~~Designation:E1997–99 (Reapproved 2003)$^{\epsilon 1}$~~ Designation: E 1997 – 07

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.

~~ϵ^1 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-5Metallic Materials and Elements for Aerospace Vehicle Structures[4]~~

MIL-STD-889 Dissimilar Materials

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

MIL-HDBK-17 Properties of Composite Materials

2.4 *European Space Agency (ESA) Standard:*

~~PSS-07/QRM-0Guidelines for Space Materials Selection~~

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,

---

[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 E1997–99.~~

Current edition approved Dec. 1, 2007. Published January 2008. Originally approved in 1999. Last previous edition approved in 2003 as E 1997 – 99(2003) $^{\epsilon 1}$.

[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.

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 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.~~ such as cadmium and zinc also can grow whiskers and should not be used.

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. Certain applications such as elevated temperature service may require use of ceramics or refractory metals. That should not reduce the need for careful review and functional design of the equipment. 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.~~ 1—The test is defined as performed at 125°C unless clearly stated otherwise; therefore, acceptability is limited to exposures below 125°C. The test temperature of 125°C was assumed to be significantly above the expected operating temperature in service. If expected operating temperatures exceed 65 to 70°C the test temperature should be increased. It is suggested that the test temperature be at least 30°C higher than expected maximum service temperature in order to provide material comparisons for TML and CVCM.

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.

---

[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.

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. There have been cases of vendors supplying lots of materials that were tested and rejected by one customer to other customers without noting the prior rejection and reason. 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. 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 for particular programs, 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. The list should be configuration controlled and issued in the same manner as a specification or drawing with required approval signatures.

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,~~impacts, 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

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

7.1 applications; contamination; design; design review; materials applications; materials selection; preferred materials; problem materials; process list; processes; space applications; spacecraft materials; testing; unmanned spacecraft

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 trans-uranium 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~~85 to ~~125°C,~~90°C, the material should be tested for outgassing at ~~or~~least 30°C 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.