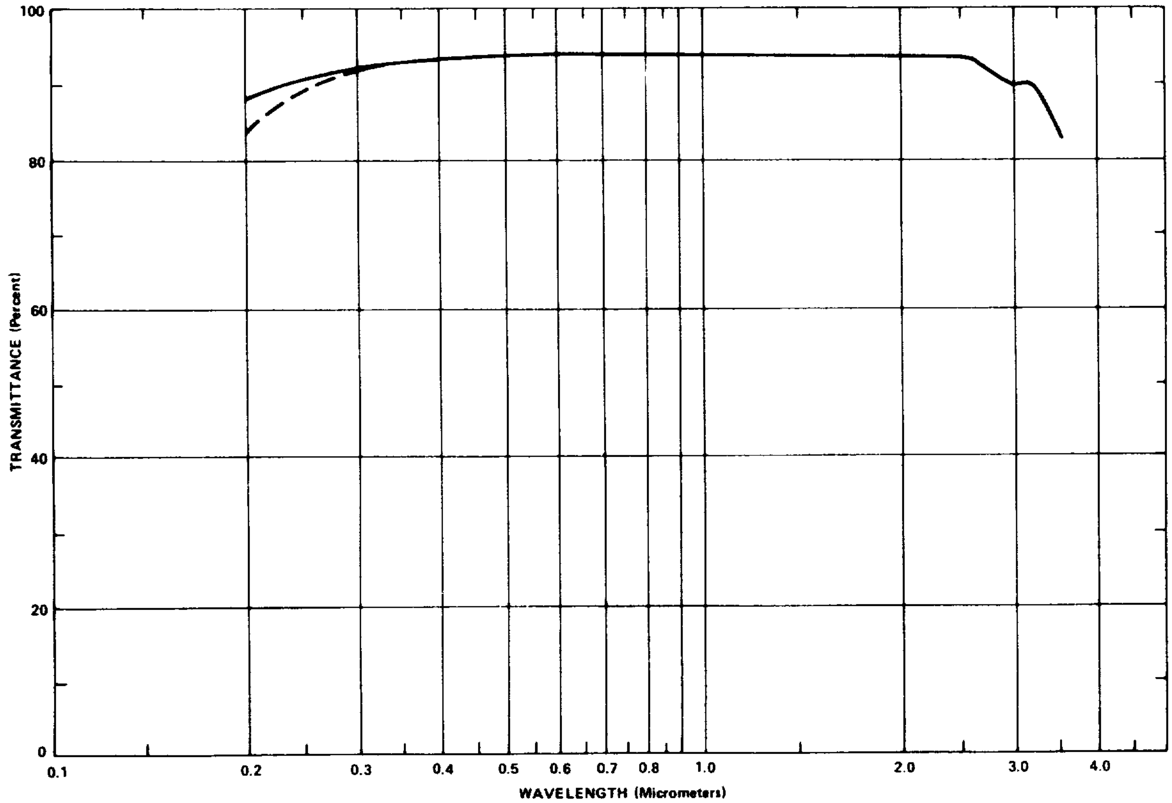

Figure 3. Transmittance of Suprasil-W before and after irradiation with 1.0-MeV electrons to a total dose of 10^{14} electrons/cm^2.

Mirror Materials

Mirror components include the substrate, the reflecting surface, and any thin-film coatings applied to the reflecting surface. Our experience has been that any fused silica having a surface smoothness acceptable for a particular application is also acceptable as a substrate material. Crystalline ceramics such as Cer-Vit have also proven to be satisfactory as mirror substrate materials. Other materials, such as the various grades of Vycor, may also be acceptable, but these glasses have not been tested at the GSFC laboratory.

Vapor-deposited gold, silver, and aluminum have been found to be satisfactory reflecting surfaces. Silver has the best reflectance in the visible wavelength region, but its reflectance decreases below about 350 nm. Aluminum, on the other hand, has much better reflectance in the ultraviolet but is not as good as silver in the visible. Table 2 gives the reflectances of silver, gold, and aluminum at selected wavelengths. Aluminum and gold are much more resistant to tarnishing and discoloration than silver; therefore, they are recommended for wavelength regions and applications where their reflectance is suitable. It may be necessary to use silver when high reflectance in both the visible and infrared wavelength regions is required. In this case, however, great care must be exercised in handling and in protective

Table 2
Normal Reflectance of Evaporated Aluminum, Silver, and Gold

Wavelength (μm)	Aluminum	Silver	Gold
0.222	0.92	0.28	0.27
0.240	0.92	0.28	0.31
0.260	0.92	0.29	0.36
0.280	0.92	0.25	0.37
0.300	0.92	0.17	0.38
0.320	0.92	0.09	0.38
0.340	0.92	0.73	0.38
0.360	0.92	0.88	0.38
0.380	0.93	0.92	0.38
0.400	0.93	0.94	0.39
0.450	0.93	0.96	0.40
0.500	0.92	0.98	0.50
0.550	0.92	0.98	0.82
0.600	0.92	0.98	0.92
0.650	0.90	0.98	0.95
0.700	0.89	0.99	0.97
0.800	0.86	0.99	0.97
0.900	0.87	0.99	0.98
2.0	0.97	0.99	0.98
4.0	0.97	0.99	0.99
6.0	0.98	0.99	0.99
8.0	0.98	0.99	0.99

procedures to prevent tarnishing. Certain overlying protective coatings are useful to accomplish this if they are applied in a pinhole-free condition.

In applying thin films, extreme care must be exercised in cleaning the substrate prior to application. The cleaning procedures are standard and are well known to experienced mirror manufacturers. Maintaining good process control is most important, and high-purity film materials and a clean, oil-free vacuum are necessary. Glow discharge or back sputtering is recommended.

Of the protective coatings for mirrors, work at GSFC has shown that magnesium fluoride and silicon oxide are most useful from the standpoints of affording tarnish protection and of being resistant to solar and charged particle radiation. Either electron-beam sputtering or vapor deposition may be used to apply these materials.

Colored-glass Filters

A number of colored-glass filters have been examined for space application. These include: Schott Filter glasses OG530, RG530, RG695, GG495, and Corning Filter glass 7-54. Of these, only the Schott Filter glasses OG530 and RG695 were found to be sufficiently radiation resistant to be used in space, and these should be protected by a cover plate of fused silica of sufficient thickness to provide shielding from charged particles. Schott filters OG530 and RG695 are being used on the Earth Radiation Budget (ERB) experiment to be flown on Nimbus-F.

Infrared Transmitting Materials

The infrared transmitting materials which were investigated by GSFC's Material Engineering Branch include germanium; Eastman Irtran materials 1 (magnesium fluoride), 2 (zinc sulfide), and 4 (zinc selenide); and single crystals of barium fluoride, cesium iodide, magnesium fluoride, lithium fluoride, calcium fluoride, and sapphire. All of these materials are acceptable for use in the infrared region and show no degradation in transmission in the infrared after exposure to solar radiation or to charged particle radiation. However, both barium fluoride and lithium fluoride are weak, that is, cleavable, in certain crystallographic directions, and care must be taken to ensure that crystals of these materials are suitably oriented and supported to avoid mechanical failure caused by stress encountered during launch. Table 3 lists some MEB-tested materials and their suitability for space use.

MECHANICAL CONSIDERATIONS

In installing optical elements in satellite systems and in experiments, it must be remembered that most of these materials are by their nature brittle and weak in tension. Therefore, to prevent cracking or chipping, care must be exercised in designing mountings so that suitable cushioning and support are provided. Suggested methods include the use of flexible materials between the optical element and the metal support element, proper matching of thermal expansion coefficients between the element and the metal support, and consideration of the thickness and size of the optical element, that is, its strength relative to the launch and service stresses that will be imposed. Because nearly every space optical system is unique in design, a detailed quantitative consideration of these factors must be left to the designer.

Table 3
Suitability of Selected Optical Materials for Space Use

Item	Suitability for Space Use	Comments
Optical Glasses		
Corning 8362	yes	Lead-containing
Corning 8363	yes	Lead-containing
Corning 8365	yes	Lead-containing
517:645	no	Suitable if not exposed to space-type radiation
541:599	no	Suitable if not exposed to space-type radiation
573:574	no	Suitable if not exposed to space-type radiation
617:336P	yes	Doped with cerium oxide
649:339P	yes	Doped with cerium oxide
Fused Silica		
C7940	yes	If exposed to charged particles or ultraviolet, slight fluorescence occurs. Little, if any, phosphorescence.
Suprasil-W	yes	
Infrasil-I	no	
Infrasil-II	no	
GE 101	no	May be suitable for short missions
GE 102	no	May be suitable for short missions
Interference Filters (Transmission Type)	yes	Note comments under interference filters.
Mirror Materials		
Fused Silica	yes	Substrate material
Cer-Vit	yes	Substrate material
Aluminum (thin film)	yes	Note comments on these reflective materials, that is, aluminum, gold, and silver in section on mirror materials.
Gold (thin film)	yes	
Silver (thin film)	yes	
Magnesium fluoride	yes	Protective coating for reflective material
Silicon oxide	yes	

Table 3 (continued)

Item	Suitability for Space Use	Comments
Colored-Glass Filters		
OG530 (Schott)	yes	
RG530 (Schott)	no	Suitable if not exposed to space-type radiation
RG695 (Schott)	yes	
GG495 (Schott)	no	Suitable if not exposed to space-type radiation
7-54 (Corning)	no	Suitable if not exposed to space-type radiation
Infrared Transmitting Materials		
Germanium	yes	Does not fluoresce or phosphoresce in visible or shorter wavelengths Not checked at infrared wavelengths
Irtran 1	yes	Not checked for fluorescence or phosphorescence
Irtran 2	yes	
Irtran 4	yes	
Barium fluoride	yes	Fluoresces and phosphoresces in the 200-nm to 700-nm region (wavelength limits of our experiments) when exposed to space-type radiation
Cesium iodide	yes	
Magnesium fluoride	yes	
Lithium fluoride	yes	
Calcium fluoride	yes	
Sapphire	yes	

LUBRICATION

Alfred J. Babecki

INTRODUCTION

Lubrication, as used in this chapter, refers to the process of providing a medium to reduce the friction developed between metal surfaces moving relative to each other, not static surfaces. Sometimes in spacecraft applications it is desirable to separate statically contacting surfaces to prevent them from bonding, euphemistically termed "cold welding." Even if the contacting surfaces move once relative to each other or only a few times, this condition is not considered one for lubrication in this chapter. However, it is known that these static surfaces are sometimes coated with a solid lubricative film or other nonmetallic coating anyway.

The usual kinds of rolling or sliding applications that require lubrication are discussed, as well as the various types of lubricants that are used, including oils, greases, lamellar solid films, soft metal platings, and plastic films. Some comments from future topics of this guide, such as bearings and gears, will be repeated here because of their relevancy to the subject of lubrication.

Function

The function of lubricative materials is to keep metal surfaces separated and to provide a low-shear boundary layer between them. The lubricative function should persist at all temperatures of operation and for the design life of the apparatus. Any condition which affects these goals should be taken into consideration, such as viscosity, speed, load changes, evaporation, excessive debris buildup, and wear of solid films. It is often mandatory that the shear force (torque) remain constant throughout the life of a device.

Performance

The performance of the lubricative material is dependent upon many factors, including the surface finish of the mating components, the loads, the atmosphere, the quantity, the storage time, and the temperature. Solid film lubricants are less affected by most of these factors than liquid lubricants; however, because solid films usually cannot be replenished, their effective operating lifetime is more dependent on the number of wear cycles. Therefore, solid film lubricants may have a shorter period of use in space applications than liquid lubricants. Generally, the frictional force increases with time for oil- and grease-lubricated systems as the lubricant degrades; but it also decreases with time for bonded solid films as they wear, until wearout or catastrophic failure from debris accumulation develops.

General Problems

Problems that arise with lubricated systems are related to the degradation of the lubricant, to the loss of the lubricant, or to some other condition in the bearing or system. These conditions are described below so that proper attention may be given to minimize or prevent their occurrence.

1. Lubricant degradation causes increased friction from:
   - Polymerized thickening of oils and greases caused by high temperatures, oxidation, or catalysis;
   - Loss of lubricant by creep;
   - Loss of lubricant by evaporation;
   - Rapid wear or loss of adhesion of bonded solid film or metal-plated lubricants;
   - Excessive wear and transfer of plastic material from lubricative ball separators; and
   - Reaction of the lubricant with contaminants.
2. Nonlubricant conditions that can cause failure of bearings or can increase the bearing torques include:
   - Excessive bearing preloads applied initially or by virtue of differential thermal expansion such that heavy metal-to-metal contact occurs;
   - Soft-metal ribbon ball separators that are guided on the race lands (shoulders) and create much wear debris because of their relative high wear rate;
   - Phenolic or sintered-nylon ball separators that are not impregnated with the liquid lubricant;
   - Fretting due to rotation or vibration of the bearing bore on its shaft;
   - Corrosion in nonstainless steel bearings;
   - Particulate contamination in the bearing;
   - Coarse ball and ball groove finishes which prevent development of hydrodynamic oil films and cause metallic wear; and
   - Manufacturing defects, such as cracked separators and bent shields, which are not detected because of inadequate inspection.
3. Marginal motive power that is not tolerant to normal frictional increases, whatever the reason.

4. Inspection of lubricated components is inadequate to ensure conformance with specifications.

OILS AND GREASES

Oils

Oils are liquid lubricants that vary widely in important properties, such as viscosity, pour point, evaporation rates, surface tension, oxidation resistance, and additive content. Therefore, consideration of these properties should be made when selecting an oil for a particular application. Operating parameters that should be considered are speed, load, atmosphere, temperature, and power available. Other considerations include component surface finishes and hardness, and ball separator type, if a ball bearing. Oils vary greatly in composition, which determines the above-named properties; mineral (petroleum) oils are good lubricants but are not as useful below approximately 263 K (-10°C) because of increase of viscosity and turning torque. Synthetic esters are fair lubricants and cover a wider range of service temperatures from 233 K to 373 K (-40°C to +100°C). Silicones are relatively poor lubricants with a very wide temperature range, from about 203 K to 473 K (-70°C to +200°C).

Problem Areas with Oils

For an oil to be able to perform the intended lubrication, it must keep the contacting metal surfaces separated, at least during most of its design life. Figure 4 depicts the well-known Stribeck Curve that relates friction to viscosity, speed, and load and also illustrates the three regimes of lubrication. Boundary lubrication is the zone of some metal-to-metal contact; hydrodynamic lubrication is the zone of full fluid film separating the metal surfaces; elastohydrodynamic (EHD) or mixed lubrication is between the two. The conditions that reduce the separating film thickness are slow speeds, high loads, high temperatures, rough surfaces, and reduction in oil quantity. As the oil film thickness fails and metal-to-metal contact occurs, high localized flash temperatures and catalytic fresh metal surfaces can be developed by the shearing of asperities, both of which can bring about evaporation or polymerization of the oils. The polymerization causes the oils to become increasingly more viscous and raises the bearing torques. If the motive power is very limited, the bearing torques could be raised to intolerable levels. In some instances, as the oil thickens through polymerization and forms a thicker film, it becomes a better lubricant for a period of time. Indeed, some oils may degrade to a point because of frictionally-induced polymerization and subsequently function satisfactorily for prolonged periods because of the increased viscosity.

For critical applications, the motor size should be large enough to allow for some increase in bearing torques due to lubricant degradation or particulate contamination. The choice of an optimum oil will delay the degradation or prevent it altogether. However, the optimum oil may have a relatively high viscosity and, therefore, may cause excessively high initial bearing torques which should remain relatively constant with time. Thinner oils that result

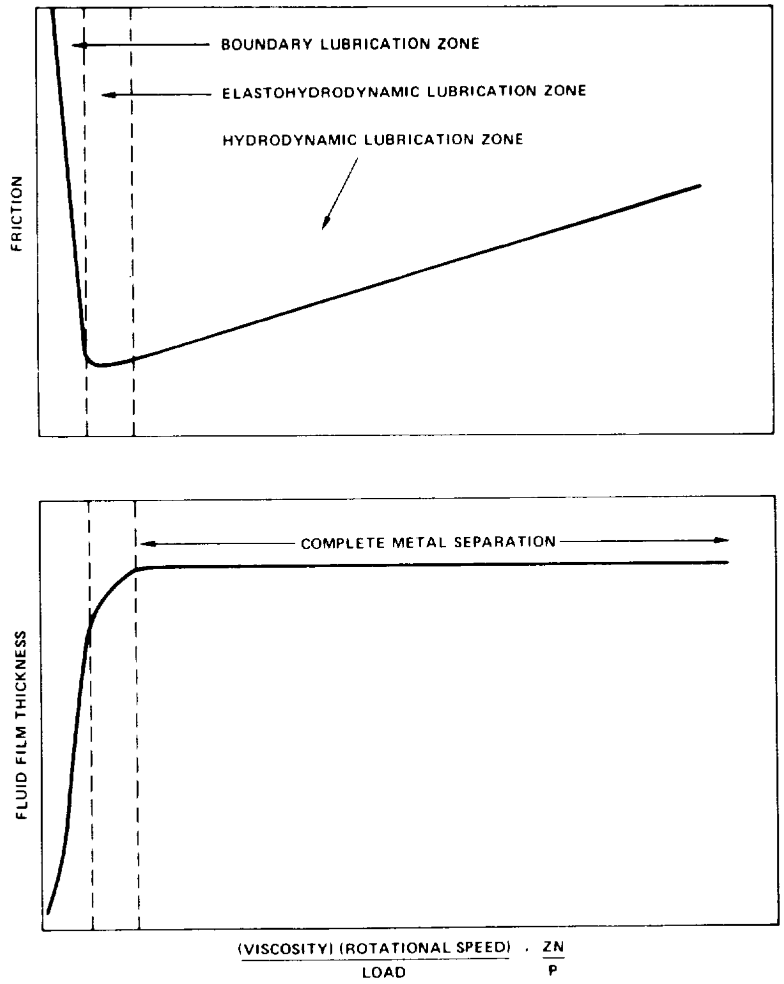

Figure 4. Stribeck Curve (top), showing the various lubrication regimes and how they relate to fluid film thickness and the factors involved.

in lower initial bearing torques will degrade through metallic wear or evaporate more quickly, promote increased torques, and lead to ultimate failure. A large torque margin can be retained when using a more viscous but better oil by reducing the quantity of free oil in the bearing. This procedure is more advisable for long life than the use of a greater quantity of a much less viscous oil. This philosophy is especially true if the bearing surface finishes are relatively coarse, about 0.05 μm (2 μin.) rms or more, that is, more than 0.25 μm (10 μin.) peak-to-peak.

The parameters that are most significant for consideration will vary with the application. High speeds, fine finishes, and light loads will permit the lower viscosity oils to be used, but if the oil is open to vacuum at temperatures above 311 K (+100°F), then the evaporation rate will be a major consideration. Figure 5 depicts the evaporation rates of some oils with increasing temperatures. Those which can maintain low oil film loss rates at higher temperatures are generally the more viscous ones.

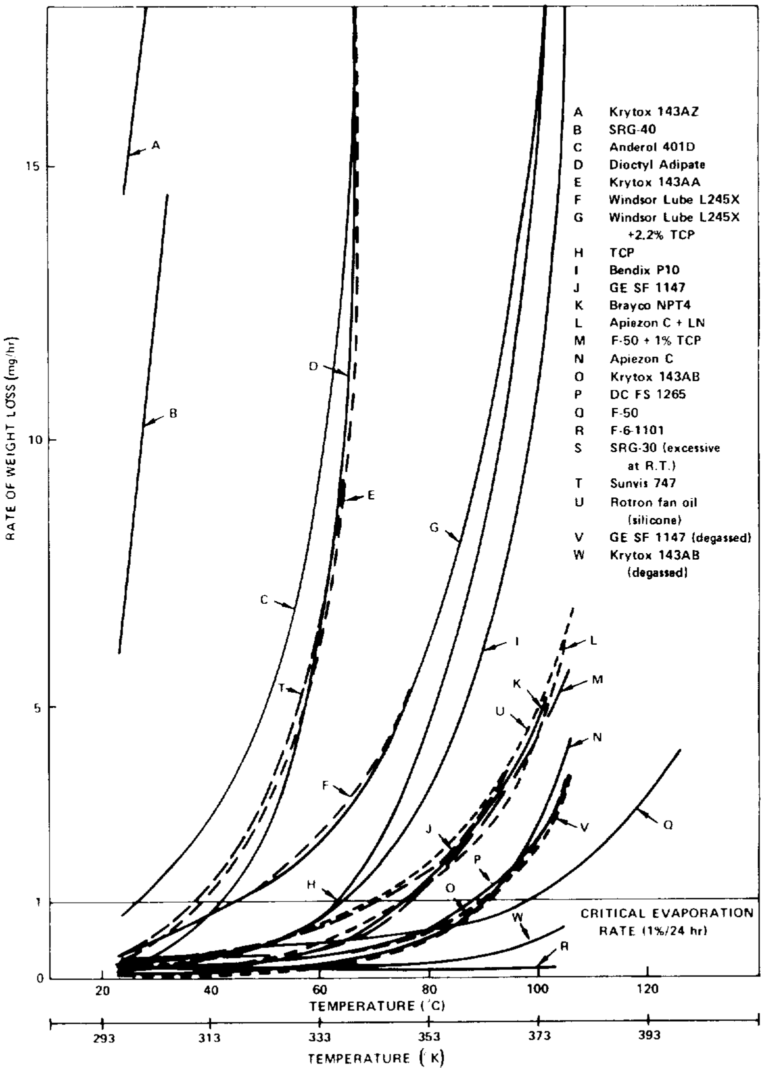

Figure 5. Weight loss rates of various spacecraft oils in vacuum versus temperature.

Another reason for oil film loss is that of surface migration (creep). The lower the surface energy of an oil, the more likely it is to creep. The silicone and fluoropolymer oils such as F-50 and Krytox have the lowest surface energy of the spacecraft oils. The mineral (petroleum) oils, such as Apiezon C, have about the highest. Low-energy fluorochemical barrier films can be used to inhibit creep of oil; but, care must be taken to prevent entry of the barrier material into the bearing. These films are covered in MIL-B-81744 and MIL-STD-1334 (AS).

Besides the surface finish of the balls and races in a ball bearing, the material of the ball separator, if one is used, must be considered when an oil lubricant is used. Metal-ribbon-type separators (Figure 6) are usually fabricated from soft stainless steel and have large areas of rubbing contact with the balls and race lands. These separators wear quite easily in bearings lubricated with low-viscosity oils and should be avoided, if possible. Figure 7 pictures a worn area on a metal ribbon separator. Metal-crown-type separators (Figure 6) are usually made of hardened stainless steel, which has a higher resistance to wear and, also, has a smaller contact area with the balls and races; they are to be preferred to the ribbon-type separators. The porous nonmetallic separators (Figure 6), which can be vacuum-impregnated with the oil, such as the laminated phenolic, sintered nylon, or sintered polyimide, are the most desirable, providing the higher strength of the metal separators is not required.

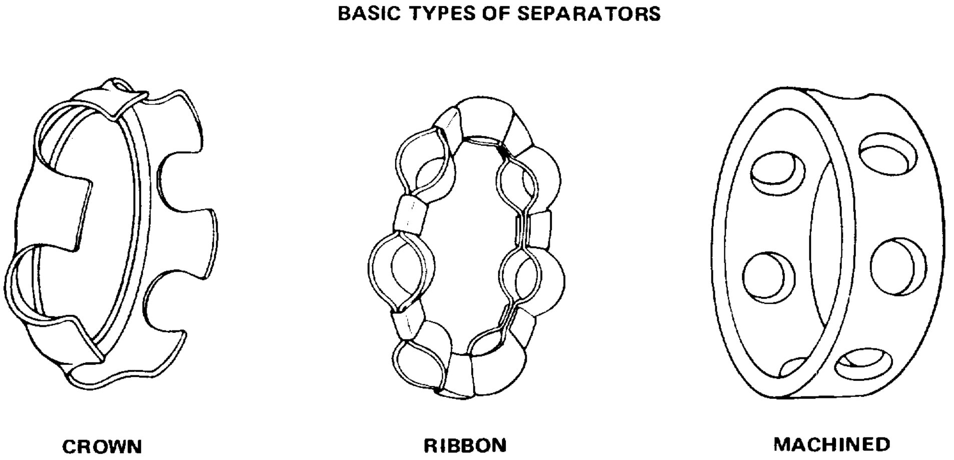

Figure 6. Various types of ball separators. These types may be made from various materials such as filled Teflon, polyimide, nylon, delrin, and various metals. Other types of ball separators include coil springs, plastic slugs or tubes, and riveted assemblies.

Oil Selection

A number of the more commonly used oils for spacecraft applications are given in Table 4, along with some of their pertinent properties. The high vacuum system used to obtain the evaporation test results is shown in Figure 8. Included in Table 4 are a few oils which have had little or no flight use but which appear by test results to be very attractive for spacecraft use. There are innumerable oils on the market, and some of them may be equivalent to or better than those listed in the table. However, information on them is not presently available to permit their listing.

Figure 7. One half of a metal ribbon ball separator showing evidence of wear at the area of contact with the inner race land (20X magnification).

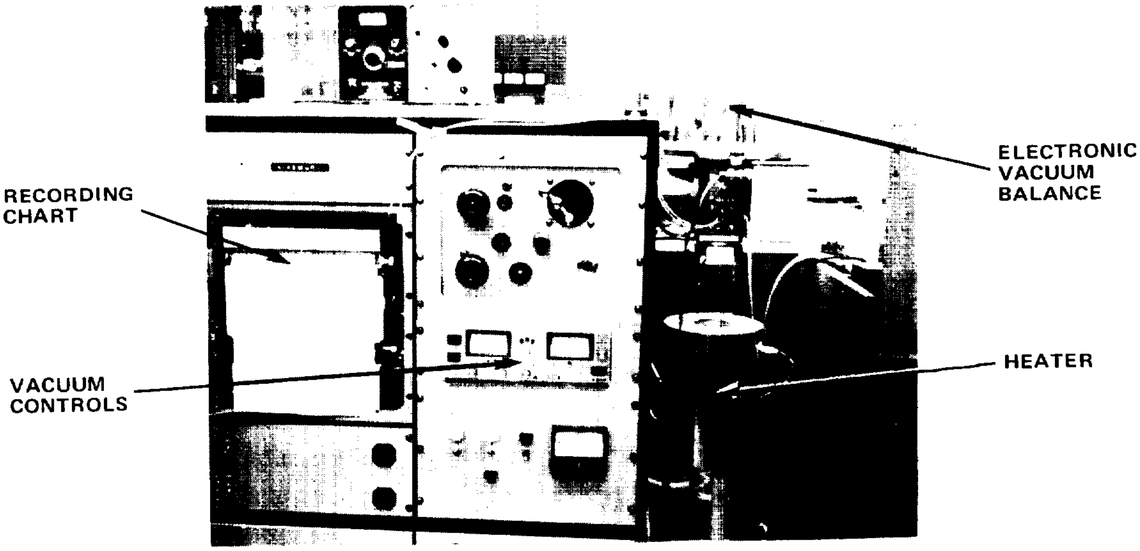

Figure 8. System used in determining the Critical Evaporation Temperature of lubricants contained in a volume of 1.7 cm^3, with a surface area of 0.87 cm^2.

Table 4
Oils for Spacecraft Use

Oil	Type	Temperature Range K (°C)	Viscosity $m^2 \cdot s^{-1} \times 10^{-6}$/K (°C) or cS/K (°C)	Critical Evaporation Temperature K (°C)*	Boundary Performance**
Windsor-Lube L-245X	Diester	216/450 (-57/+177)	20/298 (25)	311 (38)	VP
Anderol L-401D	Diester	213/511 (-60/+238)	20/298 (25)	295 (22)	P
Brayco NPT-4	Diester	219/450 (-54/+177)	30/298 (25)	345 (72)	F
Pioneer P-10	Diester	216/477 (-57/+204)	23/298 (25)	333 (60)	F
Apiezon C	Mineral	261/505 (-12/+232)	87/311 (38)	359 (86)	VG
Kendall SRG-30	Mineral	247/422 (-26/+149)	10/311 (38)	<293 (<20)	G
Teresso V79	Mineral	264/505 (-9/+232)	370/298 (25)	ND	ND
Kendall KG80	Mineral	269/477 (-4/+204)	340/298 (25)	ND	VG
Krytox 143AZ	Fluorocarbon	216/422 (-57/+149)	34/298 (25)	<293 (<20)	F
Krytox 143AA	Fluorocarbon	227/450 (-46/+177)	70/298 (25)	306 (33)	VG
Krytox 143AB	Fluorocarbon	233/477 (-40/+204)	140/298 (25)	355 (82)	VG
GE F-50	Silicone	200/477 (-73/+204)	70/298 (25)	364 (91)	P
GE SF96(50)	Silicone	233/477 (-40/+204)	50/298 (25)	ND	VP
DC FS 1265	Fluorosilicone	233/477 (-40/+204)	300/298 (25)	357 (84)	G
DC F6 1101	Fluorosilicone	233/477 (-40/+204)	11,000/298 (25)	>373 (>100)	F
GE SF 1147	Methyl alkyl polysiloxane	220/533 (-53/+260)	49/298 (25)	336 (63)	P

* Critical Evaporation Temperature is that temperature at which the rate of weight loss exceeded 1 mg/hr in a vacuum pressure of less than 1.33×10^2 N/m^2 (1×10^{-5} torr) under the MEB test conditions. It is the temperature where the weight loss would be 1 percent in 24 hours, the critical evaporation rate.

** Boundary performance rating: VG $> 1 \times 10^6$ revs., G = $5 \times 10^5 - 1 \times 10^6$ revs., F = $1 \times 10^5 - 5 \times 10^5$ revs., P = $2 \times 10^4 - 1 \times 10^5$ revs., VP $< 2 \times 10^4$ revs. under the MEB LFW-1 test conditions.
ND = Not determined.

It would be most desirable to reduce the number of candidate oils to a few that could satisfy all requirements. If attention is paid to such parameters as good labyrinthing, barrier films, narrow temperature ranges, good bearing quality, and adequate torquing power, then a relatively few oils can suffice.

One of the pertinent properties of oils to be considered is that of boundary film strength, or the ability to lubricate in a thin-film (EHD) regime. The Dow Corning LFW-1 machine (Figure 9) has been used to rate oils and greases in this property. In this test, a rotating hard steel ring is in contact with a stationary hard steel block. Both test pieces are coated liberally with the oil (or grease), allowed to drip for 5 minutes, and the test is run until the frictional coefficient between them reaches 0.33 or until 1×10^6 revolutions is passed. The load, speed, and surface finish can be varied. Weight change of the test pieces, size of the wear scar, and temperature of the block are measured. Observations of changes in the appearance of the lubricant are made and recorded, and the samples are photographed.

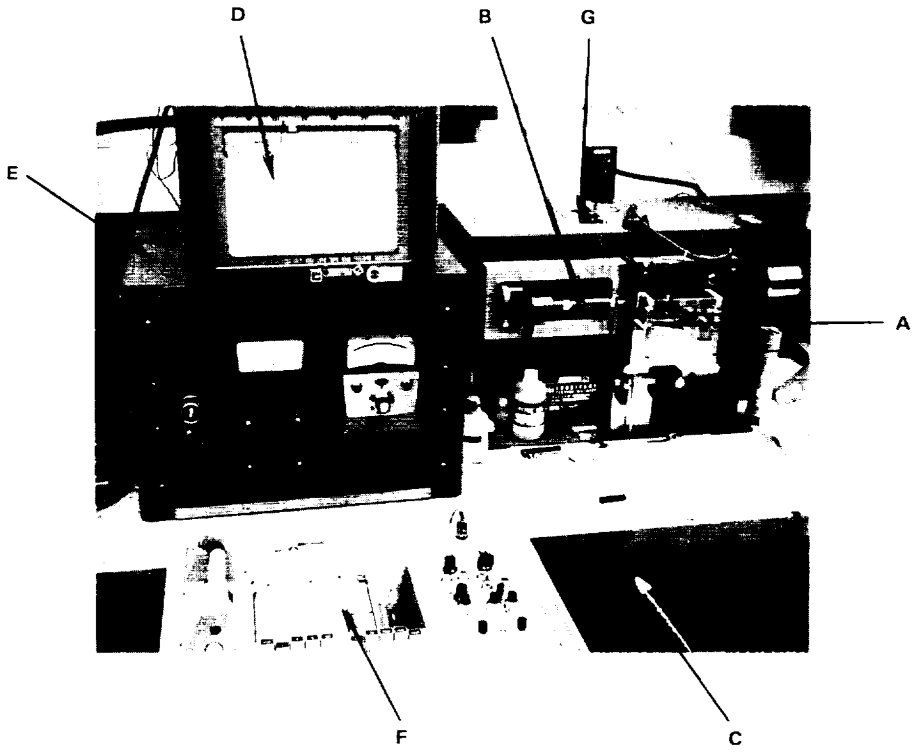

Figure 9. Dow Corning LFW-1 Friction and Wear Test Machine. A. Rotating ring and stationary block specimens. B. Friction load transducer. C. Dead weight load. D. Temperature recorder for stationary block. E. Speed controller. F. Friction force recorder. G. Revolution counter.

Table 5 provides a comparison of oils tested as determined by the number of sliding revolutions before failure under similar test conditions in air. The results shown are based upon multiple tests. The table also illustrates the influence of surface finish on formation of a hydrodynamic lubricating film. (See the GE F-50 results.)

In general, the fluoropolymer and silicone oils are the most resistant to oxidation and polymerization at elevated temperatures, have the widest service temperature range, and usually have the lowest evaporation rates. However, as indicated earlier, these oils have the disadvantage of having lower surface energies than the diesters and mineral oils, with the result that they do migrate (creep) along the metal surfaces more readily. This tendency can be minimized or restricted by the careful application of low-energy barrier films. In addition, the silicones are relatively poor boundary lubricants and do not readily accept the common additives to improve this feature. The silicones, such as F-50, should be low on the oil selection list because of their low film strength and high creep tendency.

Whatever the final decision in oil selection, the actual oil used should be reasonably fresh, that is, not oxidized or contaminated, and should be filtered through a 0.5-μm filter

Table 5
LFW-1 Sliding Friction Data for Oils

Oil	Type	Steel	Revolutions to Failure	Maximum Block Temperature K (°C)	Load kg (lb)	Surface Finish μm μin. (rms)
Apiezon C	Mineral	Low alloy	>700,000	317 (44)	330 (150)	0.13 - 0.38 (5-15)
Apiezon C	Mineral	440C	>1,000,000	330 (57)	330 (150)	0.13 - 0.38 (5-15)
SRG-30	Mineral	Low alloy	528,000	334 (61)	330 (150)	0.13 - 0.38 (5-15)
GE F-50	Silicone	Low alloy	3,000	323 (50)	330 (150)	0.13 - 0.38 (5-15)
GE F-50	Silicone	440C	27,000	330 (57)	330 (150)	0.13 - 0.38 (5-15)
DC FS-1265	Silicone	Low alloy	235,000	343 (70)	330 (150)	0.13 - 0.38 (5-15)
GE SF-96 (50)	Silicone	Low alloy	<1,000	357 (84)	330 (150)	0.13 - 0.38 (5-15)
DC F6-1101	Silicone	Low alloy	267,000	330 (57)	330 (150)	0.13 - 0.38 (5-15)
NPT-4	Ester	Low alloy	29,000	343 (70)	330 (150)	0.13 - 0.38 (5-15)
NPT-4	Ester	440C	296,000	340 (67)	330 (150)	0.13 - 0.38 (5-15)
NRL MB-20	Ester	Low alloy	6,000	323 (50)	330 (150)	0.13 - 0.38 (5-15)
P-10	Ester	Low alloy	87,000	336 (63)	330 (150)	0.13 - 0.38 (5-15)
L-245X	Ester	Low alloy	11,000	324 (51)	330 (150)	0.13 - 0.38 (5-15)
Krytox 143AA	Fluorocarbon	Low alloy	>600,000	333 (60)	330 (150)	0.13 - 0.38 (5-15)
Krytox 143AB	Fluorocarbon	Low alloy	>750,000	330 (57)	330 (150)	0.13 - 0.38 (5-15)
Krytox 143AB	Fluorocarbon	440C	>1,000,000	332 (59)	330 (150)	0.13 - 0.38 (5-15)
Krytox 143AZ	Fluorocarbon	Low alloy	134,000	366 (93)	330 (150)	0.13 - 0.38 (5-15)
Apiezon C	Mineral	Low alloy	22,000	344 (71)	660 (300)	0.13 - 0.38 (5-15)
Apiezon C	Mineral	440C	23,000	360 (87)	660 (300)	0.13 - 0.38 (5-15)
KG-80	Mineral	Low alloy	>712,000	345 (72)	660 (300)	0.13 - 0.38 (5-15)
Krytox 143AB	Fluorocarbon	Low alloy	>554,000	345 (72)	660 (300)	0.13 - 0.38 (5-15)
Krytox 143AB	Fluorocarbon	440C	46,000	365 (92)	660 (300)	0.13 - 0.38 (5-15)
GE F-50	Silicone	440C	< 10,000	329 (56)	198 (90)	0.13 - 0.38 (5-15)
GE F-50	Silicone	440C	>853,000	313 (40)	198 (90)	<0.025 (<1)
GE F-50	Silicone	440C	442,000	326 (53)	396 (180)	<0.025 (<1)

membrane before use. The addition of the oil to the bearing should be on the basis of weight rather than by the number of drops.

Oil Additives

The ability of an oil to maintain separation between metal surfaces in a bearing can be enhanced by the addition of a strong polar compound, or film former, to the oil. Such compounds are classed as mild pressure agents or extreme pressure agents. Lead naphthenate (LN) is an example of the former and tricresylphosphate (TCP) an example of the latter. These additives may be only slightly soluble in the desired oil; therefore, the solubility limit should be determined so that only highly soluble additives are used with a particular oil; otherwise separation is likely. In Versilube F-50 oil, TCP is soluble to approximately 1.75 percent by weight; in diesters, such as P-10, and in the mineral oils, such as Apiezon C, TCP is soluble in much higher percentages, up to at least 25 percent for the diesters and 10 percent in the mineral oils.

The mechanisms by which the pressure additives may improve lubrication are not completely known; indeed, different additives may involve different mechanisms. In the case of F-50 oil, a 1-percent addition of TCP causes a visible film to form on the contacting surfaces of low-alloy steel parts and provides long life and low friction. The film is thought to be a phosphate compound formed by the TCP in contact with freshly worn metal surfaces. TCP in F-50 does not appear to be as effective on high chromium steels, such as 440C. Tests with TCP in synthetic diester oils, such as P-10, also indicate that a greater quantity of the additive is required for use on the more noble 440C steel (5 percent versus 2 percent for the 52100 steel).

There are many pressure additives that are available, but their effectiveness would have to be determined by a bearing or friction test, such as that provided by the Dow Corning LFW-1 test machine. Table 6 lists some oil test data that show the influence of the additives.

Greases

Greases are oils that are thickened by the addition of (1) soaps such as stearates or (2) fillers, such as finely divided silica, in order to provide a host for the lubricating component. In most instances, the thickening agent is not a good lubricant by itself. In general, the important lubricating properties of the grease are those imparted by the oil in it. Greases are classed as either channeling or nonchanneling. Channeling greases are waxy, or stiff, and remain in place after once being pushed aside; that is, the balls make a channel through the grease. Nonchanneling greases are buttery, or adherent, and are continually dragged back into the wear zone.

The greases offer the advantages of reducing such oil problems as creep and evaporation and of inhibiting the ingress of particulate matter into the bearing wear surfaces. If enough motive power is available to operate fully packed bearings, the grease may also afford the means to incorporate more lubricant into the bearings than by oil alone.

Table 6
LFW-1 Test Data For Oil Additives *

Oil	Type	Additive and Weight Percent	Steel	Performance Without Additive (revolutions)	Performance With Additive (revolutions)
Windsor-Lube L245X	Diester	TCP - 2.2	Low alloy	10,900	>1,000,000
Brayco NPT-4	Diester	TCP - 5.0	Low alloy	28,800	>870,000
Brayco NPT-4	Diester	TCP - 10.0	440C	296,300	>1,000,000
GE F-50	Silicone	TCP - 1.5	Low alloy	3,000	>750,000
GE F-50	Silicone	TCP - 1.5	440C	<27,000	15,000
GE SF-96 (50)	Silicone	TCP - 1.5	Low alloy	1,000	1,000
Apiezon C[†]	Mineral	TCP - 5.0	Low alloy	21,700	>682,000
Apiezon C[†]	Mineral	TCP - 5.0	440C	22,700	317,100
Apiezon C[†]	Mineral	LN - 5.0	Low alloy	21,700	122,800
Apiezon C[†]	Mineral	LN - 5.0	440C	22,700	62,100

* Tests conducted under 330-kg (150-lb) load at 100 rpm.

[†] Tests conducted under 660-kg (300-lb) load at 100 rpm.

Problem Areas with Greases

As with oils, the grease must keep the metal surfaces separated in order to provide good lubrication. In the case of a channeling grease, such as Andok-C, this may not be as readily achieved as in the case of a nonchanneling grease, such as Beacon 325, because the lubricant in channeling grease does not easily bleed back into the wear zone. However, as a consequence of this channeling feature, the torque of bearings lubricated with such a grease is relatively constant from low 223 K (-50°C) to moderate 323 K (+50°C) temperatures. This feature is desirable for some applications, but bearing life depends primarily on the oil film originally established. In sealed environments, such as tape recorders, the Andok-C grease has provided virtual trouble-free operation when adequately supplied.

In general, greases will produce higher bearing torques than oils because they are stiffer. This stiffness will increase with time as the oil component may be lost due to evaporation. The use of shields on the bearings will tend to inhibit the evaporation of oil and the extrusion of the grease. In the case of channeling greases, where the oil film is not readily replenished in the wear zone, a fine finish (less than 0.025 μm (1 μin.) rms) on the contacting surfaces is recommended. In the case of the nonchanneling greases, the smoothness of the finish may not be quite as critical, although the smoothest finish feasible is desirable. The bearing torque will increase with decreasing temperature, as the oil viscosity of the nonchanneling grease increases.

In Figure 10, the evaporation (weight loss) rates of some of the commonly used spacecraft greases are pictured, and Table 7 presents their ratings as boundary lubricants. These data show that a common spacecraft grease, G-300, is a relatively poor lubricant but does have a low evaporation rate compared to the better lubricating greases.

Another problem area is the thinning of greases with solvents to a soupy consistency in order to dip the assembled bearing and, thereby, "grease plate" it. Most grease manufacturers do not recommend this procedure unless the grease is not adversely affected.

Table 7 presents some LFW-1 test data which show the detrimental effect on wear life of two solvents used to thin Andok-C for grease plating purposes. If the thinned grease or bearings are tightly packaged before all of the solvent has escaped, then needle-like crystals of the solvent/grease composition may grow, causing some concern. These crystals will disappear if the container is allowed to remain open until they sublime, or the crystals will melt if mixed back into the grease.

Another application problem can exist when the grease is injected into a ball bearing. Normally, the bearing is in the assembled condition without shields and positioned horizontally, and the grease is deposited as several individual globs on the outside surface of the ball separator, on one or both sides. As a result, the grease may not enter into the ball grooves easily, especially in the case of the stiff channeling types, and the bearing may be put into operation essentially without lubrication. If shields are installed, the inspection for this

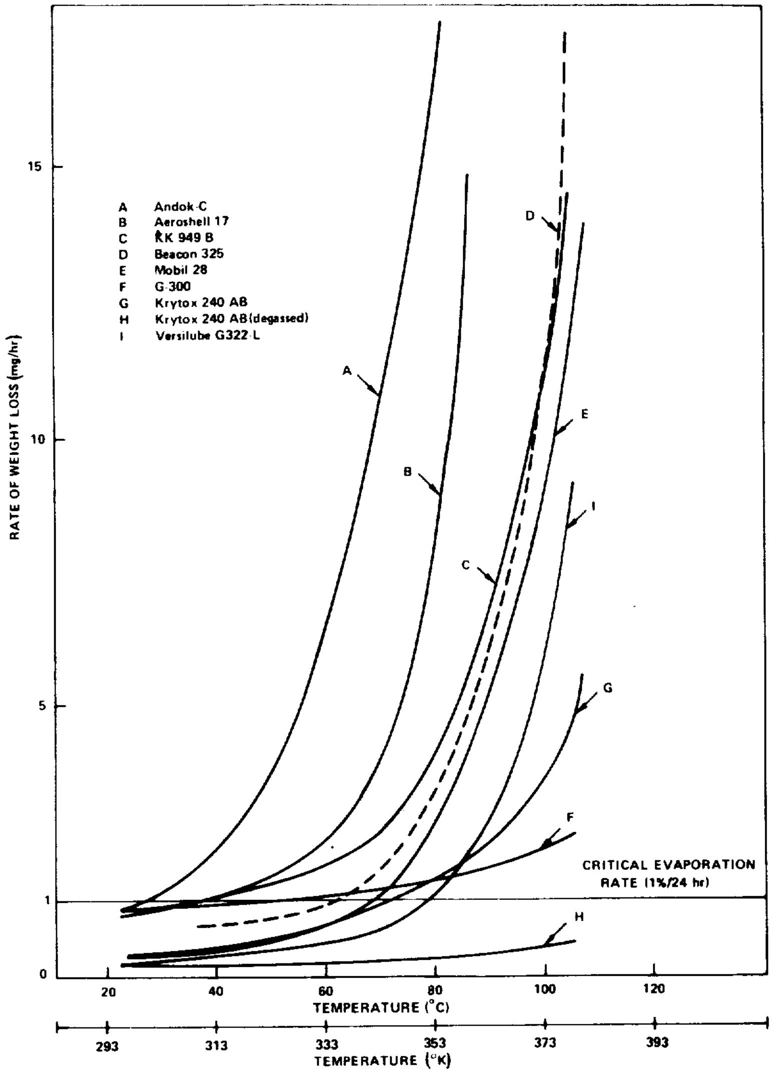

Figure 10. Weight loss rates of various spacecraft greases in vacuum versus temperature.

problem becomes virtually impossible. A more desirable method of application is to inject grease by using syringes, with the aid of visual magnification, directly into the ball groove.

Because of their consistency, greases are not amendable to filtration, and the introduction of particulate matter into the bearing by "dirty" grease is a possibility. Fortunately, such particles, unless large and numerous, are forced out of the wear zone where they may remain trapped by the excess grease. Some vendors have provided coarse filtration (>10 μm) by thinning the grease so that it can be forced through a filter. This procedure has the same objections as cited for grease plating.

Table 7
LFW-1 Sliding Friction Data For Greases

Grease	Type	Steel	Revolutions To Failure	Maximum Block Temperature K (°C)	Load (kg)	Surface Finish μm (μin.) rms
Andok-C	Mineral	440C	41,000	342 (69)	68.2	0.13 - 0.38 (5-15)
Andok-C	Mineral	Low alloy	106,000	341 (68)	68.2	0.13 - 0.38 (5-15)
Andok-C*	Mineral	Low alloy	57,000	340 (67)	68.2	0.13 - 0.38 (5-15)
Andok-C†	Mineral	Low alloy	68,500	336 (63)	68.2	0.13 - 0.38 (5-15)
Andok-C‡	Mineral	Low alloy	71,000	346 (73)	68.2	0.13 - 0.38 (5-15)
Beacon 325	Ester	Low alloy	627,000	347 (74)	68.2	0.13 - 0.38 (5-15)
Beacon 325	Ester	440C	643,000	351 (78)	68.2	0.13 - 0.38 (5-15)
Brayco KK949B	Ester	440C	450,500	351 (78)	68.2	0.13 - 0.38 (5-15)
G300	Silicone	440C	<1,000	342 (69)	68.2	0.13 - 0.38 (5-15)
G300	Silicone	Low alloy	<1,000	330 (57)	68.2	0.13 - 0.38 (5-15)
G300 + 10% TCP	Silicone	Low alloy	<3,000	342 (69)	68.2	0.13 - 0.38 (5-15)
G300 + 25% TCP	Silicone	Low alloy	15,500	344 (71)	68.2	0.13 - 0.38 (5-15)
Krytox-240AB	Fluorocarbon	Low alloy	98,000	344 (71)	68.2	0.13 - 0.38 (5-15)
Krytox-240AB	Fluorocarbon	440C	>1,000,000	336 (63)	68.2	0.13 - 0.38 (5-15)
Mobile 28	Synth. hyd. car.	440C	>1,000,000	330 (57)	68.2	0.13 - 0.38 (5-15)
Aeroshell 17	Ester	440C	598,500	330 (57)	68.2	0.13 - 0.38 (5-15)

* Thinned with Isopar-E solvent, then solvent-evaporated.

† Thinned with Toluene solvent, then solvent-evaporated.

‡ After exposure to 100-percent RH for 424 hr.

Grease Selection

Table 8 lists some of the more commonly used greases for spacecraft applications, as well as some that have indicated good performance in tests. As with oils, the grease to be used should be from a fresh batch. If soft-metal, ribbon-type ball separators are employed in a ball bearing, then the quantity of grease used should be enough to inhibit separator wear, that is, filled 25 percent or more of the maximum it can hold.

Grease is a good lubricant to use in sliding friction applications, such as gear trains. It also is a prime candidate for those applications where the movement is intermittent with long stationary periods where a liquid lubricant might evaporate or creep. If a certain grease is found to be too stiff for a particular application, it can be thinned with more oil component to the desirable consistency.

In general, a grease would be useful in those applications where a hydrodynamic oil film might not be achieved, such as where the bearing operation was at slow speed (less than 50 rpm) or frequently changing in speed and direction. In such a case, a nonchanneling grease would probably be more effective than a channeling one.

Grease Additives

Mild pressure and extreme pressure agents may be added to greases if they are compatible with the oil component. The effectiveness of the additive may be influenced by the metal composition of the contacting surfaces and should be determined by means of test results if none already exist.

SOLID FILMS

Lamellar Materials

Lamellar lubricating materials are those which have a crystal structure that allows shear to occur on certain crystallographic planes at low shear forces. Commonly used materials of this type are graphite; the disulphides, such as molybdenum disulphide (MoS_2); and the diselenides, such as tungsten diselenide (WSe_2). They provide lubrication by serving as a nonmetallic interface between the metal contacting surfaces and by their ability to shear and slide over themselves with low shear force. These materials are used in those instances where oils or greases cannot be used, for example, where condensable contaminants must be kept low or where very low or high temperatures are experienced. They are also used when long periods of nonoperation in a space vacuum are required because these materials do not evaporate or creep at normal spacecraft temperatures. The most commonly used of these materials is MoS_2. Impurities in the lubricative powder may affect their performance and should be prevented.

The MoS_2 is applied to contacting surfaces by a number of methods: burnishing it onto the surface; mixing it with a bonding agent, such as epoxy, phenolic, polyimide, or other resin, spraying it onto the surface, and baking it to cure the bonding agent; and vacuum sputtering it on in low-pressure argon.

Table 8

Greases for Spacecraft Use

Grease	Type	Temperature Range K (°C)	Manufacturer	Critical Evaporation Temperature K (°C)*	Boundary Performance**
Aeroshell 17	Ester	211 to 422 (-62 to +149)	Shell Oil	303 (30)	G
Andok-C	Mineral	273 to 394 (0 to +121)	Humble Oil	293 (20)	P
Beacon 325	Ester	219 to 394 (-54 to +121)	Humble Oil	333 (60)	G
Brayco KK949B	Ester	219 to 450 (-54 to +177)	Bray Oil	303 (30)	F
GE G300	Silicon	200 to 505 (-73 to +232)	Gen. Elec.	313 (40)	VP
Krytox 240AB	Fluorocarbon	233 to 505 (-40 to +232)	DuPont	343 (70)	VG
Mobile 28	Syn. hyd. car.	208 to 450 (-65 to +177)	Mobil Oil	338 (65)	VG

* Critical Evaporation Temperature is that temperature at which the rate of weight loss exceeds 1 mg/hr in a vacuum pressure of less than 1.33×10^2 N/m^2 (1×10^{-5} torr) under the test conditions. It is the temperature where the weight loss would be about 1 percent in 24 hours from the sample vial, the critical evaporation rate.

** Performance rating:

VG = $> 1 \times 10^6$ revs.,

G = $5 \times 10^5 - 1 \times 10^6$ revs.,

F = $1 \times 10^5 - 5 \times 10^5$ revs.,

P = $2 \times 10^4 - 1 \times 10^5$ revs.,

VP = $< 2 \times 10^4$ revs.

Another method used by one vendor is to impinge the material onto the surface with a high-pressure stream of glass beads or other particulate medium. Another method used is to tumble the parts in a ball mill containing the lubricative material and small metal or ceramic balls.

Problem Areas with Lamellar Solids

In most instances where the MoS_2 (or other lamellar solid) is applied by mechanical means (burnishing, impinging, tumbling), the adherence is not very good, and the coating often does not provide complete coverage. This may be due to the lack of cleanliness of the surface. Such films, however, may be adequate for light duty, such as a solenoid core or a slowly operating gear or bearing. The effectiveness and life of the film in a medium or long duty bearing is enhanced by supplementing it with a lubricative ball separator. Such a separator may be made of Teflon or polyimide and contain some MoS_2 which may partially replenish the original coating. The plastic also aids in the lubrication process.

With bonded solid films, the cured film may be of the order of 5 to 13 μm (0.2 to 0.5 mils) in thickness. Consequently, the bearings employing such a film should be procured with greater play in them than for oil or grease use. As this coating is put into service, a good deal of that original thickness is worn loose and will become debris that may increase the torque or jam the bearing. Such surfaces should be worn-in prior to use and the debris removed by air or gas jet, or the excess film may be burnished off with steel wool or with a rotating or oscillating stiff bristle brush and the debris removed before assembly of the coated parts.

Both the bonded and the mechanically applied solid films are susceptible to failure when exposed to liquids such as solvents, oils, and moisture. These agents tend to loosen the bond and increase the wear rate of the film. Therefore, components coated with such solid films should be kept protected from these liquids.

Many of these solid films are proprietary. Table 9 lists a number of films which have been used or suggested for spacecraft use. Their performance is dependent upon such factors as the load-on and the smoothness of the contacting surfaces. In general, these coatings are not affected by temperature, vacuum, and speed of operation. Parts which are coated with these films should be examined for coverage and uniformity. One or more witness samples, coated along with the parts, should be used for destructive tests for adhesion and wear life.

When done properly, the RF or d.c. sputtering method of applying the MoS_2 appears to be the best for ball bearings in vacuum, based on sliding friction tests conducted in vacuum by Lewis Research Center and ball bearing tests performed by New Hampshire Ball Bearing Co. for GSFC. These tests showed the sputtered film to outperform both the burnished and bonded films. However, bearing tests in air have provided mixed results and indicate that the film should not be subjected to many wear cycles outside a vacuum. The film is applied to argon-ion cleaned surfaces in a partial vacuum under high voltage conditions. Consequently, the particles are imbedded into the surface, resulting in good adhesion. The usual film

Table 9
Some Proprietary Bonded Solid Film Lubricant Used in Space Applications

Name	Company	Lubricant	Binder	Cure	Application
Lub Lok 4306	Electrofilm Corp.	MoS_2	phenolic resin	elevated temperature	In all cases, the lubricant coatings can be used on ball bearings, sleeve bearings, gears, and other sliding mechanisms from temperatures of about 88 K to 473 K (-185°C to +200°C). The substrate should be as hard as possible. In general, the room temperature-cured coatings are used on substrates that cannot take the elevated cure temperature. Because these coatings are applied by spray, dip, or brush, they are relatively thick and should be burnished after cure to remove the softer outer layers.
Molykote M88	Dow Corning	MoS_2	vinyl-butyral resin	room temperature	
Everlube 620	Everlube Corp.	MoS_2	phenolic resin	elevated temperature	
Surf Kote A1625	Hohman Plating Mfg. Inc.	MoS_2	acrylic resin	room temperature	
Lubeco 905	Lubeco Inc.	MoS_2	inorganic proprietary	elevated temperature	
Molykote X-15	Dow Corning	MoS_2 + graphite	sodium silicate	room or elevated temperature	
Lubeco M390	Lubeco Inc.	MoS_2	phenolic resin	elevated temperature	
Vitrolube 1220	Nat'l. Process Industries	MoS_2/graphite	ceramic	elevated temperature	
N.P.I. 425	Nat'l. Process Industries	MoS_2/Sb_2O_3	polyimide resin	elevated temperature	
Lub Lok 2306	Electrofilm Corp.	MoS_2	sodium silicate	elevated temperature	
MLR-2	Midwest Research Institute	MoS_2/Sb_2O_3	polyimide resin	elevated temperature	
MLR-5	Midwest Research Institute	MoS_2/graphite	sodium silicate	elevated temperature	
MLR-9	Midwest Research Institute	MoS_2/graphite	aluminum phosphate	elevated temperature	
AML-23A	Naval Air Materials Laboratory	MoS_2 + graphite	sodium silicate	elevated temperature	

thickness is only 0.2 to 0.4 μm (2000 to 4000Å), so that loose bearing clearances are not necessary. However, because of this thinness, the substrate must be smooth and hard in order to prevent rupturing of the film. It is a suitable film for ball bearings, but not for journal bearings made of soft stainless steel. Witness samples should also be coated for examination and test. In ball bearings, only the races and separator need be sputter-coated.

Soft Metal Platings

Low shear-strength metal platings, such as gold, silver, bismuth, and lead, are sometimes plated onto wear surfaces to provide some lubrication, that is, low shear operation. The films may be deposited by electrodeposition, by vapor deposition, or by ion plating, with the former method providing the heavier films. The ion plating technique, like sputtering, applies the film after ion cleaning and under high acceleration forces, so that adhesion is usually better and the film thickness control and uniformity are better than by the other two methods. Ion plating is usually applied to very low-speed operation and intermittent-type operation applications. Like the lamellar solid lubrication, the soft metal films have a finite life that is measured in cycles of operation, rather than days or months of service, because the lubricative film does not replenish itself.

This method of lubrication, in general, results in higher frictional coefficients than the lamellar solids, but it is not as sensitive to liquid exposure. In fact, some bearing systems have used the soft metal platings in conjunction with burnished or bonded MoS_2 and with liquid or grease lubricants. Ion plating is also useful where electrical conduction is required, such as slip rings and commutator surfaces.

Problem Areas with Soft Metal Platings

One chief problem with soft metal platings applied by electrodeposition is lack of adhesion and the development of flaking that leads to lubrication failure and increased friction. Such debris can also cause electrical problems if it infiltrates areas of circuitry. The adhesion problem is intensified when the metal plating is too thick or deposited on substrates too soft for the loads applied.

Such metal platings as silver, which react with gaseous components of the environment, may develop tarnish films that can increase friction and electrical resistance, as well as cause concern over the appearance.

Bearings that are to be coated with soft metal platings should have greater internal play because the coating thicknesses may be several micrometers (tenths of a mil) in thickness.

Plastic Films

Plastic, or polymer, materials that are used as solid lubricants in spacecraft applications are the Teflons (PTFE and FEP) and the polyimides. These can be sprayed and fused coatings, or they can be burnished films. The common method of burnishing a plastic film into a ball bearing is by using a plastic ball separator which transfers the lubricative film by rubbing contact onto the balls and then onto the races. Such ball separator and sleeve type bearing materials are often filled with various additional materials to achieve special properties: MoS_2 for additional lubrication, fiberglass and metal oxides for strength, metal powders for thermal conduction, asbestos to reduce thermal expansion, and others. Most of these plastic materials that are suitable for ball separators and sleeve bearings are available as bulk items; the fused plastic films are usually proprietary and are applied by the individual vendor. Table 10 lists some of the commercial materials of each type that are available and the types of applications for which they might be suited.

Problem Areas with Plastic Films

With the fused plastic coatings, the chief problems are those of lack of adhesion, nonuniformity of thickness, high thermal expansion coefficients that cause interference problems, and cold flow. The chief problems with the burnished plastic films are incomplete or nonuniform coverage, excessive transfer, wear out or breakage of the relatively weak ball separators, and development of loose debris that cause high torque.

Solid Film Selection

Any of the solid films may be usable in an application where very limited sliding operation is required. In applications, such as with ball bearings, the transfer system from plastic ball separators has given many millions of revolutions under light loads and unidirection continuous rotation, with some debris buildup. However, under intermittent operation and oscillatory operation, these transfer films have caused torque spikings that were objectionable. Bearings using the transfer method should have their races preburnished with the plastic material, or they should be run in under increasing loads for 25,000 to 50,000 revolutions to distribute the film before being installed into service. The transfer system should not be used in ball bearings where variations in torques (torque ripple) or high starting torques cannot be tolerated. Similarly, the bonded MoS_2 films, when properly applied and worn in, have provided many millions of cycles of operation. These films are not as sensitive to loading conditions and temperature variations as are the transfer films, but they may be more sensitive to moisture than the transfer film.

The fused plastic films are not used in lubricating gears, bearings, and other close tolerance devices because these films are normally too thick and are easily ruptured in such applications. They are useful to lubricate valve poppets, latches, and other devices that need to operate very infrequently under light loads or in an environment, such as a fuel system, that would be too severe or damaging to other methods of lubrication.

Table 11 lists the main advantages and disadvantages of the various solid film systems.

Table 10
Some Proprietary Transfer-Film Lubricant Materials Used in Space Applications

Name	Company	Constituents	Lubricant	Applications
Duroid 5813	Rogers Corp.	PTFE + fiberglass + MoS_2	PTFE and MoS_2	In all cases, the materials may be used as ball cages in ball bearings, as sleeve bearings, as idler gears, as burnished-on films on slots or cams. Each has individual mechanical and physical properties that should be considered in the design. In a transfer application, the wear of the plastic material is a continuous process and is load sensitive. Therefore, debris buildup can be minimized by load reduction. Although the coefficients of friction of these materials on themselves are low, debris in bearings can cause torque spikes or jitter which may be detrimental to high-precision applications.
Rulon A + MoS_2	Penn Dixon Corp.	PTFE + fiberglass + MoS_2	PTFE and MoS_2	
Bar Temp	Barden Corp.	PTFE + fiberglass + MoS_2	PTFE and MoS_2	
Salox M	Allegheny Plastic	PTFE + bronze powders	PTFE and bronze	
SP-2 Polyimide	DuPont	polyimide + graphite	polyimide+graphite	
SP-3 Polyimide		polyimide + MoS_2	polyimide + MoS_2	
Ekonol	Carborundum Co.	PTFE + 95 p-oxybenzol	PTFE	
Feuralon AW	Bemol	polyimide + Ag + WS_2	Ag, WS_2 and polyimide	
Boeing 453-3	Boeing Co.	MoS_2 + Mo + Ta + Ag	MoS_2, Ag	
Fluorosint	Polymer Corp. of America	PTFE + mica	PTFE	

Table 11
Advantages and Disadvantages of Solid Film Lubricant Systems

Advantages	Disadvantages
Low outgassing	Nonreplenishable
No surface migration	No cooling capacity
Broad service temperature range	Wear rate load sensitive (transfer films)
Long-term stability	Roughness higher than with oil (bearings)
Good radiation resistance	High starting torque spikes (transfer films)
High load capacity (bonded films)	Form loose debris (transfer films and nonburnished bonded films)
Use low precision parts	Require greater bearing play (bonded films)
Eliminate labyrinths	Bond degraded by exposure to liquids (bonded films)
Compatibility (bonded films with transfer films)	Usually proprietary

BONDING AND JOINING PROCESSES

John J. Park

INTRODUCTION

The process of joining separate pieces or components solidly together requires thoughtful consideration. For example, the type of materials to be joined (metal-to-metal, metal-to-plastic, metal-to-ceramic, or plastic-to-plastic), the temperature that can be tolerated by each, the required strength or other physical or mechanical properties of the bond, and the ease and the cost of the process must be considered as well as inspectability and repairability when deciding upon the technique for bonding materials. The constraints inherent in certain materials and bonding techniques also must not be overlooked.

The various bonding and joining techniques include welding, brazing, soldering, adhesive bonding, and mechanical joining. A weld joint is obtained by melting together a small portion of similar or compatible alloys. A solder or braze joint is a thin layer of an entirely different alloy which is compatible with both of the metals being joined. Joints that are made using an adhesive layer require a good bond to each member, making surface preparation and adhesive curing important steps. A mechanical joint made with rivets or bolts is localized and nonleakproof; the strength is dependent upon the number of rivets or bolts.

SOLDER

A solder is a low melting point alloy, usually consisting of lead and tin as the major constituents, which joins two metals without fusing or melting the separate pieces. The solder must adhere, react, or bond tightly to each of the metal surfaces, which might be dissimilar alloys. In the soldering process, the melting temperature of the filler metal is usually well below 699 K (800°F). The solder makes its bond by dissolving a small amount of the surface elements of each alloy at a temperature much lower than the alloy's melting point or by reacting with the surface to form compounds.

Solder is most commonly seen as a roll of hollow-core or solid-core wire which is applied manually. However, this is not the only technique for using solder. To solder solar cell connectors, small, thin, preformed disks of solder are placed beneath the connector and then melted. Another technique is to precoat a surface, for example, by dipping the piece into molten solder or by electrodeposition of a solder layer, perhaps 0.0127 mm (0.0005 in.) thick. Electrodeposition is often used on electronic circuit boards.

Only two solders are listed in the GSFC Preferred Parts List (for electronic soldering): SN 60 and SN 63, which have two different types of flux. These solders are 60 percent tin and 63 percent tin, respectively. The 63-percent tin alloy (SN 63) melts at 455 K (360°F), which is the eutectic temperature for tin-lead mixtures, and the 60-percent tin alloy (SN 60) becomes completely molten at 463 K (375°F) but has a liquid-solid mix from 455 K (360°F) to 463 K (375°F).

The identification of the solders, as found in Federal Specification QQ-S-571, includes the letters WRAP or WRMAP, where:

W	identifies the form as Wire
RA	identifies the form as Rosin flux core – Activated
RMA	identifies the form as Rosin flux core – Mildly Activated, and
P	identifies the flux core condition, Plastic (as different from Dry powder).

The GSFC Preferred Parts List will soon include type R solder (Resin Core–nonactivated), which may be used for critical applications, though a good joint may be more easily made using RMA or RA. In order of preference for R, RA, and RMA, the RMA is the most desirable and the RA is the least desirable.

The fluxes are necessary in promoting or accelerating the wetting of the metal surfaces by removing or excluding oxides or other impurities from the joint areas. These fluxes, reactive as they should be, may range from the highly corrosive to the noncorrosive; in any case, the residual flux must be removed by cleaning with the appropriate solvent. The corrosive fluxes are commonly inorganic acids and salts, such as hydrochloric acid, zinc chloride, or sodium fluoride. These corrosive fluxes must be removed by hot water, sometimes acidified, and then removed by a hot water rinse. The intermediate fluxes are mainly mild organic acids or bases, such as lactic acid or urea; their residue is usually soluble in hot water. The rosin residues, as in the R, RA, and RMA, are soluble in both ethyl and isopropyl alcohols, trichloroethylene, and most common organic solvents.

Problems

Cracking encountered in bonding a window of Irtran 4 (polycrystalline zinc selenide) using a tin-silver solder was resolved by the use of pure indium solder. In this case, the plastic deformation of the indium occurs at stress levels that are lower by an order of magnitude than the tin-silver-alloy deformation stress levels; the effect of temperature changes resulted in cracks in the Irtran 4 window when using the tin-silver solder but no cracks when using the indium solder. In addition, the joint area of the Irtran 4 window had to be metallized by vapor deposition before soldering; a titanium-Inconel layer and an Inconel-platinum-gold metallization layer were each separately applied to the Irtran 4 and each was satisfactory.

Problems have been encountered in the soldered solar cell tab-joint on OAO solar paddles. The tabs (electrical leads) lifted as a result of thermal cycling between 344 K and 167 K (+160°F and -160°F), lifting occurring in fewer than 200 cycles. The system consisted of silver-plated copper tabs, lead-tin solder, and vapor-deposited silver on titanium on the solar cell. Extensive investigation of the materials and techniques showed a number of reasons for the lifting. These included contamination of the surface by the silicone solar cell cover adhesive, lack of sufficient filler or lack of sufficient solder joining the tab, and probable reheating of the solder area. The reheating of the solder resulted in a dissolution of the silver plating to form a three-element alloy of lead, tin, and silver. Additional brief heating can increase the melting point of the solder by 5 K (5°C) for each remelt and as much as a 25 K (25°C) increase with repeated remelting. The failure analysis conclusions indicated poor manufacturing techniques. The problem was not related to the solder alloy or its inherent lack of adhesion but more to the technique of applying the solder.

Another problem with tin-lead-silver solder occurred in sealing a gold-plated Kovar lid to the gold-plated Kovar can of a flat-pack device. During testing the lid came off. During failure analysis of the solder region, grainy-appearing surfaces and crystalline areas were observed in the solder. Metallographic examination, X-ray diffraction, and electron probe analysis were used in identifying the intermetallic compounds and in detecting the locations of the reacting elements. The analysis indicated that the formation of gold-lead compounds occurred from the reaction between the solder and the gold plating. Suggested solutions included removal of the gold or use of a thinner gold plating, or substitution of tin-plating for the gold. If temperature limitations would permit, a gold-germanium solder alloy, having a melting point of 633 K (360°C), could be a replacement for the lead-tin solder.

Recommendations

As a first step, one should obtain handbooks on soldering, such as NASA SP-5002 "Soldering Electrical Connections" and NHB5300.4 "Requirements for Soldered Electrical Connections." Such publications will provide useful information on the techniques of soldering. These publications include pictures and drawings to show techniques and joint appearances.

Another problem that can occur with gold plating, mentioned above, is the failure of the solder joint. While gold plating protects the base metal from oxidation or corrosion, more than 5 percent of the gold in the solder results in a brittle joint. Removal of the gold just before soldering will improve the joint. Removal of the gold by using a typewriter eraser or by wicking and removal from a solder cup connector are desirable preliminary steps.

When alcohol is used to dissolve the flux, it is desirable to use the minimum volume of alcohol. It is possible for the solution to "wick up" between the wire lead and its insulation, resulting in corrosion. Stripping of the lead for a short distance and the use of minimal amounts of solvent are simple precautionary steps.

BRAZING

Brazing is a metal joining process, similar to soldering, in which the space between adjacent surfaces is occupied by a relatively thin solidified metal alloy. Brazing also refers to a higher temperature reaction than does soldering, specifically for temperatures of 698 K (425°C) and above. Brazing filler metals usually are nonferrous metals or alloys that have a melting temperature above 698 K (425°C) but below that of the pieces being joined. Brazing filler metals must wet the surfaces to be joined, must flow sufficiently to fill irregular surface areas by capillary action, must be sufficiently stable to remain uniform in composition upon solidification, and must have the required strength and ductility characteristics for particular applications.

Because brazing is by definition a relatively high temperature reaction, caution must be exercised in its use for each particular application. The choice of the filler metal composition must be specific for two metals to be joined. For example, aluminum brazing filler metals are useful for joining two aluminum alloys but are not satisfactory for joining aluminum to copper. Titanium may be brazed using pure silver or a silver alloy filler metal, and beryllium may be brazed using aluminum-silicon filler metals or using a silver +1 percent lithium alloy.

There are different techniques for brazing depending upon the number of items to be brazed and their complexity. Thus, one may torch braze by hand, as in soldering; because of the higher temperatures required in brazing, acetylene or propane torches with oxygen are used. Furnace brazing in gas-fired or electrically heated furnaces is especially suitable for numerous, repetitive joinings. Induction brazing permits a localized heating of a specific area but it also requires careful design of the joint and of the heating coil to ensure that the joining surfaces reach the required temperature at the same time. Dip brazing is carried out by immersing the part with the brazing filler metal into a molten salt as the heat source. The choice of brazing technique to use thus depends upon the parts to be joined, their complexity, and their number.

The brazing filler metal, which forms the joint, must wet the surfaces of the base metals to be joined and must flow properly by capillary action. Various alloys are available as filler metal, such as silicon-aluminum, copper-phosphorus, and copper-gold, but these must be selected for the specific application. The filler metal can be either wire, preformed sheet, or even in the form of parts or powder. In addition, it may be necessary to use a flux or a nonreactive atmosphere to prevent oxidation. The necessity for high temperatures in brazing adds another variable to be considered in deciding how this joint should be made.

Dip brazing should not be attempted without giving careful consideration to the possibility of some warping, particularly in cases where parts having strict dimensional requirements are joined. Another point to consider is the type of material to be subjected to this elevated temperature treatment, specifically with reference to whether or not it is a heat-treatable material.

Problems

Brazing Beryllium

A type of problem often encountered involved the brazing of beryllium. A beryllium piece with 17-μm (0.7-mil) copper plating was brazed with an 88-percent aluminum, 12-percent silicon alloy. This was compared with the braze of an unplated beryllium piece brazed with a 99-percent aluminum alloy. It was found that the copper plating resulted in reactions leading to the formation of hard, brittle compounds in the braze. These compounds consisted of copper-beryllium particles, copper-aluminum particles, and also large silicon crystals. By comparison, the braze area for the unplated beryllium resulted in good penetration into the surface irregularities and a soft, ductile aluminum matrix with uniformly dispersed silicon particles. Recommendations were made that the copper plating be removed and that the aluminum, 12-percent silicon alloy be selected over the 99-percent aluminum braze filler metal to provide a higher strength joint.

Mercury Leaks

All conditions of the brazed system must be considered, as is illustrated by the following mercury leak problem. Mercury leaks occurred in a stainless steel system brazed using a silver solder. The amalgamation of mercury with the silver of the 45-percent silver, 15-percent copper, 16-percent zinc, 24-percent cadmium braze alloy resulted in a leakage path through the braze metal. The solution of the problem is the selection of a silver-free braze alloy. A more desirable solution is to weld the joint, which would provide a nonreactive joint.

Melting Point Considerations

The heaters for the ATS-F cesium ion engine, which could not pass on-off cycling tests to 1273 K (1000°C), provide an example of thermal problems. These sheath heaters consisted of a nichrome wire packed in aluminum oxide, placed in a stainless steel tube. This stainless steel sheath was joined to an outer stainless tube by welding. A braze joint, made by using 88-percent copper, 12-percent nickel alloy which melts at 1393 K (1120°C), was employed to join two tubes adjacent to the heater. By metallographic investigation and electron probe analysis, a copper-rich alloy was found between the sheath and the tube, though this joint had been made by welding. The failure analysis showed that liquid metal corrosion by the copper in the brazing alloy had attacked the stainless steel grain boundaries of the sheath and the tube and had penetrated completely through the wall. This weakened the joint sufficiently to cause separation and resulted in heater failure. Because of conduction and heat losses, temperatures above 1273 K (1000° C) were needed in order to reach the 1273 K operating temperature. Temperatures were well in excess of the melting point of the braze at 1393 K (1120° C) and were reached quickly after turn-on, even though a difference of 120 K was believed to be a sufficient safety factor to avoid braze remelting. The most desirable solution was the substitution of a welded joint for the brazed joint; the use of a heat sink to reduce the temperature of the metals in the area of the braze was feasible but was the less desirable solution.

Recommendations

Prior to brazing, the surfaces of pieces to be mated must be cleaned of grease, oil, surface films, and other contaminants. A flux may be necessary to provide a chemical cleaning or deoxidizing. The relative positions of the separate pieces must be maintained during the heating and cooling phases of the bonding procedure. The heat distribution, heating rate, and the proper brazing temperatures must be carefully controlled. After the brazing, a postcleaning operation may be necessary to remove residual flux.

WELDING

Practically all of the necessary information on good liquid-phase welding practices can be found in the literature, such as the American Welding Society's "Welding Handbook." However, all too often this information is overlooked or ignored.

In welding, it is important to use a good welding specification. Certain precautions should be emphasized:

- Preheating is necessary in order to reduce the cooling rate of the weld metal and the heat-affected zone;
- Stress-relieving or post-heating is necessary to reduce or to equalize the residual stresses within the weld-affected volume;
- Proper fixturing will keep the pieces aligned properly before and after welding;
- Heat-sinking will assist in keeping the heat within the desired weld area, though it should not be so effective as to absorb too much heat and so "quench" the weld; and
- The correct atmosphere for the specific metal, as titanium or beryllium, must be maintained.

It also should be apparent that controllable inputs, such as heat, gas purity, and weld alloy, are all critical factors.

Problems

A specific example of poor technique occurred in the welding of aluminum pipes to an aluminum forging. Cracks appeared in the forging adjacent to the weld zone. The cracks were attributed to excessive heat-sinking by the relatively large forging; a contributing factor was the too-tight fixturing which provided an excessive restraining force.

Spot Welding

Spot welding is a resistance welding process in which a localized molten volume is produced by the heat generated by the electrical resistance to the current flow between the electrodes. The size and shape of the weld nugget are limited primarily by the size and the contour of the electrodes. Force must be applied between the electrode before, during, and after the current surge to ensure a continuous electrical path and to forge the heated parts together.

The operation of spot welding involves the coordinated application of the proper amount of current for the correct time. The current must go through a closed circuit between the electrodes, which are shaped to provide the necessary current density and pressure density. Sufficient heat is generated in a confined volume of metal to melt portions of both metal pieces; the molten portion must be retained while solidifying and forming the joint. The joint is influenced by the electrical current, the time, the electrodes, the surface condition of the metal parts, and the metal composition.

The speed and ease of spot welding makes the technique appear extremely simple. However, certain fundamental properties of the metal pieces being joined can cause some problems. The thermal conductivity and the electrical resistivity of two metals may be widely different and may cause a weld nugget to be wholly in one piece or the other unless the weld parameters are optimized.

- *Nickel-Stainless Steel*–The selection of the spot-welding parameters often depends upon the development of a weld schedule for the specific alloys. In one instance, the welding of a 0.0635-mm-thick by 50.8-mm-diameter (0.025-in.-thick by 2-in.-diameter) stainless steel shell to a 0.17-mm-thick by 6.35-mm (0.007-in.-thick by 0.25-in.) strip of nickel resulted in the weld nugget being confined solely to the stainless steel. In this instance the difficulty lay primarily in the large heat imbalance caused by the lower thermal and electrical conductivity of the stainless steel and the unfavorable size ratio of the two pieces. A series of test spot welds utilizing various power settings were examined metallographically after being pull-tested; information derived from these welds helped in the establishment of the proper weld parameters. The resultant weld schedule of 25 watt-seconds at 12.7 kg (28 lb) produced good interpenetration of the nickel and of the stainless steel, good bond strengths, and a sound, nonporous weld nugget.
- *Kovar-Nickel*–In a similar manner, the spot welds of a Kovar cup, 1.43 cm (9/16 in.) high, 4.77 mm (0.188 in.) outer diameter, 0.38 mm (0.015 in.) wall thickness, and 1.60 mm (0.063 in.) bottom thickness, to a nickel strip 0.78 mm (0.031 in.) thick, were examined because of poor welds. The weld nuggets were confined almost entirely to the Kovar. The problem was basically one of achieving a heat balance across the parts being welded so that the interface between the Kovar and the nickel has a higher resistance than either the electrode-work piece interfaces or the bulk of the material being welded. Following a series a weld changes and the metallographic examinations, the recommendations included: reduce the thickness of the Kovar cup bottom from 1.60 mm to 0.75 mm (0.063 in. to 0.030 in.); use a 3.17-mm (1/8-in.) diameter domed tungsten electrode against the nickel; inspect the electrode surface after each weld; and replace the electrodes after every fifth weld.

OTHER TECHNIQUES

While it is unlikely that the designer can specify a particular welding technique, it may be useful to review a number of joining processes in current use such as TIG, MIG, laser, and electron beam.

Tungsten-Inert-Gas (TIG) Welding

Tungsten-inert gas provides the acronym for TIG welding and partially describes the method, but the procedure is actually gas tungsten-arc welding. This is an arc welding process that utilizes a nonconsumable electrode of tungsten and has a gas to protect the metal being welded. Ideally, the tungsten does not melt and drop into the area of the weld. The electrode, the puddle of molten metal, and the adjacent areas must all be protected by the flowing gas. The gas must be nonreactive with the welded pieces and is usually argon gas, helium gas, and argon-helium or argon-hydrogen mixtures. The gas must be pure and only "welding grade" gas is safe to use. Notwithstanding the fact that this is a highly sophisticated process, it has become perhaps the most universal joining technique available; however, it is a rather slow process when welding large thick plates. For example, with a 6.6-m (260-in.) diameter rocket motor with a wall thickness of 1.5 cm (0.6 in.), more than 12 passes were used to make the joint.

Metal-Inert-Gas (MIG) Welding

Metal-inert-gas (MIG) welding is a considerably faster welding process; however, there can be a high incidence of porosity. Consequently, the TIG welding process often should be used in order to meet radiographic requirements which are set forth in the various specifications.

MIG welding occurs with the formation of an arc between a consumable electrode and the work piece. The metal electrode is a bare solid wire of unlimited length, and it is melted to become the filler metal in the desired area. Note that the electrode is consumed and it is extremely long, as opposed to the short (perhaps 25-cm long) electrode of the more common arc welding. The inert gas flows past the electrode and must also protect the molten tip of the electrode, the weld puddle, the arc, and the whole surrounding area from oxidation or reaction. MIG welding is not solely an inert gas technique, since carbon dioxide and argon plus controlled percentages of oxygen are used, as well as argon, helium, and nitrogen. Choices of weld metal and of protective gas depend upon the metals being joined. For example, carbon dioxide is the proper gas for carbon and low alloy steels if one uses a deoxidizing electrode wire; helium is the choice for aluminum and copper alloys; but argon may be used for virtually all metals.

The advantages of MIG welding include continuous electrodes of any necessary length, the absence of slag from any flux, and the use of smaller diameter electrodes which permit a higher current density and greater weld-metal deposition rate. The disadvantages, when compared to the shielded-arc process, include the possibility of weld cracking due to the absence of a flux to reduce the cooling rate; the use of the inert gas which may be disturbed by air currents, especially when welding outdoors; the need to get quite close to the weld area, which may be a problem in reaching confined or inconvenient areas; and the higher cost of the equipment.

Electron-Beam Welding

The electron beam can be easily generated at the cathode but the stream of electrons must be accelerated, collimated, and focused at the desired area for the weld. The focusing of the electrons may be as small as 0.3 to 0.9 mm (about 0.01 to 0.03 in.), but the beam may have a power density of about 1.6 X 10^4 watts/cm^2 (10^5 watts/in.^{2}), which is sufficient to vaporize metals. The electron beam and the work piece must be enclosed in a vacuum of 1.3 X 10^{-3} N/m^2 (10^{-5} torr) or better. This information implies some of the disadvantages of electron-beam welding, namely: the cost of the equipment, the necessity of having the work piece within the vacuum chamber, and the necessity of proper alignment and holding of the welded pieces within the vacuum. However, there are certain advantages, such as the ability to make deep, narrow, and less tapered welds than arc welding provides and with a lower total heat input; excellent control over the weld dimension and properties; and the cleanliness of the weld, all of which tend to ensure consistent quality and joint integrity.

Laser Welding

Aside from the fact that lasers have other uses in measuring, sighting, and aligning, the concentrated laser beam may also be of sufficient power to melt metals. The laser (from "light amplification by stimulated emission of radiation") achieves its power from the release of energy as an atom returns from the "excited" state to the "ground" state. Rather than describe the workings of the laser, it should be sufficient to say that the released photons are coherent, namely, being in the same direction, in phase, and of the same wavelength. There may be different crystals, such as doped ruby (Al_2O_3 doped with a little Cr_2O_3), carbon dioxide gas carrier, helium-neon gas, or YAG (yttrium-aluminum-garnet), all containing excited atoms and able to release the energy in a coherent wave. The beam may be focused and concentrated at a desired spot to achieve melting, cutting, or welding of even the refractory metals.

Recommendations

In automatic spot welding it is highly desirable that an evaluation of the variables related to the welding apparatus, the electrodes, and the materials be carried out to ensure achieving consistent, reliable welds. An isostrength diagram should be constructed, and a number of weld joints made by varying the power input and the time; the weld joints should be tensile tested. In conjunction with metallographic examination, the proper range of power settings to give consistently strong welds can be determined. It is also important that a periodic calibration of the equipment be undertaken to ensure that the isostrength diagram is not being altered by unexpected equipment errors.

ADHESIVES

Adhesives have many advantages in spacecraft joining applications. Adhesives produce a continuous bond to distribute stress loads more uniformly over the area being joined and can join sheet to frames, heavy gage metal to thin gage metal, or metals to nonmetals. Adhesives can be flexible, which improves the resistance to vibrational fatigue and permits the transfer and distribution of stresses. In providing a continuous contact between mating surfaces, adhesives also act as a sealant and a liquid barrier. Adhesives can produce a joint that has no external projections nor surface irregularities. Joints can be made simultaneously at room temperature and on large areas. The ease of application, along with the above advantages, make adhesives a very attractive bonding technique.

The selection of the adhesive is dependent upon the function of the completed structure. Factors to consider include bond strength (peel, shear, or tensile strength), fabrication techniques, cure times or temperatures, or unique requirements. The adhesive for holding a 2-cm by 2-cm by 2-mm glass cover slide to a solar cell will be different than the adhesive used in structural honeycomb. Additionally, the techniques of applying these two adhesives will be very different.

Problems

Solar cell covers were adhered by using the Dow Corning XR-6-3489 adhesive. After machine soldering the solar cell interconnects, it was found that a large number of the covers were delaminated. Upon prying off the covers, it was also found that the adhesive was slightly tacky, even though the adhesive had been cured 4 hours at 338 K (65°C). The dual problem was a dirty surface on the cover and the uncured adhesive. A procedure to clean the covers to a water-drop-free condition was developed, which greatly improved adhesion. The adhesive was changed to the room-temperature-curing Dow Corning 93-500, though a later test showed that the XR-6-3489 cured after an additional one hour at 373 K (100°C).

Recommendations

The use of adhesives is relatively simple, although certain precautions should be observed. Certain one-component adhesives, none of those listed below, release acetic acid as they cure; the one-component Dow Corning C-6-1104 gives off the less harmful methanol. In using the two-component adhesives, be sure to check the shelf life remaining and avoid using outdated materials. Storage at temperature below 305 K (90°F) is required, and refrigerated storage extends the shelf life. In mixing the adhesives, use only glass, plastic, or metal containers and a glass or metal stirring rod in order to avoid the absorption of components or the release of poisoning compounds. The mixture should be degassed briefly in a vacuum of about 1.3×10^3 N/m^2 (10 torr) to remove the entrapped air.

The adhesive should be applied to clean, dry surfaces. Clean and degrease the metal or plastic surfaces and wipe with a solvent such as acetone. Rubber surfaces should be roughened, as with sandpaper, to improve adhesion and then should be wiped off with acetone. Maximum adhesion is obtained by using a primer, which should dry for up to an hour in air.

In applying the adhesive, the thickness of the adhesive layer should be about 0.25 to 0.38 mm (10 to 15 mils), though for solar cell covers the adhesive thickness is from 0.038 to 0.075 mm

(0.0015 to 0.003 in.). When applied as a thin film of 0.076 mm (0.003 in.), the Dow Corning 93-500 must not be exposed uncovered for more than 90 minutes or a significant loss of catalyst may occur. All adhesives may have their own idiosyncrasies, and, consequently, the information in the manufacturer's literature should be followed.

The use of adhesive films or sheets, such as for honeycombs, often involves those types which must be kept refrigerated before use. The proper storage of such adhesives is important, and the storage life must be closely followed. In addition, these are used by applying temperature and pressure to the honeycomb components of up to 438 K (165°C) and 10×10^4 N/m^2 (15 psi).

In Appendix C, a wide assortment of adhesives for various applications, along with their respective outgassing data, is given. The adhesives had been tested for their outgassing in the standardized screening test, which involves determining the total mass loss (TML) at 398 K (125°C) for 24 hours in a vacuum of 1.3×10^{-4} N/m^2 (10^{-6} torr) and determining the collected volatile condensable materials (CVCM) at 298 K (25°C) for the same 24 hours in the same vacuum system.

APPENDIX A

THIXOTROPIC COATING

PROCEDURE FOR INSULATING WITH A THIXOTROPIC COATING

1. Weigh out 30.0 g of fresh (from an unopened can and less than two months old) Solithane C-113* and 3.4 g of dried Cab-o-sil into a 250 cc glass beaker. (The Cab-o-sil must have been previously preheated at 423 K (150°C) for 48 hours in a clean shallow pan to remove moisture). Blend thoroughly with a stainless steel spatula or stirrer. If the *dry* Cab-o-sil is not used, improper cure will occur.

2. Weigh out the remaining ingredients, and add to the above:

   21.9 g of fresh Solithane C-113-300;
   0.05 g of Vyac Luminescer 174;
   0.05 g of dibutyl tin dilaurate, and blend thoroughly.

3. Place prepared blend in a vacuum chamber at 0.133 N/m^2 (10^{-3} torr) or lower for 6 to 8 minutes to remove occluded air. During this period, the chamber pressure should be cycled from 0.133 N/m^2 (10^{-3} torr) to atmospheric pressure several times ('bumped') to facilitate air elimination.

4. Remove blend from chamber and transfer via spatula to the pressure gun dispenser cartridge, being extremely careful not to entrap air bubbles.

5. The gun dispenser is then locked and pressurized with from 413×10^3 to 482×10^3 N/m^2 (60 to 70 psi) of ultra-dry nitrogen. The viscous thixotropic resin is applied in and around the insulated cable wires and connector pins by easily controlled trigger action.

6. Upon completion of Step 5, it is important that the resin be inspected for air bubbles, uncoated areas, and pin holes. These defects are easily observed with an ultraviolet lamp and should be corrected at this time by removing or adding resin as needed. The dye fluoresces a light blue-green color when activated by a 3650-Å excitation source.

7. The resin has a long pot life and may be allowed to cure at room temperature for one week. After 48 hours, the surface is almost tackfree. An option for faster curing would be to initially gel the resin at 306 K (33°C) for 2 hours, followed by 316 K (43°C) for 2 hours, and 338 K (65°C) for one hour. This is a complete application process in itself.

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*Sources are listed on the following page.

However, requests for additional information indicating how this initial insulation application is related to the process of RF shielding unprotected wire between braid shielding and connector is also available.

SOURCES OF MATERIAL

1. Solithane C-113	Thiokol Chemical Company Trenton, New Jersey
2. Solithane C-113-200	Thiokol Chemical Company Trenton, New Jersey
3. Cab-o-sil MS 5	Cabot Corporation Boston, Massachusetts
4. Vyac Luminescer 174	American Cyanamide Bound Brook, New Jersey
5. Dibuty Tin Dilaurate (T-12)	General Electric Company Waterford, New York
6. Brookfield Mixer Model L-2789	Brookfield Engineering Laboratory Stoughton, Massachusetts
7. Ultra-Violet Lamp UVSL 25	Ultra Violet Products San Gabriel, California
8. Resin Dispenser - Model 102 Kit Nozzle 2" with 0.065" orifice. 20 cc - capacity cartridge	Kenics Corporation Wakefield, Massachusetts
9. Nitrogen-Ultra-dry	Local Source

APPENDIX B

LOW OUTGASSING POTTINGS AND CONFORMAL COATINGS

There are extensive numbers of potting and conformal coating materials. Those materials which have low outgassing rates are listed in the following tables.

Table B-1
Low Outgassing Pottings

Material	Manufacturers Code	Code*	Composition	Comments and Previous Cure History	Percent Weight Loss	Percent Condensables	Data Source *
Epoxy	AV-100/HV 100	CI	AR	7 day R.T.	0.78	0.10	GSFC
Epoxy	Bacon Ind.	BN	AR	4 hr. 71°C + ** 16 hr. 100°C	0.12	0.01	GSFC
Epoxy	BSL 208	CI	AR	1 hr. 164°C	0.82	0.11	GSFC
Epoxy	BSL 308	CI	AR	1 hr. 175°C	0.49	0.10	GSFC
Epoxy	EC 1751 A/B	NM	50p./1751 A 100p./1751 B 15p./phenyl glycidyl ether	24 hr. R.T.	0.75	0.06	GSFC
Epoxy	Eccomold L-28	EC	AR	64 hr. 127°C	0.18	0.01	GSFC
Epoxy	Eccoscal 1207/20	EC	100p. 1207/1.5p. 20	4 hr. 71°C + 1 hr. 177°C	0.27	0.01	GSFC
Epoxy/iron	Eccosorb MF 112	EC	AR	AR	0.26	0.01	GSFC
Epoxy/iron	Eccosorb MF 114	EC	AR	AR	0.22	0.01	GSFC
Epoxy	Epocast N4E-053	FU	AR	24 hr. R.T. + 2 hr. 93°C	0.07	0.02	GSFC
Epoxy	Epon 828/A	SH	100p. 828/8p.A	3 hr. 95°C	0.70	0.06	SRI
Epoxy	Epon 826/Z	RO	100p. 826/20p.Z	2 hr. 77°C + 2 hr. 135°C	0.91	0.02	JPL
Epoxy	Epon 828/Z	SH	100p. 828/20p.Z	2 hr. 75°C + 2 hr. 135°C	0.42	0.03	SRI
Epoxy/versam.	Epon 828/140	GS	50p. 828/50p.140	24 hr. R.T.	0.20	0.02	GSFC
Epoxy/semirigid	Epon 828/871/AEP	GS	35p./828 65p./871 15.5p./AEP	12 hr. R.T.	0.86	0.05	GSFC

* Code to sources follows Table B-2.

** Conversion from °C to K, add 273° to °C values.

Table B-1
Low Outgassing Pottings (continued)

Material	Manufacturers Code	Code*	Composition	Comments and Previous Cure History	Percent Weight Loss	Percent Condensables	Data Source*
Epoxy/semirigid	Epon 828/871/AEP	GS	40p./828 60p./871 15.5p./AEP	18 hr. 65°C	0.46	0.02	GSFC
Epoxy	Epon X-24	SH	AR	10 hr. 100°C	0.42	0.05	GSFC
Epoxy	Epotek-301 A/B	ET	20p.A/5p.B spectrally transparent	24 hr. R.T.	1.08	0.01	GSFC
Epoxy	HP-16-92	HA	100p. DER 332 LC/18p. HV	5 hr. R.T. + 12 hr. 90°C + 24 hr. 90°C P.C.	0.33	0.02	GSFC
Epoxy	Hysol C9-4188/3469	HY	10p. 4188/.75p. 3469	1 hr. R.T. 1 hr. 49°C 1 hr. 171°C	1.01	0.08	JPL
Epoxy	Hysol C9-4188/3469 Ferro V-780	HY	10p. 4188/.75p. 3469	1 hr. R.T. 1 hr. 49°C 1 hr. 171°C	0.96	0.03	JPL
Epoxy	Hysol C9-5340/3426	HY	100p.5340/8.3p.3426	8 hr. R.T.	0.60	0.05	GSFC
Epoxy	Hysol R8-2038/ H2-3475	HY	AR	24 hr. R.T.	0.53	0.01	GSFC
Epoxy	Hysol XC9-G710/ H2-3561	HY	AR	AR	0.90	0.02	GSFC
Epoxy	Hysol 0151	HY	AR	24 hr. R.T.	0.78	0.02	GSFC
Epoxy	Maraset 655/553	MR	100p.655/20p.553	16 hr. 82°C	0.59	0.01	SRI
Epoxy	Maraset 655/553	MR	100p.655/20p.533	16 hr. 82°C + 24 hr. 150°C	0.32	0.01	SRI
Epoxy	Maraset 655/555	MR	100p.655/7p.555	16 hr. 82°C	0.41	0.01	SRI
Epoxy	Maraset 655/555	MR	100p.655/7p.555	16 hr. 82°C + 24 hr. 150°C	0.25	0.01	SRI

* Code to sources follows Table B-2.

Table B-1
Low Outgassing Pottings (continued)

Material	Manufacturers Code	Code*	Composition	Comments and Previous Cure History	Percent Weight Loss	Percent Condensables	Data Source*
Epoxy	MPC 52	GE	AR	4 hr. R.T. + 2 hr. 66°C	0.17	0.01	GSFC
Epoxy	MY 750/HY 974	CI	AR	30 hr. 60°C	0.19	0.01	GSFC
Epoxy	MY 750/HY 974	CI	AR	.75 hr. 100°C	0.27	0.03	GSFC
Epoxy	R-179	RD	aliphatic epoxy	.5 hr. 160°C	0.81	0.03	GSFC
Epoxy	R-6005	RD	aliphatic epoxy	10 min 160°C	0.82	0.03	GSFC
Epoxy	Scotchcast 260	MM	AR	.5 hr. 150°C	0.52	0.03	SRI
Epoxy	Scotchcast 281 A/B	MM	100p.A/150p.B	20 hr. 75°C	0.36	0.05	SRI
Epoxy	Scotchcast 282 A/B	MM	2p.A/3p.B	20 hr. 75°C	0.74	0.10	JPL
Epoxy	SMRD 49	GE	AR	AR	0.98	0.05	GSFC
Epoxy	Stycast 1263/31	EC	100p.1263/3p.31	16 hr. 107°C	0.12	0.01	SRI
Epoxy	Stycast 1269 A/B	EC	100p.A/100p.B	16 hr. 100°C + 24 hr. 150°C	0.18	0.05	SRI
Epoxy	Stycast 2651/9	FW	AR	AR	0.23	0.01	GSFC
Epoxy	Stycast 2651/11	EC	AR	AR	0.14	0.01	GSFC
Epoxy	Stycast 2850 FT/9	EC	100p.2850FT/3p.9	AR	0.25	0.01	GSFC
Epoxy	Stycast 2850 FT/9	EC	100p.2850FT/3.5p.9	16 hr. 25°C	0.34	0.04	SRI
Epoxy	Stycast 2850GT/11	EC	100p.2850GT/4-5p.11	40 hr. 54°C	0.85	0.03	JPL
Epoxy	Stycast 2850GT/11	EC	AR	AR	0.33	0.02	JPL
Epoxy	Stycast 2862 A/B	EC	100p.A/100p.B	16 hr. 120°C 24 hr. 150°C	0.01	0.01	SRI
Epoxy	Stycast 2862 A/B	EC	100p.A/100p.B	16 hr. 120°C	0.32	0.04	SRI
Epoxy	Stycast 3050/11	EC	100p.3050/9.5p.11	16 hr. 77°C	0.68	0.06	SRI

* Code to sources follows Table B-2.

Table B-1
Low Outgassing Pottings (continued)

Material	Manufacturers Code	Code*	Composition	Comments and Previous Cure History	Percent Weight Loss	Percent Condensables	Data Source *
Epoxy	Trucast 111/ Trucure 901	FW	100p.111/34p.901	24hr. R.T.	0.36	0.01	GSFC
Epoxy	2850/24LV	EC	AR	24 hr. 49°C + 24 hr. 60°C	0.73	0.10	GSFC
Epoxy/syntactic	MPC 49	GE	AR	4 hr. R.T. + 2 hr. 66°C	0.52	0.01	GSFC
Epoxy/syntactic	MPC 49	GE	AR	18 hr. R.T. + 2 hr. 66°C	0.39	0.01	GSFC
Epoxy/versam.	Type II Class 2.	HA	35p.DER332LC/30p.140	3 hr. 71°C	0.92	0.05	GSFC
Polyethylene	Stycast TPM-4	EC	AR	16 hr. 107°C 4 hr. 121°C 4 hr. 135°C	0.23	0.08	JPL
Silicone	77-002	DC	10p.77-002/1p.cat.	7 day R.T.	0.31	0.02	JPL
Silicone	77-002	DC	10p.77-002/1p.cat.	4 hr. 65°C	0.39	0.06	JPL
Silicone	93-500/cat.	DC	10p.93-500/1p.cat.	24 hr. R.T.	0.29	0.01	GSFC
Silicone	93-500/cat.	DC	10p.93-500/1p.cat.	7 day R.T.	0.22	0.02	JPL
Silicone	93-500/cat.	DC	10p.93-500/1p.cat.	7 day R.T.	0.16	0.01	GSFC
Silicone	E691-22E	DC	Sylgard 184 stripped of low molecular weight fraction by Dow Corning Corp.	AR	0.19	0.04	SRI
Silicone	RTV 11/T-12	GE	100p.11/2p.T-12	24 hr. R.T. 24 hr. 130°C	0.33	0.10	JPL
Silicone	RTV 566 A/B	GE	100p.A/.1p.B	24 hr. R.T.	0.14	0.02	GSFC
Silicone	RTV 566 A/B	GE	100p.A/.2p.B	24 hr. R.T.	0.25	0.03	GSFC
Silicone	RTV 566 A/B	GE	100p.A/.1p.B	7 day R.T.	0.07	0.04	JPL

* Code to sources follows Table B-2.

Table B-1
Low Outgassing Pottings (continued)

Material	Manufacturers Code	Code*	Composition	Comments and Previous Cure History	Percent Weight Loss	Percent Condensables	Data Source*
Silicone/clear	SC-GSFC-19C	GS	12p.RTV602 devol. + .031p. SRC-05 cat.	G.E. prepolymer 602 heated 24 hr. 150°C 1.33 X 10^{-4} N/m^2 (10^{-6} torr) at GSFC to visc. of 2000-2200 centipoise and cooled prior to catalyzing 7 day R.T. cure	0.35	0.02	GSFC
Polyurethane	–	EM	100p. Sol. 113 51p. Sol.C-113-300 4.5p. Sol.C-113-328 10p. Eccosphere-SI	16 hr. 57°C	0.53	0.01	GSFC
Polyurethane	–	GS	150p. Adiprene L-100 16.5p. MOCA	3 hr. 100°C	1.06	0.06	GSFC
Polyurethane	–	GS	100p. Sol. 113 73p. Sol. C-113-300 4 drops T-12	7 day R.T.	0.37	0.01	GSFC
Polyurethane	–	GS	100p.Sol. 113 73p. Sol. C-113-300 6p. Cab. MS-5 4 drops T-12	7 day R.T.	0.42	0.01	GSFC
Polyurethane	–	GS	100p. Sol. 113 73p. Sol. C-113-300 10.4p. Cab. MS-5 4 drops T-12	7 day R.T.	0.40	0.01	GSFC
Polyurethane	–	GS	100p. Sol. 113 73p. Sol. C-113-300 7.8p. Cab. MS-5 .086p. Vyac 4 drops T-12	7 day R.T.	0.37	0.01	GSFC

* Code to sources follows Table B-2.

Table B-1
Low Outgassing Pottings (continued)

Material	Manufacturers Code	Code*	Composition	Comments and Previous Cure History	Percent Weight Loss	Percent Condensables	Data Source *
Polyurethane	–	GS	100p. Sol. 113 73p. Sol. C-113-300 7.8p. Cab. MS-5 .040p. Vyac	16 hr. 70°C	0.42	0.01	GSFC
Polyurethane	–	GS	100p. Sol. 113 73p. Sol. C-113-300 10.4p. Cab. MS-5 .02p. Vyac 4 drops T-12	7 day R.T.	0.38	0.02	GSFC
Polyurethane	–	GS	100p. Sol. 113 73p. Sol. C-113-300 6.9p. Cab. MS-5 .04p. Rhodamine base 4 drops T-12	7 day R.T.	0.31	0.01	GSFC
Polyurethane	–	GS	100p. Sol. 113 51p. Sol. C-113-300 4.5p. Sol. C-113-328	18 hr. 70°C	0.34	0.01	GSFC
Polyurethane	–	GS	100p. Sol. C-113 36.5p. Sol. C-113-300 7.5p. Sol. C-113-328	7 day R.T.	0.31	0.02	GSFC
Polyurethane	–	GS	100p. Sol. C-113 36.5p. Sol. C-113-300 7.5p. Sol. C-113-328	20 hr. 70°C	0.30	0.02	GSFC
Polyurethane	–	GS	100p. Sol. 113 73p. Sol. C-113-300	5 hr. 54°C	0.51	0.09	JPL
Polyurethane	–	GS	100p. Sol. 113 73p. Sol. C-113-300 87p. Al powder, MD5100	7 day R.T.	0.69	0.09	GSFC

* Code to sources follows Table B-2.

Table B-1
Low Outgassing Pottings (continued)

Material	Manufacturers Code	Code*	Composition	Comments and Previous Cure History	Percent Weight Loss	Percent Condensables	Data Source *
Polyurethane	Conath.RN1510	RD	AR	20 min 149°C	1.09	0.10	GSFC
Polyurethane	Hysol 13-105/MOCA	HY	100p.13-105/13p.MOCA	3 hr. 100° + 30 day R.T.	1.09	0.08	GSFC
Polyurethane	PC-22	HY	AR	Sh. 66°C	0.72	0.01	GSFC
Polyurethane	PR 1527 A/B	PD	26p.A/100p.B	5 day R.T. 72 hr. 52°C 1 X 10^{-6}	0.92	0.10	GSFC
Polyurethane	PR-1538	PR	AR	20 hr. 70°C	0.97	0.02	GSFC
Polyurethane	RB-8-133B	AO	AR	7 day R.T.	0.75	0.01	GSFC
Polyurethane	Stycast CPC-41A/B	EC	100p. A/120p. B	48 hr. 65°C + 24 hr. 150°C	0.58	0.10	SRI
Polyurethane	240-2	AB	AR	7 day R.T.	0.44	0.07	GSFC

* Code to sources follows Table B-2.

Table B-2
Low Outgassing Conformal Coatings

Material	Manufacturers Code	Code*	Composition	Comments and Previous Cure History	Percent Weight Loss	Percent Condensables	Data Source*
Epoxy	PCA/16	EC	100p.A/2p.16	1 hr. 25°C + ** 2 hr. 95°C + 2 hr. 150°C	0.18	0.02	SRI
Epoxy	SMRD 100A/B	GE	57p.A/44p.B	16 hr. 100°C	0.46	0.04	GSFC
Epoxy	Stycast 1467/9	EC	100p.1467/7p.9	18 hr. R.T. + 1 hr. 77°C	0.14	0.01	GSFC
Epoxy/versam.	Epon 828/140	RO	70p. 828 30p. 140 1 p.SR-82	1 hr. R.T. + 2 hr. 60°C	0.27	0.02	GSFC
Polyester/imide	Isomid	SC	AR	Air dry + 2 min. 204°C	0.44	0.03	GSFC
Fluorocarbon	Fluoroclad V78-VP21	SW	AR	Air dry + .5 hr. 93°C + 25 hr. 260°C	0.05	0.01	GSFC
Fluorosilicone	94-003-dispersion	DC	AR	75 day R.T.	0.18	0.01	GSFC
Polyurethane	FC-GSFC-20/w	GS	100p. Sol. 113 73p. Sol. C-113-300 .25p. TiO_2 1 drop T-12	7 day R.T.	0.29	0.01	GSFC
Polyurethane	JPL 1002	AB	AR	4 hr. 75°C	0.19	0.02	SRI
Polyurethane	JPL 1001	AB	AR	4 hr. 75°C	0.20	0.10	SRI
Polyurethane		TH	100p. Sol. 113 73p. Sol. C-113-300	5 hr. 54°C	0.51	0.09	JPL
Polyurethane	–	GS	100p. Sol. 113 73p. Sol. C-113-300	22 hr. 70°C	0.31	0.01	GSFC
Polyurethane	–	GS	100p. Sol. 113 150p. Sol. C-113-300	7 day R.T.	0.37	0.09	GSFC

* Code to sources follows Table B-2.

** Conversion from °C to K, add 273 to °C values.

Table B-2
Low Outgassing Conformal Coatings (continued)

Material	Manufacturers Code	Code*	Composition	Comments and Previous Cure History	Percent Weight Loss	Percent Condensables	Data Source*
Polyurethane	–	GS	100p. Sol. 113 150p. Sol. C-113-300	18 hr. 50°C	0.31	0.04	GSFC
Polyurethane	–	SB	100p. Sol. 113 51p. Sol. C-113-300 4.5p. Sol. C-113-328 20.5p. B-35A gl. bubbles	16 hr. 38°C	0.21	0.01	GSFC
Polyurethane	RCA-A-4875	RO	100p.1155A/70p.1155B + 30p. cellosolve acetate	10 min R. T. + .25 hr 49°C for each of two coats + 3 hr 60°C final	0.81	0.05	GSFC

* Code to sources follows Table B-2.

Code to Sources

Code	Sources
AB	Ablestik Adhesive Company
AO	Allaco
BN	Bacon Industries
CI	Ciba Corporation
DC	Dow Corning Corporation
EC	Emerson & Cuming Incorporated
EM	EMR Company
ET	Epoxy Technology Incorporated
FU	Furane Plastics Incorporated
FW	Fenwall Company
GE	General Electric Company
GS	Goddard Space Flight Center
HA	Hughes Aircraft Corporation
HY	Hysol Corporation
MM	Minnesota Mining and Manufacturing Company
MR	Marblette Corporation
NM	National Metallizing Company
PD	Products Research Incorporated
PR	Products Research & Chemical Corporation
RD	Resdell Company
RO	Radio Corporation of America
SB	Santa Barbara Research Center
SC	Schenectady Chemical Company
SH	Shell Chemical Company
SW	Sherwin Williams Paint Company
TH	Thiokol Chemical Company

Data Sources

GSFC	Goddard Space Flight Center
JPL	Jet Propulsion Laboratory
SRI	Stanford Research Institute

APPENDIX C

ADHESIVES

There are an extensive number of potential spacecraft adhesives. However, with the additional space requirement of low outgassing, only those adhesives which have acceptably low outgassing as determined with the Micro-VCM apparatus are listed. The cure listed is the lowest temperature cure which resulted in an acceptable outgassing profile. The adhesives are subdivided into potential uses.

The adhesives may be two-component mixture or even three-component; the components are given in order in their respective amounts along with the necessary temperature cure. In addition, the outgassing data for total mass loss (TML) and for collected volatile condensable materials (CVCM) are given.

GENERAL ADHESIVES	% TML	% CVCM
Ablebond 41-5 30 minutes at 423 K (150°C)	0.46	0.01
Ablebond 41-6 30 minutes at 423 K (150°C)	0.34	0.01
Ablebond 224-8 A/B as 100 A/7.3 B by weight (BW) 1 hour at 325 K (52°C)	0.40	0.00
Armstrong A31 A/B as 6 A/4 B BW 2 hours at 333 K (60°C)	0.56	0.03
Armstrong A-271 A/B as 7 A/3 B BW 14 days at 298 K (25°C)	0.73	0.02
Armstrong C7/W as 1 C7/1W BW 21 days at 298 K (25°C)	0.36	0.02
Armstrong C7/W as 2 C7/3W BW 7 days at 298 K (25°C)	0.81	0.10
AY 105/HY 951 as 100 AY 105/12 HY 951 BW 3 hours at 338 K (65°C)	0.61	0.05

	% TML	% CVCM
Bondmaster E645 A/B as 10 A/3 B BW 1 hour at 373 K (100°C) plus 4 hours at 453 K in 1.3 N/m^2 (180°C in 10^{-2} torr) vacuum	0.50	0.01
Bondmaster 620 2 hours at 353 K (80°C) plus 1 hour at 423 K (150°C) plus 2 hours at 473 K (200°C)	0.75	0.03
BR 34 30 minutes at 298 K (25°C) plus 30 minutes at 377 K (104°C) plus 90 minutes at 450 K (177°C)	0.66	0.00
Chemlok 220 30 minutes at 298 K (25°C) plus 10 minutes at 433 K (160°C)	0.39	0.01
Conap K-20 A/B as 20 A/9 B BW 2 hours at 323 K (50°C) plus 30 minutes at 358 K (85°C)	0.75	0.05
Crest 3135/7111 as 1/1 BW 24 hours at 298 K (25°C)	0.47	0.01
Crest 7343/7139 as 100/11 BW 3 days at 298 K (25°C)	0.85	0.10
DC 6-1104 7 days at 298 K (25°C)	0.19	0.01
DC 93-500 as 10/1 BW 24 hours at 298 K (25°C)	0.16	0.00
DER 332 LC/Versamid 140 as 6/7 BW 12 hours at 313 K (40°C)	0.55	0.02
Easypoxy K-20 A/B as equal lengths A/B 24 hours at 298 K (25°C)	0.65	0.01
Easypoxy K-40 A/B as equal lengths A/B 24 hours at 298 K (25°C)	0.60	0.02
Easypoxy K-256 A/B as equal lengths A/B 24 hours at 298 K (25°C)	0.60	0.04

	% TML	% CVCM
Eccobond 51/9 as 100/7 BW 24 hours at 298 K (25°C)	0.44	0.02
Eccobond 276/cat 17 as 10/1 BW 2 hours at 353 K (80°C) plus 1 hour at 423 K (150°C) plus 2 hours at 473 K (200°C)	0.49	0.01
Eccobond 285/9 as 25/1 BW 24 hours at 298 K (25°C)	0.49	0.01
Eccobond 285/11 as 20/1 BW 8 hours at 355 K (82°C)	0.28	0.01
Eccobond 285/24LV as 25/2 BW 24 hours at 298 K (25°C)	1.00	0.01
Epibond 123/cat 952 as 20/3 BW 24 hours at 298 K (25°C)	0.63	0.03
Epibond 123/cat 9615-10 7 days at 298 K (25°C)	0.86	0.03
Epibond 1210/9615 as 100/65 BW 3 hours at 339 K (66°C)	0.66	0.02
Epibond 8510 A/B as 10/3 BW 5 days at 298 K (25°C)	0.05	0.00
Epon X-24 15 minutes at 333 K (60°C) plus 45 minutes at 298 K (25°C) and pressure plus 4 hours at 298 K (25°C) plus 10 hours at 373 K (100°C)	0.42	0.05
Epon 820/TETA as 10/1 BW 3 days at 298 K (25°C)	0.43	0.06
Epon 828/EM 308 as 2/1 BW 30 hours at 298 K (25°C) plus 72 hours at 324 K and 0.00013 N/m^2 (51°C and 10^{-6} torr)	0.86	0.01
Epon 828/TETA as 10/1 BW 3 days at 298 K (25°C)	0.51	0.01
Epon 828/Versamid 125/MD as 100/21/13 4 hours at 344 K (71°C)	0.70	0.02

	% TML	% CVCM
Epon 828/Versamid 140 as 1/1 BW 24 hours at 298 K (25°C)	0.41	0.03
Epon 828/Versamid 140 as 6/4 BW 24 hours at 298 K (25°C)	0.74	0.05
Epon 929 1 hour at 422 K (149°C)	0.60	0.01
Epon 934 A/B as 100/33 BW 7 days at 298 K (25°C)	0.28	0.01
Epon 956 A/B as 100/58 BW 7 days at 298 K (25°C)	0.19	0.01
Epo-Tek 920 45 minutes at 353 K (80°C)	0.65	0.01
Epoxy-patch kit 1C as equal lengths 24 hours at 298 K (25°C)	0.82	0.03
Epoxy 220 A/B as equal lengths 24 hours at 298 K (25°C)	0.89	0.08
EPY 150 pre-pack kit 16 hours at 298 K (25°C)	0.99	0.04
EX 8762 1 hour at 433 K (160°C) plus 2 hours at 513 K (240°C)	0.08	0.01
FM 37 10 hours at 394 K (121°C)	0.73	0.05
Fiberite E-3938 10 minutes at 422 K (149°C) plus 2 hours at 433 K (160°C)	0.44	0.01
Gelva MP sol RA 263 Pressure sensitive 7 days at 298 K (25°C)	0.79	0.08
Gelva MP sol RA 784 Pressure sensitive 24 hours at 298 K (25°C) plus 24 hours at 339 K (66°C)	1.00	0.05
Gelva MP sol RA 858 Pressure sensitive 24 hours at 298 K (25°C) plus 24 hours at 339 K (66°C)	1.02	0.02

	% TML	% CVCM
Hysol EA 956 A/B as 100 A/58B BW 7 days at 298 K (25°C)	0.69	0.03
Hysol XC9 - G710/H2-3561 as 100/26 BW 24 hours at 298 K (25°C) plus 6 hours at 342 K (69°C)	0.90	0.02
LCA 4/ACT BA5 as 100/4.5 BW 16 hours at 373 K (100°C)	0.19	0.00
Metre-grip 3446/T9 as 1% catalyst BW 2 hours at 366 K (93°C) plus 16 hours at 477 K (204°C)	0.50	0.00
MMM EC2258 24 hours at 448 K (175°C)	1.01	0.00
MMM EC2290 30 minutes at 355 K and 0.013 N/m^2 (82°C and 10^{-4} torr) plus 30 minutes at 450 K and 0.013 N/m^2 (177°C and 10^{-4} torr)	0.02	0.02
Narmco 3135/7111 as 1/1 BW 24 hours at 298 K (25°C)	0.60	0.01
PR 1710 16 hours at 298 K (25°C) plus 1 hour at 394 K (121°C)	0.38	0.01
PS 18 72 hours at 298 K (25°C)	0.74	0.00
PS 269 A/B as 1/1 BW 24 hours at 298 K (25°C)	0.79	0.10
R8-2038/H2-3475 24 hours at 298 K (25°C)	0.53	0.01
Resdel 01-02-01 Ciba 6005/Resdel 41 as 5/1 BW 10 minutes at 433 K (160°C)	0.82	0.03
Resyn 30-1215 16 hours at 298 K (25°C) plus 2 hours at 339 K (66°C)	0.63	0.02
Rhoplex N-619 30 minutes at 298 K (25°C) plus 1 hour at 343 K (70°C)	0.52	0.01

	% TML	% CVCM
RTV-566 as 0.075% BW catalyst B 7 days at 298 K (25°C)	0.11	0.01
RTV-566 as 0.08% BW catalyst B 7 days at 298 K (25°C)	0.11	0.01
RTV-566 as 0.09% BW catalyst 7 days at 298 K (25°C)	0.11	0.01
RTV-566 as 0.10% BW catalyst 7 days at 298 K (25°C)	0.10	0.02
RTV-566 as 0.2% BW catalyst B 24 hours at 298 K (25°C)	0.27	0.00
RTV-566 as 0.3% BW catalyst B 24 hours at 298 K (25°C)	0.34	0.00
RTV-566 as 0.5% BW catalyst B 24 hours at 298 K (25°C)	0.41	0.01
RTV-566 as 0.7% BW catalyst B 24 hours at 298 K (25°C)	0.36	0.01
RTV-567 as 0.3% BW catalyst 5 days at 298 K (25°C)	0.53	0.02
RTV-567 as 0.5% BW catalyst 5 days at 298 K (25°C)	0.51	0.03
Scotchweld 1838 A/B as 1/1 BW 24 hours at 298 K (25°C)	0.66	0.03
Scotchweld EC2214 NMF unfilled 1 hour at 394 K (121°C)	0.78	0.02
Scotchweld EC3500 A/B as 3/2 BW 1 hour at 394 K (121°C)	0.20	0.07
Solithane 113/300/TIPA as 100/51/4.5 BW 7 days at 298 K (25°C)	0.36	0.02
Stycast 1263/31 as 100/3 BW 16 hours at 380 K (107°C)	0.33	0.04
Stycast 2850 FT/24LV as 100/7 BW 24 hours at 298 K (25°C) plus 72 hours at 333 K (60°C)	0.39	0.01

	% TML	% CVCM
Stycast 2850 GT/9 as 100/0.3 BW 7 days at 298 K (25°C)	0.33	0.00
Tra-Bond 2248 Bipax kit 16 hours at 298 K (25°C) plus 2 hours at 338 K (65°C) plus 2 hours at 363 K (90°C)	0.72	0.01
Y-663 thermopoxy 1 hour at 450 K (177°C)	0.41	0.08
ADHESIVE FILMS, SUPPORTED AND UNSUPPORTED		
Ablefilm 517 glasscloth support/epoxy film 3 hours at 347 K (74°C)	0.07	0.01
CMC 10 film, thermosetting 30 minutes 438 K (165°C)	1.02	0.04
Coast epoxy prepreg F161-83-1P08/20 2 hours at 436 K (163°C)	0.67	0.12
FM 123-2 LVC 1 hour at 394 K (121°C)	0.69	0.01
FM 150-1 supported epoxy, aluminum filled 1 hour at 450 K (177°C)	0.50	0.05
FM 150-2 supported epoxy film EP15 1 hour at 450 K (177°C)	0.87	0.07
FM 150-2U unsupported 1 hour at 450 K (177°C)	0.90	0.03
HX-1000 laminating film 15 minutes at 492 K (216°C)	0.10	0.01
Hysol A9-601 1 hour at 394 K (121°C) and pressure	0.37	0.03
Metlbond 227 1 hour at 400 K (127°C)	0.99	0.08
Narmco 328 90 minutes at 438 K (165°C)	1.00	0.11

CONDUCTIVE OR FILLED ADHESIVES	% TML	% CVCM
Eccobond 56C/9 as 20/1 BW 16 hours at 323 K (50°C)	0.30	0.03
Electrobond 2015 A/B as 10/1 BW, silver filled 2 hours at 338 K (65°C)	0.44	0.02
Epon 815/DER 732/V9/silver powder/AEP 4 hours at 347 K (74°C)	0.57	0.08
Epon 828/Versamid 140/Silflake 135 as 5/5/40 BW 7 days at 298 K (25°C)	0.50	0.04
Epo-Tek H21D A/B as 10/1 BW 30 minutes at 373 K (100°C)	0.19	0.00
Epo-Tek H 31 1 hour at 423 K (150°C)	0.59	0.06
Epo-Tek H 41 1 hour at 423 K (150°C)	0.14	0.00
Epo-Tek H 43 1 hour at 423 K (150°C)	0.21	0.00
Epo-Tek H 44 1 hour at 423 K (150°C)	0.27	0.01
Epo-Tek H 74 A/B as 10/0.3 BW 30 minutes at 423 K (150°C)	0.56	0.01
Epo-Tek H 80 silver filled 24 hours at 323 K (50°C)	0.17	0.01
Epo-Tek H 81 A/B as 10/1 BW 12 hours at 323 K (50°C)	0.06	0.02
Hysol K8-4238/H2-3475 as 25/4 BW 24 hours at 298 K (25°C)	0.32	0.01
K-16 A/B as 3/1 BW 48 hours at 298 K (25°C)	0.22	0.01
P-61 silica filled 2 hours at 373 K (100°C) plus 8 hours at 408 K (135°C)	0.31	0.04
Resdel epoxy with iron filling 10 minutes at 433 K (160°C)	0.67	0.03

	% TML	% CVCM
Scotchweld 2214 HD aluminum filled 40 minutes at 394 K (121°C)	0.49	0.05
Tecknit 72-0002 48 hours at 394 K and 0.0013 N/m^2 (121°C and 10^{-5} torr)	0.02	0.01
Tecknit 72-08116 A/B as 1/1 BW 30 minutes at 372 K (99°C)	0.61	0.03
Tra-Bond 2151 Bipax kit 72 hours at 298 K (25°C)	0.65	0.02
Traduct BA 2902 silver filled 2 hours at 333 K (60°C)	1.06	0.04

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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