Designation: E 1997 – 99 (Reapproved 2003)ε1

Standard Practice for the Selection of Spacecraft Materials[1]

This standard is issued under the fixed designation E 1997; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

ε1 NOTE—Keywords were added editorially in October 2003.

1. Scope

1.1 The purpose of this practice is to aid engineers, designers, quality and reliability control engineers, materials specialists, and systems designers in the selection and control of materials and processes for spacecraft, external portion of manned systems, or man-tended systems. Spacecraft systems are very different from most other applications. Space environments are very different from terrestrial environments and can dramatically alter the performance and survivability of many materials. Reliability, long life, and inability to repair defective systems (or high cost and difficultly of repairs for manned applications) are characteristic of space applications. This practice also is intended to identify materials processes or applications that may result in degraded or unsatisfactory performance of systems, subsystems, or components. Examples of successful and unsuccessful materials selections and uses are given in the appendices.

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E 595 Test Method for Total Mass Loss and Collected Volatile Condensable Materials from Outgassing in a Vacuum Environment

G 64 Classification of Resistance to Stress-Corrosion Cracking of Heat-Treatable Aluminum Alloys

2.2 *Marshall Space Flight Center (MSFC) Standard:*

MSFC-SPEC-522 Design Criteria for Controlling Stress Corrosion Cracking[3]

2.3 *Military Standards:*

MIL-STD-889 Dissimilar Materials[4]

MIL-HDBK-5 Metallic Materials and Elements for Aerospace Vehicle Structures[4]

2.4 *European Space Agency (ESA) Standard:*

PSS-07/QRM-0 Guidelines for Space Materials Selection[5]

2.5 *Federal Standard:*

QQ-A-250 Aluminum and Aluminum Alloy Plate and Sheet, Federal Specification for[4]

3. Significance and Use

3.1 This practice is a guideline for proper materials and process selection and application. The specific application of these guidelines must take into account contractual agreements, functional performance requirements for particular programs and missions, and the actual environments and exposures anticipated for each material and the equipment in which the materials are used. Guidelines are not replacements for careful and informed engineering judgment and evaluations and all possible performance and design constraints and requirements cannot be foreseen. This practice is limited to unmanned systems and unmanned or external portions of manned systems, such as the Space Station. Generally, it is applicable to systems in low earth orbit, synchronous orbit, and interplanetary missions. Although many of the suggestions and cautions are applicable to both unmanned and manned spacecraft, manned systems have additional constraints and requirements for crew safety which may not be addressed adequately in unmanned designs. Because of the added constraints and concerns for human-rated systems, these systems are not addressed in this practice.

4. Design Constraints

4.1 *Orbital Environment*—The actual environment in which the equipment is expected to operate must be identified and defined. The exposures and requirements for material performance differ for various missions. Environment definition includes defining the range of temperature exposure, number and rate of thermal cycles, extent of vacuum exposure, solar electromagnetic radiation particulate radiation, (trapped by the earth's magnetosphere, solar wind, solar flares, and gamma rays) micrometeroids, launch loads and vibration, structural loads, and so forth. Materials suitable for one orbit or mission

[1] This practice is under the jurisdiction of ASTM Committee E21 on Space Simulation and Applications of Space Technology and is the direct responsibility of Subcommittee E21.05 on Contamination.

Current edition approved Oct. 1, 2003. Published October 2003. Originally approved in 1999. Last previous edition approved in 1999 as E 1997 – 99.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Marshall Space Flight Center, AL 35812.

[4] Available from the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402.

[5] European Space Agency, 8–10, Rue Mario-Nikis, 75738 Paris Cedex, France.

environment may be unsuitable for others. The applications and requirements will define the suitability of the materials.

4.2 *Low Earth Orbit (Up to 100 km)*—Materials in this region could be exposed to trapped Van Allen belt (ionizing) radiation, solar ultraviolet radiation, corrosive attack by atomic oxygen (A.O.), and more frequent and more extreme thermal cycling and thermal shock as a result of frequent excursions into and out of the earth's shadow. Orbital impacts may be a problem because of the large amount of debris in low orbits. Design life in orbit typically is on the order of 5 to 15 years. Inclination of the orbit affects the service environment, that is, polar orbits have a different flight profile than equatorial orbits and have different profiles for radiation exposure.

4.3 *Synchronous Orbit (35 900 km)*—Materials in this region are not exposed to significant atomic oxygen or very high energy trapped radiation but may have more exposure to medium energy ionizing electrons and protons, solar flares, and relatively high levels of electromagnetic solar radiation (ultraviolet, VUV photons, and X-rays). The number of thermal cycles is less and may be over a narrower temperature range than low earth orbit. Meteoroids also should be considered but are less likely to be significant compared to the manmade debris found in low orbits. Design life in orbit typically is 5 to 15 years, with recent designs ranging from 10 to 17 years.

4.4 *Interplanetary (Out-of-Earth Orbit)*—In addition to the thermal extremes and environments of synchronous orbit, in the interplanetary environment, temperatures may be more extreme, and micrometeoroids, solar wind, and cosmic rays may be critical. Ability to survive and remain functional for many years is important. Probes to the inner plants typically have design lifetimes of 5 to 10 years. Those to the outer planets and beyond may have design lifetimes of 15 to 30 years.

5. Materials to Avoid

5.1 Certain materials are known to be undesirable and should be avoided no matter what the mission. Others are of concern for certain missions or of more concern for some missions than others. In general, it is recommended that one avoid the materials described below:

5.1.1 *Metals with High Vapor Pressure in Vacuum and Unusual Behaviors*—Avoid the use of metals such as mercury, cadmium, and zinc, either as plating or monolithic metals. It is important to exclude these metals both from the flight equipment and vacuum chambers. If these metals are used in vacuum and heated even moderately, they will vacuum metallize both the cold walls of the chamber and any cold surfaces on equipment in the chamber. Also, pure tin has the curious property of dendritic growth as a result of compressive stresses, or thermal or electrical gradients, forming whiskers which can cause shorts in electrical components or break off and become conductive contaminants. Some other metals have similar whisker-growing properties, but not to the extent that tin has.

5.1.2 *Stress-Corrosion Sensitive Metals*—Metals, which are stress-corrosion sensitive, should be avoided. Examples are 2024 T6 and 7075 T6 Aluminum, which can be used if heat treated to conditions, such as 2024 T81 and 7075 T73, which are not stress-corrosion sensitive. Many brasses and some steel alloys also are stress-corrosion sensitive; however, even alloys, which are stress-corrosion sensitive can be used if loaded in compression or if loaded to low sustained tensile stress levels, typically no more than 25 % of yield strength (see Classification G 64 and MSFC-SPEC-522).

5.1.3 *Materials Forming Galvanic Couples*—Material combinations, which form galvanic couples greater than 0.5 ev when exposed to a temperature and humidity controlled environment, such as during fabrication, testing, and storage, should be prohibited under most circumstances. Providing protection from electrolytes and maintaining them in a controlled environment, such as during fabrication and testing, inhibits galvanic corrosion. Some alloys, such as magnesium, magnesium lithium alloys, and gold, form a galvanic couple with most common structural materials and must be protected adequately to prevent creating galvanic couples which cause the anodic metal to corrode. Carbon composites are included in the materials, which must be evaluated for galvanic potential, since carbon forms galvanic couples with metals. If there is no electrolyte present, galvanic couples greater than 0.5 ev are permissible. Galvanic protection can be obtained by preventing electrolyte from contacting the interfaces, interposing a dielectric material, or adding a material that is compatible with each of the other materials separately.

5.1.4 *Materials With Thermal or Environmental Limitations*—Materials that are weak or brittle at the expected service temperature or environment should be avoided. These materials included polymeric materials used at very low or very high temperatures and some metals used at low temperatures. In this context, "low" can be from -40 to -120°C and "high" can be from 150 to 200°C for polymers. Some materials are readily attacked by certain chemicals or solutions. For example, aluminum alloys should not be used in strongly basic or acidic environments. Steels, particularly high carbon and ferritic grades, are embrittled by halogens and hydrogen. Silicones are attacked by toluene. Titanium is attacked by methanol.

5.1.5 *Materials Difficult to Fabricate or Test*—Materials that are difficult to fabricate, form, test, or inspect, or do not have a history of consistency of properties or performance, should be avoided. Some materials, such as ceramics and most refractory metals, are relatively difficult to machine or form. Others are difficult to weld by conventional means. Some cannot be formed easily. All materials must be very carefully evaluated to assure successful, economic fabrication and that the fabricated parts can be inspected easily for hidden defects.

5.1.6 *Materials That Have Excessive Outgassing*—If the materials have high collected volatile condensable materials (CVCM) or total mass loss (TML) when exposed at 125°C and tested, they generally are excluded from spacecraft applications. Normal acceptance limits for outgassing according to Test Method E 595 are no higher than 1.0 % TML and no higher than 0.10 % CVCM. Some of these materials release condensates that react adversely with solar radiation or radiation and vacuum and may degrade sensitive surfaces. Others can contaminate surfaces or equipment such that functionality is impaired. High mass loss can indicate a loss or properties and functionality in space. Sometimes, a material will have acceptable outgassing per normal requirements, but it may be in a particularly sensitive location, or the outgassing product may have an adverse effect on specific sensitive equipment. These conditions can require establishing lower levels for acceptable outgassing or may require analysis of outgassed components and evaluation of the acceptability for the specific application.

NOTE 1—The test is defined as performed at 125°C unless clearly stated otherwise; therefore, acceptability is limited to exposures at that temperature or below.

NOTE 2—Metallic materials do not "outgas," but some metals, such as zinc and cadmium, do exhibit high vapor pressure at relatively low (<150°C) temperatures in vacuum. (See 5.1.1.)

5.1.7 *Materials That Release Undesirable Components*—For example, acetic acid is released when curing certain silicones. The acid can attack and corrode electrical wiring and contacts and cause failures. In some applications, the alcohols released when silicones cure may be harmful.

5.1.8 *Unstable Polymeric Materials*—Some polymeric materials may revert or change character when exposed to other materials or to the space environment. For example, certain silicones in contact with amine-cured epoxy can become fluid; some polymeric materials are degraded by radiation or atomic oxygen (A.O.), or both. Polyamide may become brittle in vacuum and lose mechanical strength. PTFE and FEP become brittle when exposed to radiation in vacuum. Lubricants containing graphite may lose lubricity in vacuum. ETFE wire insulation may become brittle and crack if heated to high temperatures and flexed or strained. Sulfur, which may be present in some latex and rubber gloves, can prevent proper curing of the silicones.

5.1.9 *Unstable Nonmetallic Materials in Particular Environments*—Most nonmetallic materials are attacked by A.O. found in low earth orbit. They must be protected from direct exposure to A.O. either by coating them with a resistant material, such as metal or oxide, or by shadowing or covering them from direct exposure to A.O.

5.1.10 *Reproducible Properties Uncertain*—Materials that do not have repeatable, reproducible physical or mechanical properties may not be adequately controlled to assure reliable and reproducible performance. It is important to select materials that are well understood and have established histories of consistent and predictable physical and mechanical behavior in space. It is also important that the materials be capable of being processed in a controlled, repeatable manner so that performance is dependable and reproducible in accordance with 5.1.5.

5.1.11 *Radiation Sensitivity*—Materials that are sensitive to radiation, or radiation and vacuum, require care in selection and application. Many glasses and optical coatings are damaged by radiation. Some polymeric materials may be degraded by radiation or solar flares. The susceptibility to particulate radiation damage sometimes is increased in vacuum when simultaneously exposed to ultraviolet radiation. It is important to consider radiation sensitivity and the orbital environment when selecting materials.

5.1.12 *Materials Particulate Contamination*—Emission of particles or flaking can cause interference with optical or thermal control surfaces or perhaps jam mechanisms. Thorough cleaning of materials and assemblies is important to prevent emission of particles. Conductive particles are particularly undesirable and must be avoided.

5.1.13 *Fluid Compatibility*—If the material is likely to be exposed to propellant, coolants, in-process solvents, and so forth, it is important to test and verify fluid compatibility with the materials in advance. Always check and verify the compatibility of the materials with all fluids in which they may come into contact and with all of the fluids used, including cleaning agents, solvents, and test fluids.

5.1.14 *Arc Tracking of Wires*—Kapton®[6] wire insulation is susceptible to arc tracking when used in power-carrying applications. Any damage or abrasion to this type of wire may cause dielectric breakdown and arcing, even in vacuum. Wire insulations, such as Teflon-polyimide-Teflon®[7], which are not susceptible to arc tracking and have been qualified as such are available and should be considered as replacements for Kapton wire insulation.

5.1.15 *Inadequately Controlled Materials*—Any material that is purchased and controlled only by vendor data sheet or material certification, or both, has questionable controls. This type of product control should be viewed with caution. Data sheets are not assurances of performance and often are misleading. For example, a maximum use temperature of a polymer may be given as 200°C, but at that temperature it may have low dielectric strength, poor modulus of elasticity and strength, excessive outgassing, or significant loss of other properties. Relying on vendor certifications alone can result in acceptance of lots, which, in fact, fail some specific property. Suppliers have been known to send substandard lots of material to customers without properly testing and verifying properties and quality. Critical properties should be tested and verified frequently, even every lot if necessary. Materials should be defined and controlled by a specification and should not be accepted and used based only upon vendor data sheets and certifications.

5.1.16 *Mismatched Coefficient of Thermal Expansion*—Assemblies or equipment may use materials with significantly different coefficients of thermal expansion (CTE). Severe thermal stresses and even bond or material rupture can occur if these assemblies are subjected to wide temperature excursions of if the polymeric material isothermally cycled through its glass transition point. If a low expansion material, such as a ceramic substrate, is bonded to a high expansion material, such as aluminum sheet, there can be a large strain induced in the bond joints as a result of CTE mismatch. This type of joint often fails during thermal cycling. Another potential problem is fatigue stress on various types of joints (solder, thermal, electrical, light duty structural) as a result of thermal cycling of an assembly composed of materials with greatly different CTEs. Materials and designs must be selected to minimize incompatibility caused by CTE mismatch between the various elements in the joints.

[6] Kapton®, DuPont de Nemours, E.I., & Co., Inc., Barley Mill Plaza, Bldg. 10, Wilmington, DE 19880–0010.

[7] Teflon®, DuPont de Nemours, E.I., & Co., Inc., Barley Mill Plaza, Bldg. 10, Wilmington, DE 19880–0010.

6. Methods of Controlling Materials

6.1 Selection of materials always should be done by material specialists, preferably those with experience in space applications and requirements. Aircraft, ships, and weapons exist in different environments and have different requirements. Engineers who are not materials specialists rarely are aware of the properties, peculiarities, and problems inherent in materials; therefore, it is vital to appoint an experienced materials specialist to oversee spacecraft materials selection, specification, control, and approval. This overall responsibility is exercised best with an organized system of materials control. The materials specialist should work closely with the program office, reliability, designers, and manufacturing to assure proper use of materials and processes. There should be a single responsible materials engineer, supported as necessary by additional materials and processes engineers.

6.2 *Approved Materials List*—Each program should have a list of approved materials for use in specific applications. All materials must be listed, both those used by the prime contractor and those used by all subcontractors and subtier subcontractors. The list should include item numbers for each material; the name of the material, commercial name, manufacturer or supplier of the material; usage information such as heat treat condition, mix ratio, cure cycle, post-cure, or bakeouts; governing specification or other documentation; application or use; pertinent properties, such as outgassing, protective coatings, or special precautions; and so forth. It is useful to indicate examples of previous successful use of the material in the same or a similar application, for example, used on the XXXYYY program. The mass and surface area of polymeric materials may be given to help in evaluating contamination potential. This list could begin as a list of allowed materials, and by the end of the program, should reflect all materials actually used both internally and by subcontractors. Restricted and waived materials may be listed in separate sections to facilitate identifying any materials that are not fully acceptable as normally used, but which require special treatment or are used despite failure to meet normal requirements.

6.3 *Materials Review of Design*—The responsible materials specialist should assist in internal reviews of designs and applications of materials. This is particularly important for composites, thermal control materials, adhesives, any materials used at high or low temperatures (below about −20°C or above about 80°C), or when any material is used in a new or different application or environment.

6.4 *Drawing Review*—An effective method for assuring adequate materials design review is to require materials specialists to review and sign all drawings and drawing revisions, except those with no materials or process centers, such as schematics or dimensional identification.

6.5 *Design Reviews*—Materials specialists should be active participants in design reviews whenever materials or processes are topics of discussion. These reviews allow direct interactions with designers, program office, users, and subcontractors. It is an effective method for preventing selection of unacceptable or inappropriate materials.

6.6 *Materials Specifications*—Materials specialists should prepare and approve all materials and processes specifications. This approach permits identification of important materials properties for test and control and provides interaction between designers, materials, specification control, and purchasing. Identification of properties to test and verify property requirements, specification of test methods, and selection of approved sources can be aided by materials participation. This process also allows selection of processes most appropriate for the particular material and application.

6.7 *Approved Process Lists*—Each program should have a list of approved processes for use in specific applications. The process list must include the process number, the revision letter, and a description of the process. It is desirable to cross-reference the process to the materials used as shown on the materials list. All materials specified in any process, which become part of the deliverable equipment, must be included on the materials list. The list should be configuration controlled and issued in the same manner as a specification or drawing with required approval signatures.

6.8 *Process Preparation*—Materials and processes specialists should be involved in the preparation or revision of all process specifications to assure that the materials used are properly applied and processed and that the processes are valid and that they are used correctly. All process modifications identified during development or production must be documented and recorded fully in the process history to ensure repeatability. New processes, processes used with a new or unusual material, and processes that may represent a significant risk to the hardware, if incorrectly applied, shall be tested and qualified on a test article before use on flight hardware.

7. Keywords

7.1 applications; design; materials applications; materials selection; preferred materials; problem materials; space applications; spacecraft materials; testing

APPENDIXES

(Nonmandatory Information)

X1. SPECIFIC MATERIALS RECOMMENDATIONS—METALS

X1.1 *Metals*—Important considerations are strength, strength/density ratio, stiffness or modulus of elasticity, thermal conductivity, electrical conductivity, magnetic properties, sensitivity to stress corrosion, fracture toughness, toxicity, fabricability, and sometimes cost and availability.

X1.1.1 *General*—Pure tin should be avoided. It can grow whiskers, which may create shorts, or the whiskers may break off and float around the equipment in orbit causing arcing, shorts, or intermittent electrical upsets. Often, tin plate is specified on terminals, wires, or solder lugs. Pure tin in these applications should be overcoated, reflowed, or alloyed with other materials such as lead or antimony which inhibit whisker growth. As little as 3 to 5 % of an alloying element can prevent whisker growth. Fusing or oxidizing the pure tin, for example in hot peanut oil, also prevents whisker growth. Cadmium and zinc also can grow whiskers and should not be used.

X1.1.2 Some metal combinations result in undesirable alloys. For example, gold and aluminum form a brittle intermetallic known as purple plague, which causes failures in electronic circuits. This alloy forms at elevated temperatures, so one means of avoiding the problem is to keep exposure temperatures below 200°C. Porous plating, such as gold on silver, may result in lack of adherence and flaking.

X1.1.3 Mercury and aluminum form an amalgam that destroys the physical properties of aluminum. Mercury must be banned or very tightly controlled in the presence of aluminum.

X1.1.4 Direct contact of bare metals usually is undesirable. If both metals have cubic crystal lattices, they may cold weld in space. Metals in direct contact under load or moving over each may cold weld. It is preferable to coat one or both metals or use metals with different crystal lattices in contact with each other if cold welding is possible as a result of the application.

X1.2 *Mechanical and Physical Properties*—When selecting metals for stiffness, consider specific stiffness, that is, modulus divided by density. Often magnesium is selected over aluminum because it has lower density. In fact, the specific stiffness of aluminum and magnesium alloys are almost identical. The disadvantages of fabricating and protecting magnesium from corrosion and galvanic corrosion often exceed any gain from lower density.

X1.2.1 Magnesium is never a better choice than aluminum when the design is stiffness limited. Composites, such as ceramic-reinforced metals or metal-reinforced metals, can be designed and fabricated to have high specific stiffness.

X1.2.2 Strength and strength/density ratio are key properties in selecting metals. This is particularly true for structural applications or when highest strength for a given thin section or light mass is required.

NOTE X1.1—As in the case of specific modulus, do not just consider high strength but also consider strength/density ratio for best structural efficiency.

X1.2.3 Toxicity and safety are concerns for some metals. Beryllium and heavy metals, such as lead and the transuranium elements, are toxic and must be handled with care. Magnesium, lithium, and magnesium lithium alloys, as well as lithium and some uranium alloys, can be ignited and produce fires, which are very difficult to extinguish. They must be selected, fabricated, and handled with care.

X1.2.4 Methods of joining must be considered. Some metals, particularly refractory metals, such as tungsten, and reactive metals, such as magnesium, are difficult to braze or weld and are best used with mechanical joints. Ease, cost, and reproducibility of joining or assembly should be considered.

X1.2.5 Fatigue behavior must be considered in applications in which frequent repetitive stresses occur. Sometimes heat treating or other processing will make metals more susceptible to fatigue. When assessing fatigue behavior, it is important to look at various heat treatments or other processes, such as shot peening which improve fatigue strength and fatigue resistance.

X1.3 *Corrosion and Stability*—Corrosion resistance of metals and the presence of combinations of metals that create galvanic couples must be considered. In addition to atmospheric corrosion, it may be important to know or determine the corrosion compatibility with specific fluids, such as propellants, solvents, heat transfer fluids, lubricants, and cutting fluids. Galvanic corrosion normally is not a concern if the EMF between two materials is 0.25 ev or less for severe environments or 0.50-ev EMF or less for temperature- and humidity-controlled environments. Since most spacecraft assembly, integration, and storage is done in environmentally controlled areas, it should be acceptable to use metals in direct contact, which have up to 0.50-ev EMF between them. Use of MIL-STD-889 to select approved galvanic couples for spacecraft is inadvisable. This practice fails to give actual values for galvanic couples and is intended for exposure to seawater and industrial atmospheres, neither of which apply to spacecraft. A better reference is ESA PSS-07/QRM-0, which gives actual EMF and is related directly to spacecraft. It is possible to use metals with unacceptable galvanic electropotential if they are insulated from each other or sealed to exclude electrolytes. For example, anodized aluminum in direct contact with silver is acceptable, but bare aluminum in direct contact with silver forms an impermissible large galvanic couple.

X1.4 *Environmental Concerns*—These concerns do not apply.

X1.5 *Outgassing*—This property does not apply.

X1.6 *Control of Properties*—Most metals are defined and controlled adequately by national society, military, or federal specifications, for example, QQ-A-250, Mil-HDBK-5, AMS and ASTM specifications, and so forth. These specification controls do not release using organizations from testing and verifying actual properties on specific lots of materials as required.

X1.7 *Preferred Materials*—The clear preference is to use materials that are well characterized, readily available, have reproducible and reliable properties, fabricate readily, and have a history of successful use in the intended applications.

X1.8 *Materials To Be Avoided*—Avoid the use of metals with high vapor pressure at low temperature in vacuum, such as mercury, cadmium, and zinc, either as plating or monolithic metals. Mercury must be banned or very tightly controlled in the presence of aluminum. Pure tin and other metals that grow whiskers should be avoided.

X2. SPECIFIC MATERIALS RECOMMENDATIONS—ADHESIVES

X2.1 *General*—Adhesives may be structural or nonstructural. Structural adhesives must be selected for bond strength; peel strength; and vacuum stability including outgassing behavior, thermal properties, glass transition point, cost, availability, and consistency of performance. Selection of the proper adhesive for particular applications requires an understanding of the materials to be bonded; proper surface preparation; the need and suitability of primers or coupling agents; and the operating environment including temperature, radiation exposure, loading, and compatibility with other materials. Adhesive process control is as important as selection of the adhesive itself. Structural bonds (>1000-pi design loads) require specific training to apply the adhesive, including surface preparation and process controls for consistency and effective, reliable strength.

X2.2 *General Usage Precautions*—Usage precautions must be observed to avoid undesirable or unacceptable results and even system failures. The importance of thermal sensitivity must not be overlooked. For example, the elastomeric seals, which failed and resulted in the loss of the Challenger, were operated at a temperature below their known limits. Epoxies often have brittle points in the −20 to −60°C range. Epoxies should not be used in direct contact with ceramic parts, such as ceramic-cased diodes when usage temperatures are low. A flexible intermediate material must be applied to prevent brittle fracture of the ceramic. Silicones are normally flexible at temperatures as low as −110°C. Flexible silicones should be used rather than epoxies to bond ceramics for low temperature applications directly (see 5.1.14). Urethanes tend to become brittle at temperatures of approximately −20 to −40°C and should be used with great care or avoided at lower temperatures. High temperatures result in significant loss in bond strength for adhesives. Few adhesives retain useful bond or peel strength at temperatures above 60°C. Some polyimides may have useful strengths at temperatures up to 300°C. A more typical adhesive upper use temperature is 80 to 100°C. If the expected use temperature is above about 80°C, the bond strengths of adhesives should be verified either from vendor test data or by actual test.

NOTE X2.1—Outgassing in accordance with Test Method E 595, at standard conditions, is performed at 125°C. If operating temperatures are expected to exceed 120 to 125°C, the material should be tested for outgassing at or above the expected operating temperature.

X2.3 *Mechanical and Physical Properties*—Normally, suppliers provide data sheets that list material properties of adhesives. This information is not directly transferable to specifications and standards. In fact, the vendor data sheets usually have a disclaimer that the properties are typical only and not to be used for specifications. Users are advised to perform tests of properties of interest and to use those values to generate specifications.

X2.4 *Corrosion and Stability*—Some adhesives are sensitive to contact with organic materials or certain metals. For example, silicones can be degraded by contact with amines commonly used as a curing agent in epoxies. RTV silicones, which cure by reaction with moisture, cannot be cured faster by heating them. Such heating reduces the humidity at the adhesive and inhibits cure. If heated to too high a temperature during cure, the silicone may even be damaged and never cure properly. It is inadvisable to use silicones, which require moisture to cure properly, to bond large area sandwich bonds because of the long times for moisture diffusion to the center of the joint. Moisture can inhibit cure of some epoxies but is essential to the cure of some silicones. Carbon dioxide may react with and impair function of some curing agents. Adhesives, such as cyanoacrylites, cure in the absence of air. It may not be possible to assure exclusion of air during curing or to inspect and verify proper cure afterwards.

X2.5 *Environmental Concerns*—Environmental effects on adhesives must be considered as must compatibility of the manufacturing process and expected operating conditions. Exposure to atomic oxygen may degrade or attack adhesives. Some adhesives lose mechanical and physical properties when exposed to radiation, especially in vacuum. Epoxies are more likely to be darkened by radiation than silicones. Solar cell cover glasses are bonded with silicones that are not damaged by solar radiation. If the application is inside the spacecraft envelope, such as in electronic boxes, adhesives and other organic materials are considered to be protected from radiation and atomic oxygen and will exhibit normal behavior. Improper curing processes must be avoided to prevent uncured or partly cured coatings or bonds.

X2.6 *Outgassing*—Adhesives are common sources of organic contamination in space applications as a result of outgassing and deposition on flight surfaces. Before approving any adhesive for space applications, the existing literature should be reviewed for outgoing values when tested in accordance with Test Method E 595. The actual mix ratio and cure cycle of the tested samples must be taken into account and compared with planned processing conditions. If no outgassing data are available, the material should be tested and TLM and CVCM determined early in the test and evaluation phase for the material.

X2.7 *Controls on Properties*—It is a general requirement that all materials used on spacecraft be identified fully and uniquely. This is not possible for almost all military or federal specification products. Any adhesive must be tested and qualified for the specific application of use. This normally requires hardness and mechanical strength testing and evaluation.

X2.8 *Preferred Materials*—The clear preference is to use materials that are well characterized, readily available, have reproducible and reliable properties, are fabricated readily, and have a history of successful use in the intended applications.

X2.9 *Materials To Be Avoided*—Adhesives to be avoided include any that are not intended for or qualified for space use. There are many commercial products available, most of which have high outgassing, poor reproducibility and reliability of properties, or unacceptable behavior at high or low temperatures, or both, or have compatibility concerns when used with other materials. If shelf life is less than 180 days, it may be relatively expensive to purchase and stock supplies of these materials. It is inadvisable to use adhesives specified to a military or federal specification since they have no requirements for outgassing or shelf life control. In addition, a number of different materials may be on the QPI for various military and federal specifications, but all of them may not be equally acceptable for space use.

X3. SPECIFIC MATERIAL RECOMMENDATIONS—POTTING COMPOUNDS

X3.1 *General*—Potting compounds may be used to coat magnetics, pot connector backshells, pot inserts, fill honeycomb, or encapsulate electronics. Most potting compounds are epoxies, silicones, or polyurethanes. The same concerns discussed in Appendix X2 regarding changes in properties at the glass transition point apply to these classes of materials when they are used for potting. In addition, there may be significant differences in the coefficient of thermal expansion between potting compounds and items being potted, resulting in significant stresses on the parts or solder joints. Processing conditions must be controlled and repeatable. There are additional specific concerns when the materials are used in potting applications.

X3.2 *Mechanical and Physical Properties*—In addition to the limits on thermal stability and functional suitability at high and low temperatures, potting compounds may have exothermic reactions. Since they are used in larger quantities than adhesives, the heating during cure could be enough to damage components. It may be necessary to cure the potting compound in separate castings or in a controlled environment to reduce thermal stresses during curing. Because the mass of potting compounds is greater than adhesives in most applications, high and low temperature exposure may result in noticeable dimensional changes or component stresses as a result of potting growth at higher temperatures. Thermal cycling of potting compounds can cause cracking or crazing and loss of physical and mechanical properties.

X3.3 *Corrosion and Compatibility*—Compatibility of potting compounds should be established before use. Sequence of use, and which potting compounds are used together, must be considered carefully. For example, if silicones are used to seal surfaces that are then potted in epoxy, the epoxy will not adhere to the silicone and may interact adversely with it. Amine-cured epoxies should be avoided in contact with silicones. Moisture-curing systems, such as one-part silicones, may be sealed from sources of moisture, if overcoated, before they are cured. Curing agents may be toxic or may attack other materials. Examples are the MOCA-curing agent, which is considered toxic, and dibutyl tin, which corrodes copper.

X3.4 *Environmental Concerns*—Foams and soft potting compounds present a particular problem. They contain significant amounts of air or foaming agents. After launch, the trapped gases can expand in vacuum and cause physical damage to components. Gases, which are emitted over time, can cause arcing or multipacting if electrical equipment is turned on before all the gases have dissipated. It may be necessary to vacuum degas foams and potting compounds or postcure them under vacuum. It is important to verify that the particular foam under consideration has adequate stability, does not crumble or generate particles, and is stable over the temperature range of interest. Some foams may be susceptible to biological attack before launch.

X3.5 *Outgassing*—Materials that should be avoided include any with excessive outgassing, such as polysulphides or nonspace-grade silicones. Some materials, such as nylons and inks, have high TML and may produce significant amounts of water and solvents. They should be evaluated for each specific application before they are approved and used. Potting compounds that have high exothermal reactions, shrink severely, or have high coefficients of thermal expansion should be avoided.

X3.6 *Controls on Properties*—It is a general requirement that all materials used on spacecraft be identified fully and uniquely. This identification is not possible for almost all military or federal specification products. Any adhesive must be tested and qualified for the specific application of use. This normally requires hardness and mechanical strength testing and evaluation.

X3.7 *Preferred Materials*—The clear preference is to use materials that are well characterized, readily available, have reproducible and reliable properties, have acceptable outgassing, are fabricated readily, will survive the anticipated environment, are compatible with other materials in the system, and have a history of successful use in the intended applications.

X3.8 *Materials To Be Avoided*—It is preferable to avoid materials that undergo phase transformations in the expected service temperature range, have high outgassing, do not have a history of successful use in similar applications, are not well characterized, do not have dependable and reproducible properties, are difficult or expensive to procure, or are unstable or have short shelf lives.

X4. SPECIFIC MATERIAL RECOMMENDATIONS—TAPES

X4.1 *General*—Adhesive tapes have two materials of concern: both the backing material and the adhesive need to be evaluated. Backings should be selected from materials that are acceptable generally for space applications, such as polyimide (Kapton), polyester (Mylar®[8]), fiberglass, metal foils, such as copper or aluminum, or PTFE (Teflon). High outgassing materials, such as polyvinyl chloride (PVC), paper, polyolefin, cellulose (cellophane), and cellulose acetate should be avoided. Thermal properties of tape adhesives also should be considered, as well as adhesive outgassing. Lot testing is advisable when applications are critical.

X4.2 *Applications*—Applications of tapes typically are for insulation, thermal control, or light duty bonding. When used under integrated circuits or electronic devices, tapes with low outgassing adhesives are functionally useful and stable. Other applications are to protect wires or cables from rubbing or abrasion and to seal rough edges of honeycomb and prevent damage and aid in handling. When used as honeycomb edging, it is important to provide venting by piercing the tape so that vacuum exposure does not result in tape lifting or bubbling. Another application is for electrical grounding and sealing. Transfer tapes are used to attach ceramic substrates to chassis, bond together thermal control surfaces, or join light-weight metallic components. Selection of the proper tape depends on the application and environment.

X4.3 *Mechanical and Physical Properties*—There are three tape properties that normally are of interest. These include dielectric strength, adhesion, and tensile strength and elongation. Some tapes have metallized surfaces for thermal control applications. These must be applied carefully to avoid damage to the optical surface of the tape and ensure proper operation. Optical properties of these tapes is of interest and should be verified.

X4.4 *Corrosion and Stability*—Corrosion is not applicable. Adhesives on the tapes are age sensitive and must have shelf-life controls imposed. Over time, adhesives will lose bond strength and not provide adequate adhesion.

NOTE X4.1—Metallized tapes may be subject to corrosion of the metal coating and alteration of optical properties.

X4.5 *Environmental Effects*—Tapes that are exposed to atomic oxygen must be selected to resist degradation. Polyimide (Kapton) is attacked if directly exposed to atomic oxygen. Teflon also is embrittled by exposure to radiation in vacuum. Metallized tapes, which have the metallization on the adhesive side, also may be attacked by atomic oxygen or radiation.

X4.6 *Outgassing*—Outgassing properties of tapes are determined mainly by the adhesives used. High outgassing backing materials, such as polyvinylchloride, normally will be excluded from consideration because the TML and CVCM clearly are excessive.

X4.7 *Controls on Properties*—It is a general requirement that all materials used on spacecraft be identified fully and uniquely. This is not possible for almost all military or federal specification products. Any adhesive tape must be tested and qualified for the specific application of use. This normally requires adhesion testing, mechanical strength testing, and dielectric strength.

X4.8 *Preferred Materials*—In general, acrylic adhesives have acceptable outgassing properties and do not leave contaminating residues. They have been used successfully in all of the applications described in X4.1-X4.7. Fiberglass tapes with no adhesive, or with acrylic adhesives, have been used successfully for wrapping and protection of wires, cables, and propulsion lines. Kapton and Mylar tapes with acrylic adhesive may be used to insulate electronic devices, as wrapping on magnetics, and to tie down lightweight components, such as wires. Teflon tapes with acrylic adhesive may be used for insulation or to reduce friction in light duty applications.

X4.9 *Materials To Be Avoided*—Adhesives that should be avoided include rubber, butyl, and silicones. Some silicones have been found to have acceptable outgassing properties, but they must be tested by individual lots to verify outgassing properties. Tapes that are used for in-process applications, but are removed before flight, still should be tested to determine whether or not they leave a residue on surfaces. Such residues may outgas in space, darken when exposed to radiation and affect optical/thermal properties of surfaces, or contaminate surfaces and interfere with bonding or coating operations. Adhesive residues also can interfere with bonding or painting since they are surface contaminants.

[8] Mylar®, DuPont Films, Barley Mill Plaza, Wilmington, DE 19880.

X5. SPECIFIC MATERIAL RECOMMENDATIONS—VARNISHES AND COATINGS

X5.1 *General*—Varnishes may be used for coating coils and magnetics for insulation and occasionally for mechanical support or cushioning. Coatings are considered here in the context of conformal or protective coatings. Materials used may be polyesters, polyimides, alkyds, polyurethanes, silicones, polyesterimide, or epoxies. Typical application is by brushing, dipping, or spraying, as a thin film or coating no more than 0.1 to 2 mm (0.4 to 8 mils) thick. Thicker coatings may impose stresses on components, either during curing or when exposed to temperature extremes. If a coating is cured at an elevated temperature, it may impose stresses when it cools. It is particularly important to be wary of using thick coatings that are cured at high temperatures. Reparability also may be a concern, depending upon the extent of processing after the coating is applied.

X5.2 *Mechanical and Physical Properties*—Properties of interest include dielectric strength, viscosity, coefficient of thermal expansion, thickness, glass transition temperature, outgassing, and adhesion to surfaces that will be coated.

X5.3 *Corrosion and Stability*—Coatings are age sensitive and must have an expiration sticker on each container of the varnish or potting compound. Varnish coatings are not corrosive or likely to attack magnet wires or magnetics.

X5.4 *Environmental Concerns*—Atomic oxygen and radiation normally are not concerns for varnishes and conformal coatings because they are used inside equipment and are protected. Wide thermal excursions in space also are unlikely for normal application of these materials.

X5.5 *Outgassing*—Coatings with high percentages of solvents generally have excessive outgassing. In addition, the solvents may interact with other adjacent materials. Coatings, which contain cellulose varnishes, alkyds, polysulfides, polyester, and many acrylics, may have excessive outgassing. If a particular varnish has higher than normally acceptable outgassing, it may be overcoated or sealed with at least 0.020 in. of an acceptable material to prevent any significant contamination.

X5.6 *Controls on Properties*—It is a general requirement that all materials used on spacecraft be identified fully and uniquely. This identification is not possible for almost all military and federal specification products. Any varnish must be tested and qualified for the specific application of use. This normally requires test and verification of both physical and mechanical properties, such as specific gravity, viscosity, and so forth.

X5.7 *Preferred Materials*—The most commonly acceptable varnishes and coatings are polyesterimides, polyimides, silicones, and urethane. Before using any of these systems, it is best to verify that they have adequate dielectric strength, acceptable outgassing behavior, and possess the ability to be applied in thin, uniform coatings. Compatibility with the materials to be coated and adjacent materials also are major considerations. It is important to establish functional suitability of the varnish in the intended application. Varnishes, which are acceptable when applied to polymers or metals, may crack or damage ceramic parts or glasses as a result of thermal coefficient of expansion mismatch. The clear preference is to use materials that are well characterized, readily available, have reproducible and reliable properties, are readily fabricated, and have a history of successful use in the intended applications.

X5.8 *Materials To Be Avoided*—Thixotropic coatings, materials with high coefficients of thermal expansion, or those with high outgassing or low dielectric strength are undesirable and should be avoided.

X6. SPECIFIC MATERIAL RECOMMENDATIONS—PAINTS

X6.1 *General*—The most common use of paints is for thermal control, but occasionally, they are used for light diffusion or for marking instead of inks. Properties of concern are outgassing, ability to bond to various substrates, solar absorptance, thermal emittance, tendency to chip or flake, and space environment stability. Some applications also require electrically conductive paints, which are available, but lack long-term exposure history. Common paint binders are polyurethane, silicones, silicates, epoxies, and acrylics. Primers to aid paint adhesion are recommended for most applications.

X6.2 *Mechanical and Physical Properties*—Mechanical behavior is not a concern. Physical properties of major interest include ease and consistency of application, reflectance and absorptance, resistance to damage and darkening in service, and stability and shelf life.

X6.3 *Corrosion and Stability*—Paints and primers are age sensitive and must have an expiration sticker on each container. Out-of-date paint must be requalified before use or scrapped.

X6.4 *Environmental Concerns*—Stability in electromagnetic radiation, vacuum, particle flux, and atomic oxygen are serious problems for most paints. White paints are particularly susceptible to degradation from environmental attack. Atomic oxygen damages almost all organically based paints. A notable exception to this is S13-GLO,[9] which is a methyl silicone binder paint. Zinc orthotitinate/potassium silicate white paint has been used when atomic oxygen is a concern, but this paint is difficult to apply, hard to handle, and almost impossible to

[9] S13-GLO, IITRI, 10 W. 35th St., Chicago, IL 60616.

clean if it becomes contaminated. It can chip easily if handled excessively.

X6.5 *Outgassing*—Outgassing is a problem because of the solvents and water present in paints. Paints often have TML values greater than 1.0% because of outgassing from water and solvents. If the paint is cured at a high enough temperature, or for a long enough time at room temperature, enough solvent and water may evolve so that TML is less than 1.0 %. Recent investigations demonstrated that even paints that pass the normal outgassing test may have unacceptable outgassing behavior at temperatures above 75°C but below 125°C.

X6.6 *Controls on Properties*—It is a general requirement that all materials used on spacecraft be identified fully and uniquely. This identification is not possible for almost all military or federal specification products. Any paint must be tested and qualified for the specific application of use. This normally requires adhesion testing on reference samples, optical properties, such as solar absorptance and thermal emittance, and viscosity.

X6.7 *Preferred Materials*—Selection of paints is very dependent on past successful experience with the paint or similar flight environments and applications. Ease of application, consistency of properties, long-term stability of optical properties in space, and low outgassing are the major concerns. Polyurethane is the most widely used black paint. Silicones and polyurethane are the most widely used white paints. Anodizing on aluminum also has been used successfully for applications in which exposure to atomic oxygen is a problem. There are acceptable conductive black polyurethane paints, but no fully acceptable conductive white paints at the present time, although development efforts to create such paints are in process. Conductive fillers in white paint evaluated so far cause degradation of reflectance and absorptance resulting in unacceptable thermal control performance.

X6.8 *Materials To Be Avoided*—It is preferable to avoid materials that have high outgassing, do not have a history of successful use in similar applications, are not well characterized, do not have dependable and reproducible properties, adhere poorly to surfaces that require painting, are difficult to handle and clean, have unstable optical properties when exposed to solar radiation in vacuum, are difficult or expensive to procure, or which have short shelf lives.

X7. SPECIFIC MATERIAL RECOMMENDATIONS—FILMS

X7.1 *General*—Films are used for electrical insulation, circuit substrates, and thermal control blankets. Materials may be polyesters, polyimides, PTFE, TFE, glass/epoxy, polyolefins, polyesters, acetyls, and polycarbonates. Thin metallic coatings may be applied to the films for optical/thermal properties. Metallized polymeric films often are used for thermal control blankets. They are fragile because the metal films are thin and easily damaged or eroded. Exercise care not to crack metal films during application. Atomic oxygen can attack these films and destroy the optical properties. Materials used inside the spacecraft body are protected from radiation and atomic oxygen, while thermal control materials are exposed and must be selected for resistance to those environments. Important properties are dielectric strength, outgassing, flexibility, thermal stability, flammability, electrostatic discharge (ESD) behavior, resistance to radiation, and resistance to atomic oxygen. Transfer of film coatings, such as adhesives to flight equipment, may be a problem and must be considered when selecting films for packaging or in contact with critica/ surfaces.

X7.2 *Mechanical and Physical Properties*—Mechanical properties normally are not a concern when selecting films. Physical properties, such as dielectric strength, absorptance, emittance, tear resistance, and fabricability, are of more interest.

X7.3 *Corrosion and Stability*—These concerns do not apply here.

X7.4 *Environmental Concerns*—Kapton (and FEP and TFE in orbits <500 km) are attacked by atomic oxygen and radiation. Multilayer blankets may require protection by putting a metallic or fiberglass cloth outer layer over the organic films. High humidity may attack metallized surfaces.

X7.5 *Outgassing*—Films generally have acceptable outgassing characteristics. Stability in vacuum is more of a problem and must be considered in the context of the application and space environment. ETFE is more stable in vacuum and radiation than TFE or FEP. Kapton is acceptable if not exposed to atomic oxygen. Polyester film is less stable, but acceptable for lower temperature applications. Polyolefins, polyvinyl, and acetates have high outgassing and are undesirable. Glass/epoxy boards are the standard circuit board material. Glass/polyimide also is acceptable for circuit boards when service conditions, such as temperature, are more severe, but it is more difficult to fabricate.

X7.6 *Controls on Properties*—It is a general requirement that all materials used on spacecraft be identified fully and uniquely. Military or federal specifications normally are adequate for bare films. Films must be tested and qualified for the specific application. Testing can include electric strength, outgassing, and absorptance and emittance when optical properties are important.

X7.7 *Preferred Materials*—The clear preference is to use materials that are well characterized, readily available, have reproducible and reliable properties, are fabricated readily, and have a history of successful use in the intended applications.

X7.8 *Materials To Be Avoided*—Polyolefins, polyvinyl, and acetates have high outgassing and are undesirable. Films with antistatic additives also tend to have excessive outgassing.

Galvanic couples can be induced between the metallized surface and other conductive materials if an electrolyte or a conductive path is present. It is preferable to avoid materials that do not have a history of successful use in similar applications, are not well characterized, do not have dependable and reproducible properties, or are subject to damage when exposed to solar radiation in vacuum. Some scrim-reinforced films may have excessive outgassing from the scrim or adhesives used to attach the scrim.

X8. SPECIFIC MATERIAL RECOMMENDATIONS—COMPOSITES AND REINFORCED RESINS

X8.1 *General*—Composites more than any other materials require an integrated design approach, from concept to environment, to application, materials interactions, joining and fastening, materials selection, fabrication, and lay-up. The resin matrices may be epoxies, phenolics, polyesters, polyimides, silicones, melamine, diallylphthlate, polycayanate, and polyphenylene oxide. Metal matrices that are used most often include aluminum alloys, titanium, and some refractory metals for special high temperature applications. Ceramic matrix composites are used sparingly but can be applied for special requirements. Fibers may be carbon, graphite, silicon carbide, glass, boron, various metals, and aramide. Some reinforcements have good thermal conductivity and can be used when thermal properties are important. Applications range from dielectric insulation, connector dielectric, primary structure, secondary structure, electronic trays, honeycomb face skins, antennas, solar panels, and circuit boards. Graphite-reinforced composites have low thermal expansion and can be designed to be very stable optical or radio platforms. One precaution for these applications is that certain composites may have long-term dimensional change as a result of loss of moisture in vacuum. Composites can be selected for good resistance to elevated temperatures but sometimes at a sacrifice in fabricability.

X8.2 *Mechanical and Physical Properties*—Properties of interest are modulus of elasticity, strength in tension and bending, compressive strength and modulus, coefficient of thermal expansion, dielectric strength, outgassing, resistance to atomic oxygen and radiation, availability, fabricability, possible distortion as a result of moisture absorption, and thermal stability. Mechanical and physical properties of composites are very dependant upon both the selection of the fibers and matrix materials and the method of fabrication. The same materials will give very different properties and behavior if they are laminated in a different sequence or have different arrangements of laminate stacking and orientation. When using composites, consider directionality of reinforcement and mechanical properties and methods of attachments. Crossply laminates are used to balance mechanical properties.

X8.3 *Corrosion and Stability*—Exposed carbon or graphite reinforcements can form an unacceptable galvanic couple with many metals. Stability of composites is determined by shelf life and stability of the matrix resins. It is necessary to retest and verify the important mechanical properties of any lot of composites that has exceeded normal shelf life.

X8.4 *Environmental Concerns*—Composites normally are resistant to radiation. Some composites are attacked by atomic oxygen and must be protected with a thin coating of metal. The degree of susceptibility is influenced more by the matrix materials and any external coatings than by the fibers.

X8.5 *Outgassing*—Polyesters and some polyimides have excessive outgassing, as do many silicones. Actual outgassing behavior should be verified for specific composites of interest since variations in the matrix material or methods of fabrication can influence outgassing.

X8.6 *Controls on Properties*—Circuit board materials or reinforced molding materials for connectors or dielectrics can be selected for dielectric strength, ease of fabrication, low outgassing, and availability. Structural composite selection is very application dependent. Some composites have high stiffness but lower strength, others have high compressive strength, and some have high tensile strength but lower modulus of elasticity. Some are more notch sensitive and thus harder to fasten mechanically without damage. Others have excellent mechanical properties but are difficult to fabricate or require special treatments that make them expensive and sensitive to manufacturing errors. Test and qualify the particular combination of fiber matrix and lamination or assembly that will be used in service. Specifications are required for each type of composite since the final product will be tailored for some specific application or environment.

X8.7 *Preferred Materials*—Use composite materials that are well characterized, readily available, have reproducible and reliable properties, are fabricated readily, demonstrate low outgassing, and have a history of successful use in the intended applications.

X8.8 *Materials To Be Avoided*—It is preferable to avoid materials that do not have a history of successful use in similar applications, are not well characterized, do not have dependable and reproducible properties, or are not known to be stable in the expected environment. Composites can be difficult to reproduce, so it is more prudent to use an established material with slightly inferior mechanical and physical properties than an unproven composite, which theoretically has better performance.

X9. SPECIFIC MATERIAL RECOMMENDATIONS—LUBRICANTS

X9.1 *General*—Moving parts require lubrication, even if the number of times the parts move is very limited. Metals may cold weld or gall in vacuum if there are no lubricants or barrier films. Some applications, such as gyros, scan mechanisms, thermal control louvers, rotatable antennas, and solar arrays require lubricants capable of long-term stability and operation in the space environment. Commonly, there are several types of lubricants used. Dry films are predominantly molybdenum disulfide, tantalum disulfide, tungsten disulfide, or tungsten diselenide, with or without additives. Oils and greases may be hydrocarbons, silicones, diesters, flourocarbons, flouroelastomers, polyglycols, or esters. Some materials have self-lubricating qualities, such as Teflon, some nylons, and some modified polyimides. Soft metals, such as gold, silver, and gallium occasionally are used for special applications. Cadmium sometimes is used as a lubricant for terrestrial applications, but never should be used in space.

X9.2 *Mechanical and Physical Properties*—Lubricant migration, especially of greases and oils, is a problem. Properties, such as viscosity and specific gravity, are important indicators of reproducible performance. Oils need high-speed, low-load applications to work well. For low-duty cycles and heavy loads, greases are better. Fluid lubricants can be designed into the system so that they have an adequate reservoir for intended flight lifetime and feed slowly enough to provide adequate lubrication. Newly lubricated surfaces should be run in and recleaned before use. It is common practice to lubricate components, run them in, clean off the lubricant and any wear products, and then relubricate. Dry film lubricants must be applied properly to clean dry surfaces and often require wearing or burnishing before use for proper performance. There can be tolerance buildup from application of dry film lubricants, so allowances should be made for added lubricant thickness. Vacuum stability and low outgassing is important for lubrication outside of hermetically sealed units. If the unit is hermetically sealed, such as gyros, space and vacuum compatibility is less important.

X9.3 *Corrosion and Stability*—Lubricants are age sensitive and must have an expiration sticker on each container. Do not use expired materials without first testing them and verifying proper performance. Lubricants are not corrosive and should not cause attack on surfaces. In fact, they often are used to prevent corrosive attack.

X9.4 *Environmental Concerns*—Lubricants that are used successfully on earth are not necessarily usable in space. Graphite or lubricants with significant amounts of graphite are abrasive in vacuum. Hydrocarbons tend to be unstable with high outgassing and degraded by radiation. Esters are relatively sensitive to radiation and may outgas excessively. Some oils, such as the Krytox®[10] family tend to creep and may leave the lubricated surfaces if seal and labyrinth design is inadequate. In contrast, Bray[11] oils and greases are stable in vacuum and have low tendency to creep. Molybdenum disulfide can be attacked by A.O. in low earth orbit and change into a nonlubricating oxide.

X9.5 *Outgassing*—It is essential that all candidate lubricants be tested for outgassing. Some of the highest outgassing values reported for any materials were obtained on lubricants and greases. High outgassing not only is a source of contamination for sensitive surfaces, it also can cause significant depletion of the lubricant and destroy the functionality of the grease or oil. Testing of receiving lots of oils, greases, and similar lubricants for outgassing is recommended. It is possible to devolatize some oils before use, resulting in acceptable outgassing and no loss in functional behavior.

X9.6 *Controls on Properties*—Vendor, supplier, military, or federal specifications are not likely to be adequate since they often are intended for different applications and duty cycles than spacecraft. Outgassing requirements must be stated, as well as any properties that can impact performance, such as creep and lack of wetability. Dry film lubricants may be adequately controlled by military specifications, but greases and oils are not because outgassing is not a requirement in the military specifications.

X9.7 *Preferred Materials*—Lubricating ability in vacuum and zero gravity is essential, as is stability and low outgassing. Bray oils and greases are stable in vacuum and have low tendency to creep. Krytox lubricants are stable but tend to creep and require controls on migration. Dry film lubricants, such as molybdenum disulfide, tantalum disulfide, tungsten disulfide, or tungsten diselenide, with or without additives, have been used successfully.

X9.8 *Materials To Be Avoided*—Avoid using graphite or dry film lubricants with significant amounts of graphite. Greases or oils with more than 6 to 8 % TML should be avoided because they may be too unstable in vacuum to provide adequate lubrication.

---

[10] Krytox®, DuPont Krytox® Performance Lubricants, Chamber Works, Bldg. 603, Deepwater, NJ 08023.

[11] Brayoils, Castrol Specialty Products Division, 16715 Von Karmen Ave., Suite 230, Irvine, CA 92714–4918.

X10. SPECIFIC MATERIAL RECOMMENDATIONS—CERAMICS AND GLASSES

X10.1 *General*—Ceramic materials commonly are used as substrates in electronic devices, such as hybrids, for electrical or thermal insulation and sometimes for dimensional control. Materials used for solar cells and integrated circuits can be considered classes of ceramic since the silicon crystals have ceramic rather than metallic or elastomeric mechanical behavior. Glasses most often are used as lenses in optics or sensors, covers or solar cells, or dielectric seals in electrical terminals. Because of the brittle failure mode of ceramics and glasses, they should be loaded only in compression, not in tension or shear. They are not particularly sensitive to vacuum or atomic oxygen, although optical glasses and sensors can be damaged by high fluxes of atomic oxygen. Radiation can darken or discolor some glasses.

X10.2 *Mechanical and Physical Properties*—Mechanical properties usually are of little interest. Physical properties, such as dielectric strength, loss tangent, specific gravity, and hardness, are often specified and controlled.

X10.3 *Corrosion and Stability*—Corrosion is not an issue, but some of the optical coatings and mounting materials may be unstable in vacuum or UV and should be evaluated for suitability in the intended environment.

X10.4 *Environmental Concerns*—When selecting glasses and ceramics, it is important to consider how they will be joined or mounted and the nature of environmental exposure. Thermal shock or severe thermal cycling can crack them. If they are mounted too rigidly, or not properly aligned, minor changes in loading or dimensions, as from thermal exposure, can cause fracture. Solvents should be evaluated for compatibility before they are used on sensitive surfaces, such as optical components.

X10.5 *Outgassing*—This property does not apply.

X10.6 *Controls on Properties*—The controls required depend upon the application or function. Electrical properties, such as dielectric strength, loss tangent, and electrical and thermal conductivity, are often important and must be specified. Composition is important both to ensure reproducible properties and that any beryllia is identified and can be handled so that no health hazards are imposed.

X10.7 *Preferred Materials*—Materials that are readily available with the desired properties and pose no health or functional concerns are preferred. Also, it is very desirable if the ceramics can be made with repeatable properties using standard materials and processes.

X10.8 *Materials To Be Avoided*—Avoid novel materials that are not widely available or have little or no history of successful use in the intended application. Toxic materials, such as beryillia, should be identified and avoided if possible.

X11. SPECIFIC MATERIAL RECOMMENDATIONS—RUBBERS

X11.1 *General*—Rubbers tend to be generic with widely varying properties and suitability for space applications even within the same family. Most rubbers are formulated and used in commercial applications. The special requirements for space use are of little interest to suppliers, so it is important to establish by test and evaluation which rubbers are suitable for specific functions. Rubbers may be used as formed and cast parts, they may be filled with additives to increase thermal or electrical conductivity, or they may have fiber reinforcements to improve strength or stiffness or be coated sheet or films.

X11.2 *Mechanical and Physical Properties*—Properties of interest include resistance to solvents, hardness, tensile strength and elongation, flexibility especially at low temperature, dielectric strength, and resistance to radiation and atomic oxygen (in low earth orbit).

X11.3 *Usage Precautions*—Rubbers may lose physical and mechanical properties when exposed to certain chemicals or extreme environments. Test and verify the functional acceptability of this class of materials in the intended applications, particularly for long-term service. Some property losses, such as softening or swelling in contact with solvents and fuels, or reactions with radiation, may not become apparent immediately, so long-term testing usually is required.

X11.4 *Corrosion and Stability*—Corrosion does not apply. Rubbers and elastomers can be attacked by a variety of solvents and fluids, including propellants. There are standard tests for resistance to fluids, which must be performed on any candidate rubber or elastomer, before introducing it into contact with flight components.

X11.5 *Environmental Concerns*—Rubbers and elastomers also can be damaged by atomic oxygen, solar radiation, and radiation in vacuum. Solvent and fluid compatibility is very important and must be established for any rubber in contact with fluids, solvents, or lubricants. Most rubbers are damaged by radiation exposure, so they must be used inside the spacecraft body or otherwise protected. Usable temperatures seldom are lower than −80 to −100°C or above 250 to 300°C. Most rubbers are sensitive to heat and may take a permanent set or degrade.

X11.6 *Outgassing*—There are a number of rubber formulations, including flouroelastomers (viton), silicones, butyl, polychloroprene, polyurethane, acrylics, and ethylene-propylene. Many of these, such as butyl, polysulfide, and nitrile rubbers, have excessive outgassing. Silicone rubbers may have very low outgassing, or outgassing may be excessive, depending on the grade of silicone and even the particular lot used. It is possible to prebake silicone rubbers and reduce outgassing to acceptable levels, even when the as-received silicone has high outgassing. A temperature of 175°C for 24 h has been found to reduce outgassing to acceptable levels for silicone rubbers. Often, it is more cost-effective to bake every lot of silicone rubber or lot of connectors using silicone rubber inserts, rather than lot test for outgassing.

X11.7 *Controls on Properties*—It is a general requirement that all materials used on spacecraft be identified fully and uniquely. This identification is not possible for almost all military or federal specification products. Silicone rubbers generally are supplied to federal specifications, but lots of the same class of silicone can vary widely in outgassing behavior. Lot testing or generic prebaking is advisable. Other properties, such as hardness, dielectric strength, tensile strength, tear resistance, and so forth should be tested as required to verify material quality and consistency.

X11.8 *Preferred Materials*—Selection of rubbers and elastomers is very application dependent because of the compatibility and stability problems encountered with this class of materials. The most stable types of elastomers are flouroelastomers, such as viton, ethylene-propylene, and prebaked silicone rubbers.

X11.9 *Materials To Be Avoided*—Butyl, buna-N, nitrile, and Neoprene®[12] rubbers have high outgassing and are often unstable in fluids and propellants used on spacecraft. Silicone rubbers must be approached with caution because there is wide lot-to-lot variability in properties, such as outgassing.

[12] Neoprene®, DuPont de Nemours, E.I., & Co., Inc., Barley Mill Plaza Bldg, 10 Wilmington, DE 19880–0010.

X12. SPECIFIC MATERIAL RECOMMENDATIONS—INKS AND MARKING MATERIALS

X12.1 *General*—The most common marking material is epoxy ink, which is resistant to most solvents, resists wear and abrasion, and is available in a number of colors. Inks may be applied by silk screening or rubber stamping. These epoxy inks generally will cure at room temperature, but curing can be accelerated by heating to moderate temperatures in the range of 50 to 75°C. Another type of epoxy marking ink is commonly used to identify hybrids and ceramic substrates. These inks typically cure at 125 to 150°C, and thus, have limited applicability for equipment designed for normal spacecraft operating temperatures of 75°C or less. Marking also may be done by adding colored dye to approved materials to produce custom marking. Examples are titanium dioxide or carbon added to a conformal coating to make white or black marking material and various fillers or dyes added to clear epoxy or to silicones to give a marking and identification coating. In cases in which the mass of ink is significant, or when sensitive surfaces may be damaged by deposition of water or solvents, postbaking or overcoating and sealing the ink may be necessary. Typical overcoatings are approved clear epoxy, polyurethane conformal coats, or occasionally clear silicones.

X12.2 *Mechanical and Physical Properties*—These properties do not apply.

X12.3 *Corrosion and Stability*—Inks are not corrosive, but they do have a limited shelf life. Over time, inks may separate out and lose color consistency and fluidity. Containers should have an expiration date, as well as a lot code. If the shelf life is exceeded, the ink may be used only if it is shown to still have acceptable marking, appearance, and adhesion. In general, it is more cost-effective to scrap out-of-date ink than to requalify it by testing.

X12.4 *Environmental Concerns*—Some marking materials may be attacked by atomic oxygen, for example, Kapton or Mylar labels. Others may be sensitive to propellants or strong oxidizers. Most epoxy inks and shrinkable tubing resist normal solvents and atomic oxygen.

X12.5 *Outgassing*—Almost all inks have relatively high outgassing TML because they are composed largely of water and solvents. Since the mass of ink used generally is small, the actual total amount of outgassing is small. Outgassed products decrease significantly over time as inks continue to cure, and the outgasses products condense only at low temperatures, so the use of inks with TML in the 2 to 6 % range usually is given a general approval waiver.

X12.6 *Controls on Properties*—Inks usually are purchased to military or federal specifications. These specifications do not control important properties, such as shelf life and outgassing; therefore, it is preferable to control inks and other marking materials with tailored specifications, which adequately define and control properties of interest, such as outgassing. Marking materials should be checked regularly to verify acceptable properties, such as clarity, specific gravity, adhesion for tapes and markers, and outgassing. Tests of marking durability also may be needed.

X12.7 *Preferred Materials*—Epoxy inks are the most commonly used marking materials. They have been applied successfully for decades, are simple to apply, and resist solvents and normal handling. Recently, there has been a reduction in the variety of colors available. The disadvantages of inks are the curing time required and the relatively high TML as a result of the very high percentage of water and solvents in inks. Wire and cable marking may be done with shrink tubing, which is embossed or marked with identification codes. The tubing is an approved low outgassing material modified for marking. Adhesive labels and tags also may be used for wire and cable marking if the tag material with adhesive passes outgassing and the adhesive is shown to provide adequate resistance to solvents and normal handling so that it will not come off. Typically, printed Mylar or Kapton film with acrylic adhesive is acceptable. These labels occasionally are used to mark equipment, in which case additional bonding or overcoating with an approved clear conformal coat, epoxy, or silicone is suggested, to protect the label from handling and damage and to assure it does not come off. Bar code labels sometimes are used to mark and identify parts and subsystems. They are made of the same approved film materials with approved adhesives as described in X12.4, that is, Kapton or Mylar with acrylic adhesive.

X12.8 *Materials To Be Avoided*—Decals and commercial labels should be avoided. They rarely have acceptable outgassing properties, and usually use rubber or silicone adhesives, which have excessive outgassing and often are weaker and less resistant to solvents and handling damage than Mylar/acrylic or Kapton/acrylic. Backing materials, such as paper or cloth, may be less resistant to handling damage and have higher outgassing. Metal labels should be avoided and are not recommended for any applications unless they are attached mechanically or firmly adhesively attached and overcoated. If a metal label is detached in flight, it introduces a reflective, conductive item floating around the spacecraft. It may cause shorts, arcs, reflections into optical devices, or may jam mechanisms. In addition, metal labels are significantly heavier than any other marking method and can add appreciable nonfunctional mass to the payload.

X13. SPECIFIC MATERIAL RECOMMENDATIONS—TWINE, LACING, AND MISCELLANEOUS FASTENERS

X13.1 *General*—Twine and lacing tape normally are used to secure wire and cable bundles. The commonly used materials are Dacron®[13], nylon, and Teflon. Dacron itself is acceptable, but the lacing tapes may have excessive outgassing if they are coated with lubricant or protective material, such as wax. Teflon and ETFE tapes should be heat cut rather than mechanically cut to avoid sharp edges. Nylon tapes, like nylons in general, are hydrophilic and will have high TML, much of which is water. The usual precautions regarding use of materials, that outgas water apply to nylon lacing tape.

X13.2 *Mechanical and Physical Properties*—All lacing tapes should have the tie or knot locked with a drop of epoxy or silicone adhesive, or by mechanical locking, to prevent untying and loosening of the wrapping in service. If mechanical properties, such as strength and elongation are important, it is preferable to test and verify the properties directly rather than use vendor certifications, which usually are generic and listed only as "typical" values.

X13.3 *Corrosion and Stability*—Corrosion does not apply. Stability is not a concern for most lacing tapes or fasteners. The major exceptions are nylon, Teflon, TFE, and FEP, which become brittle when exposed to radiation in vacuum. These materials must be used judiciously and protected from radiation exposure.

X13.4 *Environmental Concerns*—Teflon and nylon lacing tape should be used where they are not directly exposed to radiation and vacuum, which can cause embrittlement.

X13.5 *Outgassing*—Dacron and nylon thread is used to sew and secure thermal control blankets, attach pads to the blankets, and secure blankets to adjacent surfaces. Dacron thread is preferred since it has acceptable physical and mechanical properties and low outgassing.

X13.6 *Controls on Properties*—Lot testing of Dacron tapes is prudent to verify that no high outgassing coatings are present. If a lot of Dacron tape fails outgassing, it can be made acceptable by prebaking at 125 to 150°C for 24 to 48 h.

X13.7 *Preferred Materials*—Dacron and Teflon are the preferred lacing tape materials. Verify that Dacron tapes do not have rubberized coatings or any other surface treatment which can outgas. Dacron thread is used widely for thermal blanket sewing and assembly. Velcro®[14] tape is very useful for applications in which frequent removal and reinstallation of items is anticipated or when ease of attachment is important, and service loads are relatively light.

X13.8 *Materials To Be Avoided*—Nylon tapes and thread are less desirable because of the relatively high TML from outgassing of absorbed water and because nylon tends to become stiff and brittle in vacuum with solar radiation. Thread or tape, which is coated, should be evaluated for acceptability, since some coating outgas and others are unstable in vacuum or solar radiation, or both. Examples of possibly troublesome combinations are rubberized Dacron Velcro with silicone or rubber adhesives or Teflon, which is highly loaded in compression such that it may be cut through or creep.

X13.9 *Special Contamination Potential*—Velcro tape is used to secure blankets and occasionally other objects. The tape material and adhesives normally are made from acceptable materials, such as polyester. Physical, mechanical, and functional suitability must be demonstrated for each application. In addition, outgassing properties must be verified. Making and breaking the contacts between the Velcro hooks and eyes creates dust and debris from damaged and broken fibers. It is important to either preclean the Velcro tape before application or to vacuum and otherwise clean up any dust and debris caused by applying and opening or closing the Velcro.

[13] Dacron®, DuPont de Nemours, E.I., & Co., Inc, Barley Mill Plaza, Bldg. 10, Wilmington, DE 19880–0010.

[14] Velcro®, Velcro USA Inc., 406 Brown Ave., PO Box 5218, Manchester, NH 03108.

X14. SPECIFIC MATERIAL RECOMMENDATIONS—WIRE INSULATION AND SLEEVING

X14.1 *General*—Wires may have conductors that are copper, aluminum, silver, or combinations of these metals. The wire insulation should be selected for compatibility with the core wire, adequate physical and mechanical properties, such as the resistance to cut through and handle damage, and resistance to process environments, such as solvents, potting, and staking materials, and the flight environment. Testing for outgassing before use is essential when specifying silicone wire insulation. Kapton insulation is susceptible to arc tracking and can arc and short, even in vacuum or underwater. The specific applications for Kapton-insulated wire must be evaluated carefully to ensure that arc tracking is very unlikely to occur.

X14.2 *Mechanical and Physical Properties*—Important considerations when selecting wire insulation are the required dielectric strength, ability to strip the insulation without damage to the wire, resistance to processing materials, such as solvents, coatings, and so forth, resistance to cold flow and cut through, and resistance to the space environment. Teflon is subject to radiation damage and should not be used unprotected on the exterior part of the spacecraft. It also is subject to cold flow, so it must be used with care. It must not be routed over sharp corners or edges and must be protected from contact with surfaces that can cause indentation or cold flow. Typically, Teflon-coated wires are protected with gaskets, tape, or soft cushions of organic materials when they are routed near sharp edges or corners. ETFE is much more resistant to radiation, cold flow, and cut through than Teflon. However, ETFE may be damaged by exposure to high temperatures, above about 250°C, which can cause it to become brittle and susceptible to cracking and damage when flexed or bent. Kynar®[15] and Kapton have good dielectric strength and are not subject to cold flow or radiation sensitivity. Kapton is somewhat more difficult to strip.

X14.3 *Corrosion and Stability*—These properties do not apply.

[15] Kynar®, ELF Atochem North America, Inc.

X14.4 *Environmental Concerns*—Wire and cable insulation sleeving is used to provide protection and add insulation for wires, cables, and connections. The tubing must be usable at a temperature compatible with the specific application. For example, selecting a high temperature shrinking material such as Teflon to apply to low temperature melting solder joints is inadvisable. Materials such as PVC and polyolefin should be avoided as they have unacceptable outgassing. If use of these materials is desired, individual lots must be tested for outgassing.

X14.5 *Outgassing*—Kynar, Kapton, Teflon, ETFE, FEP, and TFE insulation and combinations of these insulations have acceptable outgassing. Silicone insulation may have excessive outgassing and must be lot tested. It is often possible to reduce outgassing of silicone wire insulation to acceptable levels by baking the wire for at least 24 h at 175°C. PVC and polyolefin wire insulations have excessive outgassing

X14.6 *Controls on Properties*—It is a general requirement that all materials used on spacecraft be identified fully and uniquely. This is not possible for almost all military or federal specification products.

X14.7 *Preferred Materials*—The preferred wire insulations are polyvinylidine fluoride (Kynar), ETFE, Kapton, mixed polyester/polyamide, and Teflon. Polyester also is acceptable for many applications. Some silicone insulations have been found to pass outgassing and are acceptable, but others fail.

X14.8 *Materials To Be Avoided*—Many commercial wire insulation and sleeking materials are unacceptable for space applications. Examples include PVC, polyolefins, and most silicones. These materials almost always have excessive outgassing. Use of Teflon, TFE, and FEP wire insulation must be done with care and attention to both the intended application and the flight environment. For example, fluorocarbons, such as FEP and TFE, are subject to cold flow and cut through when loaded in contact with sharp edges, and they become brittle in vacuum when exposed to solar radiation. This class of wire insulation must protected from radiation and loading in contact with sharp edges or corners. Kapton insulation is subject to arc tracking and should be avoided.