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Solid Lubricants and Coatings for Extreme Environments: State-of-the-Art Survey

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Summary

An investigation was conducted to survey anticipated requirements for solid lubricants in lunar and Martian environments, as well as the effects of these environments on lubricants and their performance and durability. The success of habitats and vehicles on the Moon and Mars, and ultimately, of the human exploration of and permanent human presence on the Moon and Mars, are critically dependent on the correct and reliable operation of many moving mechanical assemblies and tribological components. The coefficient of friction and lifetime of any lubricant generally vary with the environment, and lubricants have very different characteristics under different conditions. It is essential, therefore, to select the right lubrication technique and lubricant for each mechanical and tribological application. Several environmental factors are hazardous to performance integrity on the Moon and Mars. Potential threats common to both the Moon and Mars are low ambient temperatures, wide daily temperature swings (thermal cycling), solar flux, cosmic radiation, and large quantities of dust. The surface of Mars has the additional challenges of dust storms, winds, and a carbon dioxide atmosphere. Solid lubricants and coatings are needed for lunar and Martian applications, where liquid lubricants are ineffective and undesirable, and these lubricants must perform well in the extreme environments of the Moon, Mars, and space, as well as on Earth, where they will be assembled and tested. No solid lubricants and coatings and their systems currently exist or have been validated that meet these requirements, so new solid lubricants must be designed and validated for these applications.

Introduction

In the 1960s, space lubrication needs prompted increased research into solid lubrication, with an emphasis on the role of the atmosphere. Ways of using solid lubricants were explored (refs. 1 to 3). By the early 1970’s, when many of the problems had been resolved and their limitations defined, most of the research had stopped. Recently, however, a number of new applications have arisen that have prompted renewed interest. These include lightweight moving mechanical assemblies and tribological components for long-term service in space mechanisms, and cages for turbopump bearings operating in liquid hydrogen and oxygen. The new requirements are primarily long-term life and successful operation over a broad temperature range. New solid lubricants are needed to meet these requirements (refs. 1 and 4).

In the foreseeable future, NASA’s space goals include a permanent manned presence on the Moon and an expedition to the planet Mars (ref. 5). The success of habitats and vehicles on the Moon and Mars, and ultimately, of the human exploration of and permanent human presence on the Moon and Mars, are critically dependent on the correct and reliable operation of many moving mechanical assemblies and tribological components (ref. 6). It is essential, therefore, to have a thorough understanding of tribological components, such as bearings and gears, and of how to select the right lubrication for each application (ref. 7). This may require designing for new solid lubricants and design validation efforts in applications where liquid lubricants are ineffective and undesirable. Environmental interactions will have to be considered carefully in the selection and design of the required durable solid lubricants. Several environmental factors may be hazardous to performance integrity. Potential threats common to both the Moon and Mars are low ambient temperatures, wide daily temperature swings (thermal cycling), solar flux, cosmic radiation, and large quantities of dust (table I; refs. 8 to 11). The surface of Mars provides the additional challenges of dust storms, winds, and a carbon dioxide atmosphere. In this survey, the anticipated requirements for solid lubricants and their protection from wear and abrasion are described, as well as the impact of lunar and Martian environmental factors on lubricants and their durability.

TABLE I.—MINIMUM, MEAN, AND MAXIMUM SURFACE TEMPERATURES OF THE EARTH, THE MOON, AND MARS

	Temperature								
	K			°C			°F		
	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.
Earth	184	288	331	–89	15	58	–128	59	136
Moon	126	250	373	–147	–23	100	–233	–9	212
Mars	161	213	265	–112	–60	–8	–170	–76	17

The specific aim of the survey is to collect information on the following:

- Selection of lubricant type
- Advantages and disadvantages of solid lubricants
- Ranges of application of solid lubricants
- Suppliers of advanced solid lubricants and coatings
- State-of-the-art coatings research
- Designing for solid lubricants and coatings
- Tribological and surface characterization

Selection of Lubricant Type

Lubricating films have three classifications: solid films, fluid films, and thin films (table II; refs. 1 to 4 and 12 to 27). The most commonly used solid lubricants and their characteristics are summarized in table III. Solid lubricants are used when liquid lubricants do not meet the advanced requirements of modern technology (table IV). Oils or greases cannot be used in many applications because of the difficulty in applying them, sealing problems, weight, or other factors, such as environmental conditions. Solid lubricants may be preferred to liquid or gas films because they reduce weight and simplify lubrication. For many applications, solid lubricants are less expensive than oil and grease lubrication systems.

TABLE II.—TYPES OF LUBRICATING FILMS

Type	Lubricating films
Solid films	Nanotubes, nano-onions, and other nanoparticles (C, BN, MoS_2, and WS_2) Nanocomposite coatings (WC/C, MoS_2/C, WS_2/C, TiC/C, and nanodiamond) Diamond and diamondlike carbon coatings (diamond, hydrogenated carbon (a-C:H), amorphous carbon (a-C), carbon nitride (C_3N_4), and boron nitride (BN) films) Superhard or hard coatings (VC, B_4C, Al_2O_3, SiC, Si_3O_4, TiC, TiN, TiCN, AlN, and BN) Lamellar film (MoS_2 and graphite) Nonmetallic film (titanium dioxide, calcium fluoride, glasses, lead oxide, zinc oxide, and tin oxide) Soft metallic film (lead, gold, silver, indium, copper, and zinc) Self-lubricating composites (nanotubes, polymer, metal-lamellar solid, carbon, graphite, ceramic, and cermets) Lamellar carbon compound film (fluorinated graphite and graphite fluoride) Carbon Polymers (PTFE,[a] nylon, and polyethylene) Fats, soap, wax (stearic acid) Ceramics and cermets
Fluid films	Hydrodynamic film: Thick hydrodynamic film Elastohydrodynamic film Hydrostatic film Squeeze film
Thin films	Mixed lubricating film Boundary lubricating film
Gas films	Hydrodynamic film Hydrostatic film

[a] Polytetrafluoroethylene.

TABLE III.—THE MOST COMMONLY USED SOLID LUBRICANTS AND THEIR CHARACTERISTICS

Solid lubricant	Characteristics
MoS_2	MoS_2 has a low coefficient of friction both in vacuum and atmosphere, and it does not rely on adsorbed vapors or moisture. Its thermal stability in nonoxidizing environments is acceptable to 1373 K, but in air the temperature limitation of MoS_2 may be reduced to a range of 623 to 673 K by oxidation. Adsorbed water vapors and oxidizing environments may actually result in a slight, but insignificant, increase in friction. MoS_2 has greater load-carrying capacity than other commonly used lubricants, such as graphite and PTFE. MoS_2 has a hexagonal crystal structure with the intrinsic property of easy shear. The lubrication performance of MoS_2 often exceeds that of graphite, and MoS_2 is effective in vacuum where graphite is not.
Graphite	Graphite has a low coefficient of friction and very high thermal stability (2273 K and above). Graphite has a hexagonal crystal structure with the intrinsic property of easy shear, although graphite relies on adsorbed moisture or water vapors to achieve low friction. Use in dry environments, particularly in vacuum, may be limited. At temperatures as low as 373 K, the amount of water vapor adsorbed may be reduced to the point that low friction cannot be maintained, so sufficient water vapor may be deliberately introduced to maintain low friction. Practical application at high temperatures is limited to a range of 773 to 873 K because of oxidation. When necessary, additives composed of inorganic compounds may be added to enable use at temperatures to 823 K.
PTFE[a]	PTFE has a low coefficient of friction both in vacuum and atmosphere because of a lack of chemical reactivity. PTFE does not rely on adsorbed vapors or moisture. It possesses low surface energy and does not have a layered structure. The macromolecules of PTFE slip easily along each other, similar to lamellar structures. Practical application temperatures range from 173 to 523 K. PTFE does not have greater load-carrying capacity and durability than other alternatives. The low thermal conductivity of PTFE inhibits heat dissipation, which causes premature failure due to melting and limits use to low-speed sliding applications where MoS_2 is not satisfactory. PTFE shows one of the smallest coefficients of static and dynamic friction, down to 0.04. Operating temperatures are limited to about 523 K.
Soft metals	Lead, gold, silver, copper, indium, and zinc possess relatively low coefficients of friction both in vacuum and atmosphere because of their low shear strengths. These metals are extremely useful for high-temperature applications up to 1273 K and for rolling element applications, such as roller bearings, where sliding is minimal.

[a] Polytetrafluoroethylene.

TABLE IV. —APPLICATION OF SOLID LUBRICANTS

(a) Areas where fluid lubricants are undesirable.

Requirement	Applications
Resist abrasion in dirt-laden environments	Space vehicles (rovers) Lunar base Martian base Aircraft Automobiles Agricultural and mining equipment Off-road vehicles and equipment Construction equipment Textile equipment Dental implants
Avoid contaminating product or environment	Space telescopes Equipment in lunar base Equipment in Martian base Microscopes and cameras Spectroscopes Medical and dental equipment Artificial implants Food-processing machines Optical equipment Metalworking equipment Surface-mounted equipment Hard disks and tape recorders Textile equipment Paper-processing machines Business machines Automobiles
Maintain servicing or lubrication in inaccessible or hard-to-access areas	Space vehicles Satellites Aerospace mechanisms Nuclear reactors Consumer durables Aircraft
Provide prolonged storage or stationary service	Space telescope mounts Space antenna mounts Aircraft equipment Railway equipment Missile components Nuclear reactors Heavy plants, buildings, and bridges Furnaces

TABLE IV.—Concluded.
(b) Areas where fluid lubricants are ineffective.

Environment		Applications
High vacuum	Room temperature or cryogenic temperatures	Vacuum products Space mechanisms Satellites Space telescope mounts Space platforms Space antennas
	Clean room	Biomedical equipment Analytical tools Coating equipment Semiconductor manufacturing equipment
	High temperature	Space nuclear reactors X-ray tubes X-ray equipment Furnaces
High temperatures	Lunar environments	Space vehicles Space mechanisms Lunar bases
	Air atmosphere	Furnaces Metalworking equipment Compressors
	Molten metals (sodium, zinc, etc.)	Nuclear reactors Molten metal plating equipment
Cryogenic temperatures		Lunar and Martian bases Space mechanisms Satellites Space vehicles Space propulsion systems Space telescope mounts Space platforms Space antennas Turbopumps Liquid nitrogen pumps Butane pumps Freon pumps Liquid natural gas pumps Liquid propane pumps Refrigeration plants
Radiation (gamma rays, fast neutrons, x rays, beta rays, etc.)		Lunar and Martian bases Nuclear reactors Space mechanisms Satellites Space vehicles Space platforms Space antennas
Corrosive gases (chlorine, etc.)		Maneuvering Semiconductor manufacturing equipment
High pressures or loads		Metalworking equipment Bridge supports Plant supports Building supports
Fretting wear and corrosion (general)		Space antennas Space platforms Aircraft engines Turbine blades Landing gear Automobiles

Advantages and Disadvantages of Solid Lubricants, and Applications for Solid Lubricants

Table V shows some advantages and disadvantages of solid lubrication (refs. 1 to 4 and 18). Under high vacuums, high temperatures, cryogenic temperatures, radiation, high dust, or corrosive environments, solid lubrication may be the only feasible system. In addition, figures 1 to 3 present critical operating conditions under which fluid lubricants are ineffective or undesirable, along with the most common conditions requiring the use of solid lubricants:

(1) In extreme pressure conditions (i.e., high to ultrahigh vacuum conditions—a vacuum of $\sim 10^{-2}$ Pa or higher or a gas density of $\sim 10^{-12}$ molecules/cm^3 or lower at 298 K), such as space, lubricants can volatilize. In high-vacuum environments (such as space-vacuum environments), a liquid lubricant would evaporate and contaminate the device, such as optical and electronic equipment.

(2) In extremely high temperature conditions, liquid lubricants can decompose or oxidize. Suitable solid lubricants can extend the operating temperatures of systems beyond 523 or 573 K while maintaining relatively low coefficients of friction.

(3) In cryogenic temperatures, liquid lubricants can solidify or become highly viscous and not be effective. Suitable solid lubricants can extend the operating temperatures of systems down to 0 K.

(4) In radiation environments, liquid lubricants can decompose. Suitable solid lubricants can extend the operation of systems beyond 10^6 rads (radiation dose absorbed of 10^4 J/kg) while maintaining relatively low coefficients of friction.

(5) In high dust areas, hard solid lubricants, such as diamondlike carbon and boron nitride film, are useful in areas where liquid lubricants tend to pick up dust. These contaminants readily form a grinding paste, causing abrasion and damaging equipment.

(6) In weight-limited spacecraft and rovers, solid lubrication has the advantage of weighing substantially less than liquid lubrication. The elimination (or limited use) of liquid lubricants and their replacement by solid lubricants would reduce spacecraft weight and, therefore, have a dramatic impact on mission extent and craft maneuverability.

(7) Under intermittent loading conditions or in corrosive environments, liquid lubricants become contaminated. Changes in critical service and environmental conditions—such as loading, time, contamination, pressure, temperature, and radiation—also affect liquid lubricant efficiency. When equipment is stored or is idle for prolonged periods, solid lubricants provide permanent, satisfactory lubrication.

TABLE V.—ADVANTAGES AND DISADVANTAGES OF SOLID LUBRICANTS

Advantages	Disadvantages
• Are highly stable in high-temperature, cryogenic temperature, vacuum, and high-pressure environments • Have high heat dissipation with high thermally conductive lubricants, such as diamond films • Have high resistance to deterioration in high-radiation environments • Have high resistance to abrasion in high-dust environments • Have high resistance to deterioration in reactive environments • Are more effective than fluid lubricants at intermittent loading, high loads, and high speeds • Enable equipment to be lighter and simpler because lubrication distribution systems and seals are not required • Offer a distinct advantage in locations where access for servicing is difficult • Can provide translucent or transparent coatings, such as diamond and diamondlike carbon films, where desirable	• Have higher coefficients of friction and wear than for hydrodynamic lubrication • Have poor heat dissipation with low thermally conductive lubricants, such as polymer-base films • Have poor self-healing properties so that a broken solid film tends to shorten the useful life of the lubricant (However, a solid film, such as a carbon nanotube film, may be readily reapplied to extend the useful life.) • May have undesirable color, such as with graphite and carbon nanotubes

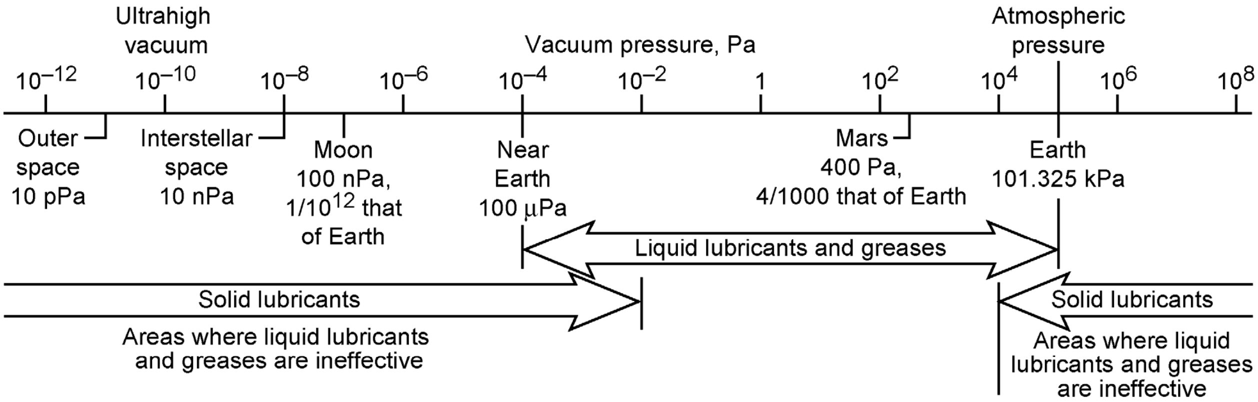

Figure 1.—Ranges of application of various lubricants in vacuum environments. (Figure has both solid and liquid lubricants.)

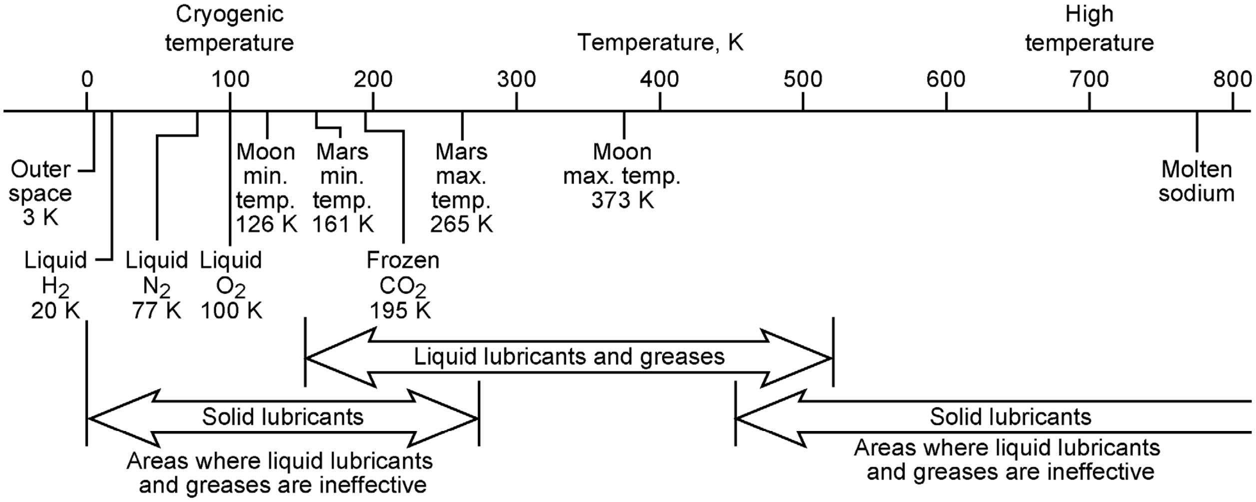

Figure 2.—Ranges of application of various lubricants in cryogenic and high-temperature environments. (Figure has both solid and liquid lubricants.)

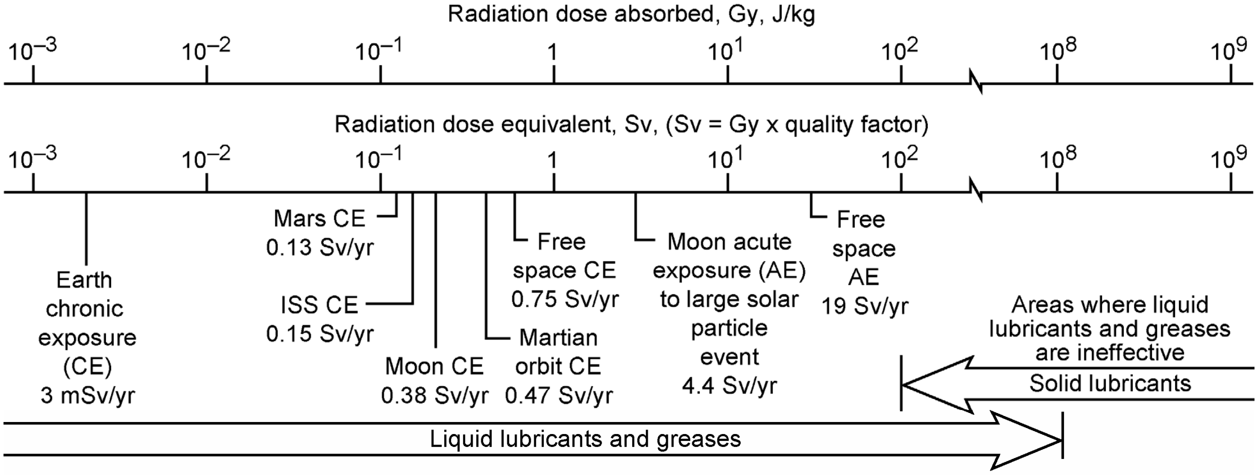

Figure 3.—Ranges of application of various lubricants in radiation environments. (Figure has both solid and liquid lubricants.)

Suppliers of Advanced Solid Lubricants and Coatings

Table VI lists some high-performance solid-film lubricant suppliers for the types of solid-film lubricants discussed earlier; gives the materials and/or services provided; and lists the supplier names, addresses, phone numbers, and fax numbers (refs. 28 to 35). It also includes important values of hardness and maximum service temperature that suppliers have made publicly available.

TABLE VI.—INDUSTRY SUPPLIERS OF ADVANCED SOLID LUBRICANTS

Supplier	Coating or material	Microhardness, Hv	Maximum service temperature, K
Balzers, Inc. Rogers Business Park Elgin, IL 60123 Phone: 847–844–1753 Fax: 847–844–3306 http://www.bus.balzers.com	WC/C (a-C:H:W) TiAlN + WC/C (a-C:H:W) DLC (a-C:H) Diamond (polycrystalline) TiAlN TiN TiCN AlCrN	1000 to 1500 3000 >2000 >8000 3300 2300 3000 3200	573 1073 623 873 1173 873 673 873
Surmet 33B Street Burlington, MA 01803 Phone: 781–272–3250 Fax: 781–272–9185 www.surmet.com	Diamond film	6000 to 8000	673
Teer Coatings Ltd. West Stone House, Berry Hill Industrial Estate Droitwich, Worcestershire WR9 9AS, UK Phone: 0870 220 39 10 Fax: 0870 220 39 11 http://www.teercoatings.co.uk	Diamondlike carbon Graphitelike carbon MoS_2 TiN CrN TiCN TiAlN CrAlTiN	>1400 >2000 >2000 >2200 >2000 >2500 >2500 >3500	673 773 723 723 823 723 1173 1173
DIAMONEX 7331 William Avenue Allentown, PA 18106 Phone: 610–366–7100 Fax: 610–366–7144	Diamondlike carbon: amorphous diamond	1000 to 3000	773
Sub-One Technology 470 Lindbergh Ave. Livermore, CA 94551 Phone: 925–455–7220 Fax: 925–606–4391	Diamondlike carbon on interior surfaces	Not available	Not available
TD Center 2020 15th Street Columbus, IN 47201 Phone: 877–832–3687 Fax: 812–378–1591	Vanadium carbide layer (thermal diffusion treatment)	3500 to 3800	Not available
TIODIZE Co., Inc. 5858 Engineer Dr. Huntington Beach, CA 92649 Phone: 714–898–4377 Fax: 714–891–7467	PTFE films PTFE and MoS_2 films MoS_2 films	Not available	561 617 922
CSEM Centre Suisse Rue Jaquet-Droz 1 P.O. Box CH–2007 Neuchâtel, Switzerland Phone: 41 32 720 5111 Fax: 41 32 720 5700	Diamond films MoS_2-based films Pure metal films (Pb, Ag, Au, In, Bi, and Sn) Oxides (PbO, MoO_3, TiO_2, and SiO_2) CrN or TiAlN nanocomposite	Not available	Not available

TABLE VI.—Concluded

Supplier	Coating or material	Microhardness, Hv	Maximum service temperature, K
Endura Coatings 2029 Riggs Warren, MI 48091 Phone: 586–758–1200 Fax: 586–758–3095	Composite diamond coatings Fluoropolymer coatings PTFE coatings	Not available	Not available
Thin Film Division—Anatech LTD 771 Crosspoint Drive Denver, NC 28037 Phone: 704–489–1488 Fax: 704–489–2177	Thin-film deposition: carbon, metal, and ceramic	Not available	Not available

The effectiveness and performance of hard to superhard coatings—such as diamondlike carbon, WC/C, TiC/C, VC, diamond films, and other solid-film lubricants—have been validated in a variety of sliding contact conditions in the atmosphere by many researchers in industry, academia, and government. For applications on the surface of the Moon and Mars, the following challenging research subjects must be investigated:

- Abrasion resistance of solid lubricants and coatings for the cryogenic temperatures, widely varying temperatures, and high dust environments on the surface of the Moon and Mars
- Adhesion strength between a solid coating film and its substrate under thermal cycling with high contact pressures and loads on the surface of the Moon and Mars
- Effects of radiation on the lubricating ability and durability of solid lubricants and coatings on the Moon and Mars

Research of Advanced Solid Lubricants and Coatings

To assess whether the current technology and manufacturing capability for solid lubricants and coatings are adequate to meet NASA's requirements for Moon and Mars exploration, the author spoke with individuals from industry, government, and academia known to be actively working in the field. The general consensus was that the current technology and manufacturing base for solid lubricants and coatings is not adequate to meet NASA's exploration requirements and that solid lubricant and coating lifetime-extension research, granular and powder tribology research, and the design of capable solid lubricant and coating systems need to be implemented.

A few current research areas are focused on designing, processing, and characterizing innovative solid lubricants and coatings technologies (e.g., refs. 36 to 40). The following technologies are showing promising performance in solid lubrication:

- Carbon nanotubes (single-walled nanotubes and multiwalled nanotubes)
- Fluorinated carbon nano-onions
- Multinanolayered, composite coatings ($MoS_2/WS_2/C$ and MoS_2/WS_2)
- Functionally graded, multilayered inorganic coatings (TiC_x/C and TiC_x)
- Multilayered composite coatings (WC/C, MoS_2/C, WS_2/C, and TiC/C)
- Nanocrystalline diamond coatings
- Large-area diamondlike carbon coatings
- TiO_2 grown on 55Ni-45Ti and titanium-based alloys
- Ceramics and advanced coatings (BN, B_4C, VC, AlN, CN_x, TiO_2, SiO_2, etc.)
- Soft metal coatings and polytetrafluoroethylene (PTFE) deposited by advanced deposition techniques

In general, the addition of these advanced solid lubricants and coatings to those currently available will enable designers to choose solid lubrication more easily and to apply it more effectively in moving mechanical assemblies and tribology applications on the Moon and Mars.

Designing for State-of-the-Art Solid Lubricants and Coatings

The most challenging research problems in durable solid lubricants and coatings for a cold, dry desert (Mars) and for a thermally cyclic, cold-to-hot desert (the Moon) are

(1) How are the solid lubricants and coatings attached to the substrate?
(2) What are their strengths and surface energies?
(3) How do they break down?
(4) How do they self-heal?
(5) How can we extend their lifetimes?
(6) Can they be reapplied to the surface at service areas in the lunar and Martian deserts?
(7) What are their performance benefits? Can they provide some or all of the following?

- Extreme abrasion and wear resistance
- Ultrahard surface
- High impact strength
- Remarkably low surface energy
- Increased thermal conductivity and thermal transfer
- High nonstick (release) properties
- Lowest friction (energy consumption) attainable
- Permanent dry lubrication to prevent galling
- Erosion protection
- Radiation protection
- Nontoxicity
- Chemical protection
- Nonwetting properties
- Precision conformance over complex geometry
- Excellent corrosion resistance
- Wide temperature range from cryogenic to 573, 823, or 923 K

Some suggested concepts and designs for achieving solid lubrication on the Moon and Mars follow:

(1) Formulate the composition and microstructure or nanostructure of an interlayer (bond coat) between a substrate and a solid lubricant or coating, minimizing the thermal expansion coefficient mismatch, the lattice parameter mismatch, and the difference in mechanical properties, while increasing the chemical affinity and bonding (e.g., a titanium or chromium interlayer on a metal substrate, a silicon interlayer on a ceramic substrate, or a zinc interlayer on a polymer substrate).
(2) Minimize the segregation of species in the substrate and contaminants at the interface between the interlayer and the substrate.
(3) Formulate the composition and microstructure or nanostructure of a solid lubricant or coating (top coat) on an interlayer deposited on a substrate.
    - For areas where high heat dissipation is desirable, formulate highly thermal-conductive solid lubricants and coatings (top coats): carbon nanotubes, nanocrystalline diamond coatings, metal-doped diamond coatings, metal-doped diamondlike carbon coatings, and soft metal films (gold, silver, copper, lead, and their alloys).

- For areas where translucency or transparency is desirable, formulate translucent or transparent solid lubricants and coatings (top coats): nanocrystalline diamond coatings, microcrystalline diamond coatings, and fluorinated and unfluorinated diamondlike carbon coatings.
- For areas where the preservation of clean air or water is strongly desired, formulate environmentally friendly solid lubricants and coatings (top coats): TiO_2 grown on 55Ni-45Ti and titanium-based alloys, TiO_2 coatings, and TiC coatings.
- For areas where abrasion and erosion due to a high dust environment are a concern, formulate ultrahard or hard solid lubricants and coatings (top coats): ceramic coatings (BN, B_4C, VC, AlN, CN_x, TiO_2, SiC, Si_3N_4, and SiO_2,), nanocrystalline diamond coatings, microcrystalline diamond coatings, and diamondlike carbon coatings.
- For areas where a low coefficient of friction is highly desirable, formulate ultralow or low coefficient of friction solid lubricants and coatings (top coats): carbon nanotubes; fluorinated carbon nanotubes or nano-onions; soft metal coatings; PTFE; diamondlike carbon coatings; diamond coatings; multi-nanolayered, composite coatings ($MoS_2/WS_2/C$ and MoS_2/WS_2); and functionally graded, multilayered inorganic coatings (TiC_x/C).
- For areas where wear control is desirable, formulate hard solid lubricants and coatings (top coats): multilayered composite coatings (WC/C, MoS_2/C, WS_2/C, and TiC/C); multi-nanolayered, composite coatings ($MoS_2/WS_2/C$ and MoS_2/WS_2); functionally graded, multilayered inorganic coatings (TiC_x/C); ceramic coatings (BN, B_4C, VC, AlN, CN_x, TiO_2, SiC, Si_3N_4, and SiO_2,); nanocrystalline diamond coatings; microcrystalline diamond coatings; and diamondlike carbon coatings.

Tribological and Surface Characterization of Solid Lubricants and Coatings

The friction and wear interactions of solid lubricants and coatings are system properties. This means that performance and behavior depend on the lubricant and materials, the operating conditions, and the system. Field testing is, however, expensive or impractical, so tribological simulation testing and surface and material characterization of innovative solid lubricants and coatings are needed. Testing and characterization are essential elements of solid lubricant and coating research and development (e.g., refs. 41 and 42). As listed in table VII, many academic institutions, commercial organizations, and government institutions have performed tribology research and development. However, selecting the correct simulation test for a given application is not always straightforward. Satisfactory correlation with the real application is the key.

TABLE VII.—TRIBOLOGY RESEARCH: ACADEMIC INSTITUTIONS, COMMERCIAL ORGANIZATIONS, AND GOVERNMENT INSTITUTIONS[a]

Organizations	Institutions
Academic sites	Case Western Reserve University (http://www.cwru.edu): Tribology Research Cleveland State University (http://www.csuohio.edu): Lubrication and Lubricants Colorado School of Mines: Advanced Coating and Surface Engineering Laboratory (ACSEL) (http://www.mines.edu/research/acsel/acsel.html) Georgia Institute of Technology: Center for Surface Engineering and Tribology, Tribology (http://www.me.gatech.edu/research/tribology.html), Tribology Research Group at Georgia Institute of Technology (http://www.me.gatech.edu/me/publicat/brochures/rb/13tri.html) Iowa State University (http://www.iastate.edu): Tribology Laboratory Northwestern University: Surface Engineering and Tribology (http://www.mech.northwestern.edu/dept/research/tribology/tribology.htm) Ohio State University: Gear Dynamics and Gear Noise Research Laboratory Homepage (http://gearlab.eng.ohio-state.edu/), Computer Microtribology and Contamination Laboratory Pennsylvania State University: Tribology Research (http://www.me.psu.edu/research/tribology.html)

[a] Source: Center for Surface Engineering and Tribology—Tribology Link, http://www.csetr.org/link.htm.

TABLE VII.—Continued.[a]

Organizations	Institutions	
	Purdue University: Materials Processing and Tribology Research Group (http://aae.www.ecn.purdue.edu/%7Efarrist/lab.html), Mechanical Engineering Tribology Web Site (http://widget.ecn.purdue.edu/%7Emetrib/) Sandia National Laboratories (http://www.sandia.gov): Tribology Southern Illinois University, Carbondale: Center for Advanced Friction Studies (http://frictioncenter.siu.edu/) State University of New York, Binghamton: Department of Mechanical Engineering (http://www.me.binghamton.edu/level2-1/aboutme.html) Texas Tech University: Tribology (http://www.coe.ttu.edu/me/Research/tribolog.htm) University of Akron: Tribology Laboratory (http://mechanical.uakron.edu/labs-tribology.php) University of California, Berkeley: Bogey's Tribology Group (http://cml.berkeley.edu/tribo.html) University of California, San Diego (http://www.ucsd.edu): Center for Magnetic Recording Research University of Florida (http://www.ufl.edu): Adair Research Group University of Illinois, Urbana-Champaign: Microtribodynamics and Tribology Laboratory (http://www.mie.uiuc.edu/content/asp/research/laboratories/tribology_and_mircro-tribology_laboratory.asp) University of Maine: Laboratory for Surface Science and Technology (LASST) (http://www.umaine.edu/lasst/) University of Notre Dame: Tribology/Manufacturing Laboratory (http://ame.nd.edu/facilities/TribologyLab.html) University of Pittsburgh (http://www.pitt.edu): Tribology Lab Western Michigan University: Tribology Laboratory (http://www.mae.wmich.edu/labs/Tribology/Tribology.html)	
Commercial organizations	Analysts, Inc. Home Page Ashland Chemical (http://www.ashchem.com) Blackstone Laboratories (http://www.blackstone-labs.com) Butler Machinery Co. (http://www.butler-machinery.com/index.asp): Fluids Analysis Lab CETR: Center for Tribology, Inc. (http://www.cetr.com) Computational Systems, Inc. (http://www.compsys.com) CTC Analytical Services (http://www.ctclink.com/public/FLhome.cfm?CFID=358369&CFTOKEN=64020916) Engineered Lubricants Co. (http://englube.com) Falex Corporation (http://www.falex.com/) Falex Tribology NV (http://www.falexint.com) FEV Engine Technology, Inc. (http://www.fev- et.com) F.L.A.G. (Fuel, Lubricant and Grease) Recruiting (http://www.flagsearch.com) Fluitec International (http://www.fluitec.com) Herguth Laboratories (http://www.herguth.com) Hydraulic Repair & Design, Inc. (http://www.hydraulicrepair.net) Hysitron Incorporated: Nanomechanics (http://www.hysitron.com) Huls America ICIS-LOR Base Oils Pricing Information (http://www.hysitron.com)	Insight Services (http://www.testoil.com) Kline & Co. Consultancy (http://www.klinegroup.com) Lubriquip (http://www.lubriquip.com) Micro Photonics Inc. (http://www.microphotonics.com) National Tribology Services (http://www.natrib.com) Noria—OilAnalysis.Com (http://www.oilanalysis.com) OMS Laboratories, Inc. (http://members.aol.com/labOMS/) PdMA Corporation (http://www.pdma.com) Petrolab Corp. (http://www.petrolab.com/pages/petrolab/default.asp) Predict/DLI—Innovative Predictive Maintenance (http://www.frontlineworldwide.com/prod04.htm) Predictive Maintenance Corporation (http://www.pmaint.com) RohMax (http://www.rohmax.com/en/oiladditives) Saftek (http://www.saftek.net): Machinery Maintenance Index Savant Group (http://www.savantgroup.com) SpectroInc. Industrial Tribology Systems (http://www.spectroinc.com) Tannis Co. (http://www.savantgroup.com/tannas.sht) Thoughtventions Unlimited, LLC (http://www.tvu.com) Tribology Consultant (http://members.aol.com/wearconsul/wear/wear.htm) TTi (http://www.tti-us.com) Wearcheck International (http://www.wearcheck.com) Wedeven Associates, Inc. (http://www.wedeven.com)

[a]Source: Center for Surface Engineering and Tribology—Tribology Link, http://www.csetr.org/link.htm.

TABLE VII.—Concluded.[a]

Organizations	Institutions
Government sites	Air Force Research Laboratory: Tribology and Coatings (http://www.ml.afrl.af.mil/tech/tech-mlb-tribcoat.html) Argonne National Laboratory (http://www.anl.gov/): Tribology Section NASA Glenn Research Center: Tribology & Surface Science Branch (http://www.grc.nasa.gov/WWW/SurfSci/) NASA Marshall Space Center (http://www.nasa.gov/centers/marshall/home/): Space Components Naval Research Lab: Tribology Section—NRL Code 6176 (http://stm2.nrl.navy.mil/%7Ewahl/6176.htm) National Institute of Standards and Technology: Nanotechnology is BIG at NIST (http://www.nist.gov/public_affairs/nanotech.htm) Oak Ridge National Laboratory (ORNL): Tribology (Friction, Lubrication and Wear Analysis) Test Systems (http://html.ornl.gov/mituc/tribol.htm) Southwest Research Institute (SwRI) (http://www.swri.org): Engine Technology Section, Petroleum Products Research (http://www.swri.org/4org/d08/petprod/)

[a]Source: Center for Surface Engineering and Tribology—Tribology Link, http://www.csetr.org/link.htm.

Many of the properties of solid lubricants and coatings are actually surface properties. For example, friction, adhesion, bonding, abrasion, wear, erosion, oxidation, corrosion, fatigue, and cracking are all affected by surface properties (refs. 1 to 3). By depositing thin films, producing multilayered coatings, and modifying surfaces, designers can enhance performance, that is lower surface energy, adhesion, and friction, and increase resistance to abrasion, wear, erosion, oxidation, corrosion, and cracking, as well as improve compatibility with the lunar and Martian environments (refs. 4 to 7).

In order to understand surface properties, and ultimately to provide better surfaces and lubrication, researchers must study the physical and chemical characteristics of a material surface obtained by a given process. A number of tools are now available for surface analysis of any solid surface (refs. 41 and 42). Because the surface plays such a crucial role in many processes, surface analyses and their tools have become important in a number of scientific, industrial, and commercial fields (refs. 11 to 21). For example, the editors of Research & Development Magazine surveyed the thin-film research community in August 2001 to determine their level of involvement with thin-film characterization tools and their immediate research concerns (ref. 22). The survey indicated that thin films and coatings are commonly used in components and devices to improve mechanical properties, material performance, durability, strength, and resistance in basic industries, such as industrial coatings (21 percent of researchers' response), nanotechnology (19 percent), optical components (19 percent), plastics (17 percent), ceramics (15 percent), biomedical technology (10 percent), instrumentation (10 percent), microelectromechanical systems (10 percent), and disk drives (6 percent). Furthermore, according to the survey, the most widely used tools for examining thin films and coatings are optical microscopy (60 percent), scanning electron microscopy (56 percent), energy-dispersive x-ray spectroscopy (29 percent), Fourier transform infrared spectroscopy (29 percent), surface profilometry (29 percent), x-ray diffraction (27 percent), Auger electron spectroscopy (25 percent), ellipsometry (23 percent), scanning prove microscopy (19 percent), transmission electron microscopy (19 percent), thermal analysis (15 percent), x-ray photoelectron spectroscopy (12 percent), confocal microscopy (10 percent), and secondary ion mass spectroscopy (8 percent).

Surface analysis is important for verifying the success of the surface preparation process, including a coating process or surface treatment for controlling the surface quality of solid lubricants and coatings as well as for identifying surface contamination that can either enhance or inhibit the surface effects of solid lubricants and coatings. Selecting the proper analytical tool and method is crucial to obtaining the right information. To select the proper tool, researchers must know the specimen size, sampling area, sampling depth, spatial resolution, detection sensitivity, whether quantitative or qualitative results are desired, whether destructive or nondestructive analysis is desired, and many other factors. Each technique has its strengths and weaknesses. Therefore, no single tool can provide the answers to all problems. In many cases, it will be necessary to use multiple tools to reach an answer.

Concluding Remarks

The success of habitats and vehicles, and ultimately, of the human exploration of and permanent human presence on the Moon and Mars, is critically dependent on the correct and reliable operation of many moving mechanical assemblies and tribological components. The coefficient of friction and lifetime of any lubricant generally vary with the environment; and lubricants have very different characteristics under different conditions. It is essential, therefore, to select the right lubrication technique and lubricant for each mechanical and tribological application. Several environmental factors are hazardous to performance integrity on the Moon and Mars. Potential threats common to both the Moon and Mars are low ambient temperatures, wide daily temperature swings (thermal cycling), solar flux, cosmic radiation, and large quantities of dust. The surface of Mars provides the additional challenges of dust storms, winds, and a carbon dioxide atmosphere. Solid lubricants and coatings for lunar and Martian applications, where liquid lubricants are ineffective and undesirable, are needed, and they must perform well in the extreme environments of the Moon, Mars, and space, as well as on Earth, where they will be assembled and tested. No solid lubricants and coatings and their systems currently exist or are validated that meet this requirement. New solid lubricants must be designed and validated for these applications.

The technology of solid lubrication has advanced rapidly in the past four decades, primarily in response to the needs of the aerospace and automobile industries. Solid lubricants are used where the containment of liquids is a problem and when liquid lubricants do not meet the advanced requirements. Under high vacuum (such as in space), high temperatures, cryogenic temperatures, radiation, dust, clean environments, or corrosive environments, and combinations thereof, solid lubrication may be the only feasible system. The materials designed for solid lubrication must not only display desirable coefficients of friction (0.001 to 0.3) but must maintain good durability in different environments, such as high vacuum, water, the atmosphere, cryogenic temperatures, high temperatures, or dust. Therefore, the successful use of materials and coatings as solid lubricants requires understanding their material and tribological properties and knowing which solid lubricant formulation is best for a chosen application. Issues such as substrate surface pretreatment, materials and coatings compatibility, the mating counterpart material, and potential debris generation must be taken into account during the design of a lubricated device or of moving mechanical assemblies.

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An investigation was conducted to survey anticipated requirements for solid lubricants in lunar and Martian environments, as well as the effects of these environments on lubricants and their performance and durability. The success of habitats and vehicles on the Moon and Mars, and ultimately, of the human exploration of and permanent human presence on the Moon and Mars, are critically dependent on the correct and reliable operation of many moving mechanical assemblies and tribological components. The coefficient of friction and lifetime of any lubricant generally vary with the environment, and lubricants have very different characteristics under different conditions. It is essential, therefore, to select the right lubrication technique and lubricant for each mechanical and tribological application. Several environmental factors are hazardous to performance integrity on the Moon and Mars. Potential threats common to both the Moon and Mars are low ambient temperatures, wide daily temperature swings (thermal cycling), solar flux, cosmic radiation, and large quantities of dust. The surface of Mars has the additional challenges of dust storms, winds, and a carbon dioxide atmosphere. Solid lubricants and coatings are needed for lunar and Martian applications, where liquid lubricants are ineffective and undesirable, and these lubricants must perform well in the extreme environments of the Moon, Mars, and space, as well as on Earth, where they will be assembled and tested. No solid lubricants and coatings and their systems currently exist or have been validated that meet these requirements, so new solid lubricants must be designed and validated for these applications.

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