Presenting PTFE:
A Potent Resin,
A Well-Kept Secret

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WELCOME

For over fifty years, our world and the quality of its inhabitant's lives has been improved by a resin known as polytetrafluoroethylene, or PTFE. Yet the widespread use of this phenomenon seems to have become the world's best kept secret, with the exception of DuPont's Teflon® (a member of the PTFE resin family).

During the 1980s, QMI developed and began manufacturing a line of PTFE resin treatments for lubricated systems. As these products have become widely used in a broad range of applications, QMI is often asked, "What are PTFE resins, and how do they function?"

While much has been recorded on the subject, the information is often tucked away in technology journals and encyclopedias, usually written in language to be deciphered only by the initiated.

So QMI opens the door to this fascinating world in the following pages, with information that reveals much about how QMI treatments achieve remarkable lubrication protection. Every attempt has been made to present the material in a condensed, readable fashion. (The nature of the FABRICATION section requires occasional use of terminology that may prove of interest to chemists only.)

QMI welcomes you to PTFE resins.

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1. HISTORY

Discovery True to the discovery pattern of so many great inventions, PTFE burst upon the scene quite by accident. In 1938 a DuPont chemist, Mr. Roy J. Plunkett, was working on the development of a new refrigerant when he discovered "polytetrafluoroethylene," shortened to PTFE and often more descriptively referred to as PTFE resins. Upon examination, DuPont learned that PTFE provided a combination of friction, temperature, chemical, mechanical and electrical resisting properties unmatched by any other material, and registered the Teflon® trademark.[1]

Promise Plunkett had struck gold. Tough and weather resistant, PTFE immediately showed promise. Promise that would culminate in recognition as the slickest substance known to man.

Guiness This "slickest substance" phenomenon is recorded in *The Guiness Book of World Records.* In the PHYSICAL EXTREMES section under the heading Lowest Friction it declares, "The lowest coefficient of static and dynamic friction of any solid is 0.02, in the case of polytetrafluoroethylene ($[C_2F_4]_n$), called PTFE - equivalent to wet ice on wet ice."[2]

War As with many technological efforts during the early 1940s, initial production of PTFE was directed toward the demands of World War II. PTFE had surfaced just in time to play decisive roles, including development of the weapon that would end the war; Plunkett's invention contributed to the Manhattan Project, created in 1942 to produce the first atomic bomb.[3] PTFE provided material for gaskets, packings and linings to handle the corrosive uranium hexafluorides, and made development of this critical weapon possible.[4]

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[1] *Teflon® Mechanical Design Data*, DuPont, Wilmington, Delaware, sec. III, 1-2

[2] Alan Russell & Norris McWhirter, *The Guiness Book of World Records*, 1988, 182

[3] J.O. Punderson, "Fluorocarbon Resins from the Original Polytetrafluoroethylene (PTFE) to the Latest Melt Processible Copolymers," SPE, Greenwich, Conn, 1976, 78-94

[4] "PTFE: 50 Years Old," *Aerospace Eng.*, **8**, 4, April 1988, 30-34.

1. HISTORY - continued

Widespread While World War II delayed commercial production until 1947[5], as early as 1946 it became known that PTFE contained ideal dielectric, or nonconductive, properties[6/7], and by the 1950s it was used as a dry lubricant in bearings and other friction surfaces.[8]

Space Rapid expansion of the technology began as PTFE proved critical to space travel. While not the exclusive focus, space applications grew to include:

- Use in early rockets through Mercury, Apollo and Space Shuttle programs, communications satellites and "star wars" defense systems.[9]
- Rocket fuel tanks utilized PTFE in linings and to support fuel lines.[10]
- NASA used PTFE electric insulation in space ships from the first Mercury programs.[11]
- The Apollo astronauts' space suits contained layers of PTFE fabric.[12]
- When Neil Armstrong took a "giant step for mankind" by first setting foot on the moon in 1969, the lunar module carried a full ton of PTFE and related materials.[13]
- In the Space Shuttle, the liquid oxygen tank's precious cargo was protected with PTFE insulation.[14]
- PTFE was used in fabrication of the Space Shuttle's critical Thermal Protection System.[15]
- PTFE proved effective as cage material in Space Shuttle main engine's high pressure oxygen pump bearings.[16]

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[5] *Kirk-Othmer: Encyclopedia of Chemical Technology*, Vol 11, 3rd Ed., 1

[6] *Physical properties of unfilled and filled polytetrafluoroethylene*, ICI, Herts, UK, 19

[7] W.E. Hanford & R.M. Joyce, "Polytetrafluoroethylene," J. Amer. Chem. Soc., **68**, 1946, 2082-2085

[8] "PTFE: 50 Years Old," *Aerospace Engineering*., **8**, 4, April 1988, 30-34.

[9] "PTFE: 50 Years Old," *Aerospace Engineering*, **8**, 4, April 1988, 30-34

[10] "PTFE: 50 Years Old," *Aerospace Engineering*., **8**, 4, April 1988, 30-34.

[11] "PTFE: 50 Years Old," *Aerospace Engineering*., **8**, 4, April 1988, 30-34.

[12] *Teflon® : the Discovery that Changed History*, DuPont, Wilmington, Delaware, 2

[13] *Teflon® : the Discovery that Changed History*, DuPont, Wilmington, Delaware, 2

[14] "Low-Flammability PTFE for High-Oxygen Environments," *NASA Tech Brief*, July/August 86/B86-10389/MFS-28127.

[15] P.M. Sawko, "Effect of Processing Treatments on Strength of Silica Thread for Quilted Ceramic Insulation on Space Shuttle," *Journal article*, NASA, **16**, July 1985, 17-21

[16] S.A. Barber, J.W. Kannel & K.F. Dufrane, "Evaluation of Transfer Films of Saloz M on 440V for Hot Bearing Cage Apps.," *Task 119*, Battelle Columbus Labs, OH, June 23, 1986, 69, sponsored by NASA

1. HISTORY - continued

- PTFE composites reduced friction and wear when utilized as dry lubricants in aerospace bearing applications.[17]
- In the "star wars" Strategic Defense Initiative, PTFE was used in light, quick valve system seals.[18]
- Looking ahead, controlled friction applications of PTFE are planned in future space station mechanisms and solar panels.[19]

Flight No less important than aerospace were applications in other modes of flight. Many bearings associated with flight-control applications in fixed wing aircraft and helicopters employed thin layers of PTFE based composites bonded to metal surfaces.[20] "Vertical take off and landing" (VTOL) aircrafts achieved essential friction reduction with PTFE in bearing rings on which the whole propeller housing of the VTOL equipment moved.[21] And PTFE mated with steel counterfaces in dry bearings was used extensively in aircraft and helicopters.[22]

Speed Closer to earth but also enhancing rapid mobility, PTFE proved a dry film lubricant of choice in the automotive racing industry through "coating" of friction surfaces. Application was achieved through a complex process involving metal preparation followed by spraying on and baking of the PTFE.[23] While occasional peeling and flaking in early applications caused initial skepticism, coating re-emerged as a viable engine performance and longevity enhancement technique.[24]

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[17] K. Friedrich, "Friction and Wear of Polymer Composites," Amsterdam & New York, Elsevier, 1986, 477

[18] "PTFE: 50 Years Old," *Aerospace Eng.*, **8**, 4, April 1988, 30-34.

[19] "PTFE: 50 Years Old," *Aerospace Eng.*, **8**, 4, April 1988, 30-34.

[20] J.K. Lancaster, "Composits for Aerospace Dry Bearing Applications," *Friction and Wear of Polymer Composites*, Amsterdam & New York, Elsevier, 1986, 363-396

[21] "PTFE Plays Role in Skyship Development," *Plast. South. Afr.*, **15**, 1, June 1985, 70

[22] B. Mortimer, J.K. Lancaster, "Extending the Life of Aerospace Dry Bearings by the Use of Hard Smooth Counterfaces," *Wear*, **121**, Feb. 3, 1988, 289-305

[23] J. W. Handzel, "Fricion-Fighting Coatings, Better durability through chemistry," *Circle Track*, June 1990. 107-112.

[24] P. Saueracker, "The Coatings Controversy," *Circle Track*, March 1991, 90-96.

1. HISTORY - continued

Alternative An alternative to coating surfaced in the form of PTFE resin "treatments," achieving PTFE protection by adding a metal treatment product to current-use lubricant. As with coatings, problem areas caused concern. However, simplicity of application and low cost generated increasing interest in the concept, while technologies surfaced to alleviate problems. Today PTFE resin treatments are well received in a wide variety of applications encompassing most closed lubricated systems.

Industry Also, in heavy industry, self-lubricated PTFE is now applied to bearings and thrust washers in applications as diverse as earth-moving machinery and snow blowers.[25] In a vast variety of other industrial applications, usage has spread from tubing and hoses to protective coatings for fabrics, to high performance films, to industrial coatings, to textile fibers, to wire and cable industries,[26] and beyond to gaskets and seals,[27/28] to electrical components and tape, to "spaghetti" tubing,[29] to computers, industrial electronics and other demanding, high-tech applications.[30]

Diverse Other uses proved invaluable in overcoming problems related to environmental hazards, exposure to ultraviolet light and oxidation, discoloration and embrittlement,[31] heat and cold and diverse climactic conditions.[32] Use in fabrics range from the sportsman's favored Gore-Tex® fabric[33] to exotic applications demanding great fabric strength and resistance to chemical and microbial attack.[34]

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[25] H.E. Sliney, "Status and New Directions for Solid Lubricnat Coatings and Composite Materials," NASA's *Tribology in the 80's*, **2**, April 1984, 665-680.

[26] *Fluoropolymers Industrial*, DuPont, Wilmington, Delaware, 3

[27] "Zero-Leakage Valves," *NASA Tech Brief*, 1972, B72-10024.

[28] "Micor Regulating Ball Valve," *NASA Tech Brief*, 1972, B72-10121.

[29] *Kirk-Othmer: Encyclopedia of Chemical Technology*, Vol 11, 3rd Ed., 21

[30] R.L. Baillie, J.J. Bednarczyk & P. Mehta, "PTFE Resin Selection for High Performance Wire and Cable," Wire and Cable Symposium, Reno, NV, Nov 18-20, 1986

[31] *Fluoropolymers Industrial*, Du Pont, Wilmington, Delaware, 4

[32] *Teflon® Mechanical Design Data*, DuPont® , Wilmington, Delaware, sec. VIII, 1

[33] U.S. Pat. 3,962,153 (June 8, 1976) R.W. Gore (to W.L. Gore & Assoc.)

[34] *Kirk-Othmer: Encyclopedia of Chemical Technology*, Vol 11, 3rd Ed., 21

1. HISTORY - continued

Gamut Today, PTFE applications run the gamut, from low-tech non-stick frying pan surfaces to high-tech exotic medical and hospital uses, including implants, surgical instruments and test equipment,[35] and dramatic uses in fire fighting equipment.[36] Applications for Mr. Plunkett's invention have grown from early use in the devastating Manhattan Project, to the recent heartwarming Statue of Liberty Restoration Project.[37]

[35] "Low-Flammability PTFE for High-Oxygen Environments," *NASA Tech Brief*, July/August 86/B86-10389/MFS-28127.

[36] "PTFE Tubing Displays 19 Minute Fire Resistance," *Jane's Defense Weekly*, Aug. 6, 1988, **010**, 005, 226.

[37] *Fluoropolymers Industrial*, Du Pont, Wilmington, Delaware, 2

2. COMPOSITION

Inside PTFE's low coefficient of friction in a wide temperature range, combined with heat resistance, chemical inertness and electrical insulation properties, makes it the most outstanding plastic in the industry.[38] Yet, while the well being of mankind is enhanced by PTFE every day, few know that they exist and very few understand how they function. A look inside opens the door to a very potent resin.

Polymer PTFE belongs to the fluoropolyer family, and understanding what they are gives us a better understanding of how they work.

Chain A polymer, which means 'many parts', is made up of a molecular structure repeated millions of times to form a chain. PTFE is a linear chain polymer of great molecular length, or a "long chain" fluorocarbon, with the chemical formula $(CF_2CF_2)_n$.[39]

Shield The molecular structure of the chain consists of a backbone of carbon atoms surrounded by a protective coating of fluorine atoms. Fluorine is an inert substance, and the fluorine atoms form a protective sheath over the chain of carbon atoms. This sheath shields the carbon chain from attack by chemicals and gives PTFE its chemical inertness and stability. It also lowers surface energy, giving PTFE a low coefficient of friction and nonstick properties.[40] The fluorine atoms surrounding the carbon atoms are too large to allow a planar zig-zag structure, which confers rigidity on the polymer.[41]

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38 *Kirk-Othmer: Encyclopedia of Chemical Technology*, Vol 11, 3rd Ed., 1

39 *Kirk-Othmer: Encyclopedia of Chemical Technology*, Vol 11, 3rd Ed., 1

40 D.I. McCane, "Tetrafluoroethylene Polymers" in N.M. Bikales, ed., *Encyclopedia of Polymer Science and Technology*, Vol 13, 1970, 623-70

41 C.W. Bunn, *Journal of Polymeric Science*, **16**, 1955, 332

2. COMPOSITION - continued

Bonds The two forces binding the PTFE structure are the carbon-carbon bonds, which form the backbone of the polymer chain, and the carbon-fluorine bonds, which form the shield. Both of these chemical bonds are extremely strong and are also key contributors to outstanding combinations of properties.[42] High thermal stability results from the strong carbon-fluorine bond, and characterizes PTFE as a very useful high temperature polymer.[43]

Tough PTFE is of extremely high molecular weight,[44] and unnotched PTFE is resistant to fracture on impact. Even at temperatures as low as -320° F (-196° C), well-fabricated specimens are tough.[45]

[42] D.I. McCane, “Tetrafluoroethylene Polymers” in N.M. Bikales, ed., *Encyclopedia of Polymer Science and Technology*, Vol 13, 1970, 623-70

[43] *Kirk-Othmer: Encyclopedia of Chemical Technology*, Vol 11, 3rd Ed., 1

[44] *Physical properties of unfilled and filled polytetrafluoroethylene*, ICI, Herts, UK, 9

[45] *Physical properties of unfilled and filled polytetrafluoroethylene*, ICI, Herts, UK, 16

3. FABRICATION

TFEThe fabrication of PTFE begins with production of the monomer tetrafluoroethylene (TFE). TFE manufacturing involves the following steps:

$$CaF_2 + H_2SO_4 \rightarrow CaSO_4 + 2\ HF$$
$$CH_4 + 3\ Cl_2 \rightarrow CHCl_3 + 3\ HCl$$
$$CHCl_3 + 2\ HF \rightarrow CHClF_2 + 2\ HCl$$
$$2\ CHClF_2 \Leftrightarrow CF_2 = CF_2 + 2\ HCl$$

Hydrogen fluoride is manufactured by the first step and chloroform by the second step. Chloroform is partially fluorinated with hydrogen fluoride to chlorodifluoromethane using antimony trifluoride as a catalyst. Chlorodifluoromethane then is converted to tetrafluoroethylene by pyrolysis.

Pure A significant amount of hydrogen chloride waste product is generated during the formation of the carbon-fluorine bonds to tetrafluoroethylene. A large amount of products are also formed in this process other than TFE and HCl. Since the pyrolysate contains multitudes of by-products that adversely affect TFE polymerization, it is imperative that TFE be very pure. This refinement process is extremely complex and contributes to the high cost of the TFE monomer. After purification, inhibitors are added to the monomer to avoid polymerization during storage.[46]

PTFE Engineering problems involved in the production of the monomer TFE are simple compared with the polymerization and processing of the various types of PTFE. TFE must be polymerized to extremely high molecular weight so that the desired properties are achieved to meet the needs of end-use applications. Polymerization and processing of PTFE to achieve desired properties is very demanding, involving complex engineering problems.[47]

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[46] *Kirk-Othmer: Encyclopedia of Chemical Technology*, Vol 11, 3rd Ed., 2-3
[47] *Kirk-Othmer: Encyclopedia of Chemical Technology*, Vol 11, 3rd Ed., 4

3. FABRICATION - continued

Methods PTFE is fabricated by a number of techniques, including raw extrusion, screw extrusion, compression molding and extrusion with an extrusion aid. Although different, these techniques all have three basic steps in common:

1. Impacting of molding powder to shape by pressing.
2. Sintering - involving bonding adjacent surfaces of particles by heating, during which the polymer particles fuse and coalesce.
3. Cooling - involving controlling crystallinity content of the fused particle through temperature reduction.[48] [49]

The strength of the preform and of the final sintered moulding depends upon the mean particle size, finer particles giving higher strength.[50]

Affect The exact manner in which the fabrication of the polymer is carried out affects certain intrinsic qualities in PTFE such as molecular weight, crystallinity, orientation and the presence of voids and interfaces. These, in turn, influence certain properties, notably tensile strength, elongation and dielectric strength.[51]

Molding and sintering conditions have an impact on mechanical, chemical and electrical properties of PTFE. Most notably affected are sheer stress, flex life, permeability, stiffness, resiliency and impact strength.[52/53]

Among the factors influencing these properties are:

1. Macroscopic flaws - internal bubbles, tears and impurities.
2. Microporisity - microscopically visible voids created by imperfect particle fusion.
3. Molecular weight - a measure of the average length of polymer chains.
4. Orientation - the alignment of polymer chains in a given direction.
5. Crystallinity - the weight of polymer chains fitted in a close-packed ordered arrangement .[54]

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[48] *Teflon® Mechanical Design Data*, DuPont® , Wilmington, Delaware, sec. II, 1-2
[49] *Physical properties of unfilled and filled polytetrafluoroethylene*, ICI, Herts, UK, 4
[50] *Physical properties of unfilled and filled polytetrafluoroethylene*, ICI, Herts, UK, 8
[51] *Physical properties of unfilled and filled polytetrafluoroethylene*, ICI, Herts, UK, 9
[52] *Kirk-Othmer: Encyclopedia of Chemical Technology*, Vol 11, 3rd Ed., 9
[53] *Teflon® Mechanical Design Data, DuPont®* , Wilmington, Delaware, sec. II, 1-2
[54] *Teflon® Mechanical Design Data, DuPont®* , Wilmington, Delaware, sec. II, 1-2

3. FABRICATION - continued

Forms PTFE is sold in three forms, each of which requires different fabrication techniques. The first, granular PTFE resins, uses little or no dispersing agent, and vigorous agitation is maintained to produce a precipitated resin. The second, fine powder PTFE resins, and the third, aqueous dispersion PTFE resins, use sufficient dispersing agent with mild agitation to produce small colloidal particles dispersed in the aqueous medium. The latter procedure, called aqueous-dispersion polymerization, prevents precipitation of the PTFE resin particles. The two procedures produce distinctly different products, although both are chemically high molecular weight PTFE polymers.

The granular product can be molded into various forms, but cannot be paste-extruded or dispersion coated. The PTFE produced by aqueous dispersion cannot be molded, and are prepared for end-use application by dispersion coating or by conversion to powder for paste extrusion with a lubricant medium.

1. **Granular PTFE Resins** are manufactured in a wide variety of grades. Granular resins are made by polymerizing TFE alone or in the presence of trace amounts of comonomers with an initiator and with or without a small amount of dispersing agent. An alkaline buffer is occasionally used.

   First an unstable dispersion is formed, but lack of dispersing agent and vigorous agitation cause the polymer to partially coagulate. The polymerized product is stringy, irregular and variable in shape. The dried granular polymer is ground to different average particle sizes, depending on the product requirements.

2. **Fine Powder PTFE Resins** are also available in various grades. Fine powder resins are made by polymerizing TFE in an aqueous medium with an initiator and emulsifying agents. The process, as well as the ingredients, has a significant effect on the end product. An attempt is made to keep the dispersion sufficiently stable throughout the polymerization process so that it does not coagulate prematurely, but unstable enough so that it can be subsequently coagulated into fine powder. The dispersion is stirred very gently during polymerization to ensure stability.

3. FABRICATION - continued

The thin dispersion rapidly thickens into a gel and coagulates in a nonwater-wet agglomeration which floats on the aqueous solvent as the agitation is continued. The agglomeration is dried very gently and care is taken to ensure absence of shearing.

3. **Aqueous Dispersions** are sold in latex form and are also available in different grades. The dispersion is made by the same polymerization process as that used to produce fine powders.

Raw dispersions are polymerized to different average particle sizes. The dispersion is stabilized with a nonionic or anionic surfactant. The stabilized dispersion is concentrated by electrodecantation, evaporation or thermal concentration. This concentrated dispersion can be modified further by other chemical additives. The fabrication characteristics of these dispersions depend on polymerization conditions and chemical additives for modification of the dispersion behavior. [55]

Cost The high cost of momomer (TFE) fabrication and purification, and of polymerization and post-treatment of PTFE are main contributors to the high cost of PTFE. Cost of converting PTFE to an end-use product is also high because PTFE fabrication techniques are different from typical thermoplastics and generally involve batch operations. Therefore, the final product is relatively expensive.[56]

Names PTFE is best recognized by DuPont's trade name Teflon® , but its many names assigned by other manufacturers include Halon® , Polyflon® , Hostaflon® , Fluon® , Algoflon® and Fluoroplast® . Utilized worldwide, PTFE resins are manufactured by many industrialized nations, including the USSR and recently The People's Republic of Red China.[57]

[55] *Kirk-Othmer: Encyclopedia of Chemical Technology*, Vol 11, 3rd Ed., 6
[56] *Kirk-Othmer: Encyclopedia of Chemical Technology*, Vol 11, 3rd Ed., 18
[57] *Kirk-Othmer: Encyclopedia of Chemical Technology*, Vol 11, 3rd Ed., 2

4. FRICTION

Low The low coefficient of friction with PTFE has been widely known, first published in 1949 when K. V. Shooter and P. H. Thomas measured coefficient of friction using a Bowden-Leben machine.[58] With loads of between 1 and 4 kg (2.2 and 8.8 lb.) and sliding velocities of 0.1 and 10 mm/s (0.02 to 2 ft/min.), they reported that the coefficient of friction was 0.04. It is significant that a coefficient of 0.01 was reported with a load of 1360 kg (3000 lb.) in a later test.[59]

Slide When PTFE comes in contact with another surface, it provides lubrication by sliding. The PTFE does not peel off, but simply slides along on its own surfaces.

Also, the orientation of PTFE resins plays a role in reduced friction. When the polymers slide along the chain, coefficient is lowered by 39%, as compared to sliding across the chain.[60]

Increase = decrease

Another critical factor is the decrease in static friction of PTFE when the load is increased.[61] Static coefficient of friction is lower than the dynamic coefficient and avoids stick-slip problems.[62]

Oil When oil comes in contact with PTFE, oil slides easily because of the low surface energy. PTFE uses this property to advantage by reducing energy loss to oil drag. Oil flows more readily over lubricated components, increasing oil's capacity to cool.[63]

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[58] K.V. Shooter & P.H. Thomas, "The frictional properties of plastics," *Research*, **2**, 1949, 533-535

[59] J.B. Thompson, G.C. Turrell & B.W. Sandt, "The sliding friction of 'Teflon® '," *S.P.E. Journal*, **11**, 4, April 1955, 13-14, 38

[60] D. Tabor & D.E.W. Williams, "Effect of orientation on the friction of PTFE," *Wear*, **4**, 5, 1961, 391-400, *Rubber Abs.* **40**, 258

[61] *Teflon® Mechanical Design Data*, DuPont® , Wilmington, Delaware, sec. V, 1

[62] *Kirk-Othmer: Encyclopedia of Chemical Technology*, Vol 11, 3rd Ed., 10

[63] J. W. Handzel, Fricion-Fighting Coatings, "Better durability through chemistry," *Circle Track*, June 1990. 107-112.

4. FRICTION - continued

Uses Recognition of potential to reduce friction and related problems of wear and heat has led to growing use of PTFE as a dry-film lubricant:

- In heavy industry, self-lubricated PTFE composites have displaced traditional oil-lubricated metallic composites for journal bearings and thrust washers in applications as diverse as earth-moving machinery and snow blowers.[64]
- PTFE was used as a lubricant in the Statue of Liberty restoration project.[65]
- PTFE mated against steel counterfaces in dry bearings are used extensively in aircraft and helicopters. Studies show that bearing life is greatly extended.[66]
- Most bearings associated with flight-control applications in fixed wing aircraft and helicopters use thin layers of PTFE based composites bonded to metal substrate.[67]
- PTFE is used in "vertical take off and landing" (VTOL) aircraft bearing rings on which the whole propeller housing of the VTOL equipment moves. Reduced coefficient of friction provides more energy for lift and propulsion.[68]
- Studies indicate that PTFE shows promise of improving ice-shedding characteristics of helicopter rotor blades.[69]
- In space travel, where lack of gravity poses unique challenges to fluid lubrication, use of PTFE has proven vital, especially when reduced wear and friction of PTFE composites proved valuable to aerospace dry bearing applications.[70]
- Studies show PTFE effective as cage material in Space Shuttle main engine high pressure oxygen pump bearings.[71]

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[64] H.E. Sliney, "Status and New Directions for Solid Lubricnat Coatings and Composite Materials," NASA's *Tribology in the 80's*, **2**, April 1984, 665-680.

[65] *Fluoropolymers Industrial*, Du Pont, Wilmington, Delaware, 2

[66] B. Mortimer, J.K. Lancaster, "Extending the Life of Aerospace Dry Bearings by the Use of Hard Smooth Counterfaces," *Wear*, **121**, Feb. 3, 1988, 289-305

[67] J.K. Lancaster, "Composits for Aerospace Dry Bearing Applications," *Friction and Wear of Polymer Composites*, Amsterdam & New York, Elsevier, 1986, 363-396

[68] "PTFE Plays Role in Skyship Development," *Plast. South. Afr.*, **15**, 1, June 1985, 70

[69] J.H. Sewell, "Development of an Ice-Shedding Coating for Helicoptor Rotor Blades," Royal Aircraft Establishement, Farnborough, UK, report Dec. 1971, 25

[70] K. Friedrich, "Friction and Wear of Polymer Composites," Amsterdam & New York, Elsevier, 1986, 477

[71] S.A. Barber, J.W. Kannel & K.F. Dufrane, "Evaluation of Transfer Films of Saloz M on 440V for Hot Bearing Cage Apps.," Task 119, Battelle Columbus Labs, OH, June 23, 1986, 69, sponsored by NASA

4. FRICTION - continued

- NASA sponsored tests on journal bearings with PTFE lubricating liners showed friction and wear characteristics compatible with airframe bearing requirements.[72]
- Tests on space manipulator drive bearings with PTFE composite retainers gave excellent wear characteristics and extended lifetime.[73]
- Studies of vacuum (space) usage of bearings, bushings, gears, cams, guides and slides, solenoids, commutators, motor brushes and sliprings with PTFE lubrication shows longer than normal life due to lack of oxygen and water.[74]
- All space efforts, including rockets, the Mercury Apollo and Space Shuttle programs, communications satellites, "star wars" defense systems, etc, utilize PTFE lubricant.[75]
- Further use of controlled friction applications of PTFE is expected in space mechanisms and solar panels.[76]

Coating In the automotive racing industry, "coating" of engine friction surfaces with PTFE or composites has proven attractive in light of the potential to improve performance and reduce wear.

In order to achieve a durable bonded coating, the surface metals must first be prepared. The parts to be coated are heated to about 800° F (426° C), a temperature higher than the final curing temperature. This is done so that any cutting fluids or foreign material that might precipitate from the parts upon curing will be removed before the coating is added. Then the parts are blasted, cleaning the surfaces to promote improved adhesion. Finally, the parts are degreased, and the coating is sprayed on, baked and cured.[77]

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[72] H.E. Sliney & F.J. Williams, "Performance of PTFE-Lined Composite Journal Bearings," presented Ann. Mtg of the Am. Soc. of Lub. Engr., Cincinnati, OH, May 10-13, 1982

[73] T. Iwata, K. Machida, Y. Toda, "Development of Harmonic Drive Actuator for Space Manipulator," *Japan Society for Aeronautical and Space Sciences Journal*, **34**, 395, 1986, 652-660.

[74] K.G. Roller, "Lubricating of Mechanisms for Vacuum Service," *Journal of Vacuum Science and Tech.*, **6**, May-June 1988, 1161-1165.

[75] "PTFE: 50 Years Old," *Aerospace Engineering*, **8**, 4, April 1988, 30-34

[76] "PTFE: 50 Years Old," *Aerospace Engineering*, **8**, 4, April 1988, 30-34.

[77] J. W. Handzel, "Fricion-Fighting Coatings, Better durability through chemistry," *Circle Track*, June 1990. 107-112.

4. FRICTION - continued

When coatings first appeared in the automotive racing industry, occasional peeling and flaking generated skepticism. However, improvements in preparation and application techniques produced promising results, as shown in a carefully controlled comparison between coated and uncoated engines.[78] The parts coated with a Teflon® (PTFE) composite included the piston skirt, valve stems, valve springs, pushrods, rod and main bearings, crankshaft, connecting rods, front cover, timing chain and gears, oil pump, block valley and oil pan. Dynamometer tests demonstrated that coating did indeed produce an increase in horsepower. Observing wear improvement after a season of racing, the study concludes that coatings can offer more horsepower, improved torque curve and reduced wear, proving "a benefit to the racer."[79]

[78] P. Saueracker, "The Coatings Controversy," *Circle Track*, March 1991, 90-96.
[79] P. Saueracker, "The Coatings Controversy," *Circle Track*, March 1991, 90-96.

Treatment

A PTFE application receiving increased attention is the "treatment" concept. This technology involves utilizing a specialized additive package to suspend PTFE resins in carrier oils along with bonding agents. The treatment product is added to current-use oil (or is added at oil change) to closed lubricated systems, ie. engines, gear boxes, compressors, hydraulic systems, air tools, etc.[80]

When the system is operated, lubricating fluids disperse suspended PTFE resins to friction surfaces where a additive-generated affinity between metal substrate and PTFE draws the resins out of suspension and into surface pores. Bonding agents and resin expansion fuses PTFE into porous metal substrate, producing a micro-thin "treatment" that remains bonded to friction surfaces without regard to the presence of lubricating fluids.[81]

Low coefficient of friction produces wear reduction, while less power absorbed by friction enhances performance and reduces energy consumption. Other PTFE properties aid in achieving long-term treatment.[82]

[80] *The Lubrication of Tomorrow is Available Today*, QMI, Lakeland, Florida, 10-12
[81] *The Lubrication of Tomorrow is Available Today*, QMI, Lakeland, Florida, 5
[82] *The Lubrication of Tomorrow is Available Today*, QMI, Lakeland, Florida, 9

5. TEMPERATURE

Stable High thermal stability of PTFE results from the strong carbon-fluorine atom bond and characterizes PTFE as a very useful high temperature polymer.[83] As a result, PTFE retains its properties after exposure to temperatures beyond the limit of almost all other thermoplastics and elastomers.[84]

Flame Also, the melt viscosity of PTFE, in response to shear stress and high temperature, is extremely high by comparison with other polymers.[85] PTFE is resistant to high temperature and flames because of exceptionally high thermal degradation thresholds, as well as high melting point and auto-ignition temperatures.[86]

Hot Within its normal range of working temperatures, the upper limit of which is generally quoted as 500° F (260° C), PTFE suffers no degradation. Weight losses observed between 500° F and 680° F (260° C and 360° C) are exceedingly small and are due to the loss of minute amounts of moisture and gas absorbed in the polymer. Only at temperatures in excess of 752° F (400° C) does thermal decomposition of PTFE became significant.[87]

Cold On the low end of the temperature spectrum, PTFE retains excellent properties at very low temperatures, maintaining great impact resistance.[88] Even at temperatures as low as -320° F (-196° C), well-fabricated specimens are tough.[89] PTFE has proven useful from -450° F (-268° C) and are highly flexible from -110° F (-80° C).[90]

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83 *Kirk-Othmer: Encyclopedia of Chemical Technology*, Vol 11, 3rd Ed., 1
84 *Fluoropolymers Industrial*, Du Pont, Wilmington, Delaware, 4
85 A. Nishioka & M. Watanabe, "Viscosity and plasticity of polytetrafluoroethylene resin above the melting point," *J. Poly. Sci.* **24**, 106, 1957, 298-300
86 *Fluoropolymers Industrial*, Du Pont, Wilmington, Delaware, 5
87 *Physical properties of unfilled and filled polytetrafluoroethylene*, ICI, Herts, UK, 24
88 *Fluoropolymers Industrial*, Du Pont, Wilmington, Delaware, 4
89 *Physical properties of unfilled and filled polytetrafluoroethylene*, ICI, Herts, UK, 16
90 *Teflon® Mechanical Design Data*, DuPont, Wilmington, Delaware, sec. IV, 2

5. TEMPERATURE - continued

Range Also, low coefficient of friction remains constant over a wide range of normal operating temperatures. A 1953 study demonstrated that the coefficient remained steady over the range of -49° F to +212° F (-45° C to +100° C). On further cooling the coefficient of friction raised somewhat, but did not alter further even when the polymer was cooled to -112° F (-80° C).[91] Add to that a 1963 study demonstrating that the coefficient of friction improved with increase in temperature,[92] and the versatility of PTFE's contribution to reduced coefficient of friction becomes apparent.

Uses It is not surprising, then, to note use of PTFE in extreme thermal applications:

- The combination of thermal and electrical resistance has been utilized for years in high performance wire and cable insulation applications, leading to use in aircraft, computers, military and industrial electronics and other applications encountering a wide range of temperature extremes.[93]
- PTFE proved critical to heat shields for rocket and satellite reentry into earth's atmosphere.[94]
- PTFE was also used in fabrication of the Thermal Protection System for the Space Shuttle vehicles.[95]
- PTFE fire resistant hose was introduced in the UK in 1988 that could withstand direct exposure to flame for up to 19 minutes. It was designed to insure that hoses would not spill their contents before fire fighters had made their way to safety, and that equipment would continue to operate in fire conditions.[96]

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[91] R.K. King & D. Tabor, "The effect of temperature on the mechanical properties and the friction of plastics," *Proc. Phys. Soc*. **66B**, 1953, 728-736

[92] K.G. McLaren & D. Tabor, "Visco-elastic properties and the friction of solids," *Nature*, **201**, 4870, 1963, 856-859.

[93] R.L. Baillie, J.J. Bednarczyk & P. Mehta, "PTFE Resin Selection for High Performance Wire and Cable," Wire and Cable Symposium, Reno, NV, Nov 18-20, 1986

[94] *Teflon® : the Discovery that Changed Industry*, DuPont, Wilmington, Delaware

[95] P.M. Sawko, "Effect of Processing Treatments on Strength of Silica Thread for Quilted Ceramic Insulation on Space Shuttle," Journal article, NASA, **16**, July 1985, 17-21

[96] "PTFE Tubing Displays 19 Minute Fire Resistance," *Jane's Defense Weekly*, Aug. 6, 1988, **010**, 005, 226.

6. CHEMICALLY INERT

Shield As we have observed, the molecular structure of PTFE is based on a chain of carbon atoms completely surrounded by fluorine atoms. The fluorine atoms shield the vulnerable carbon chain, giving PTFE the unique ability to resist interaction and break down when exposed to solvents.

Inert Therefore, PTFE is inert to almost every known chemical (not active or reactive), and resists aggressive chemicals and solvents even at elevated temperatures and pressures.[97] PTFE resins are not dissolved or swollen by any solvent within their normal range of working temperatures.[98]

The unique degree of inertness results from a combination of strong carbon-carbon and super-strong carbon-fluorine inter-atomic bonds, the almost perfect shielding of the carbon backbone by fluorine atoms, and the high molecular weight of the polymer.[99] This structure also produces other special properties, such as low friction and insolubility.[100]

Transparent Tests in Florida for periods up to twenty years in duration have proven PTFE transparent to ultraviolet light and extremely resistant to oxidation, surface fouling, discoloration and embrittlement.[101] PTFE does not change visual appearance after exposure to light ranging from ultraviolet to infrared.[102]

Water PTFE is also extremely hydrophobic. Completely resistant to hydrolysis, it is an excellent barrier to water permeation, remaining stable after long-term immersion in water.[103] Many studies of permeability to water vapor conducted in the US, France and the USSR show that PTFE has a lower permeability to vapor than almost any other plastic material known.[104]

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[97] *Fluoropolymers Industrial*, Du Pont, Wilmington, Delaware, 5

[98] B.B. Rossa, "Fluorocarbon polymers in the Chemical Industry," *Praktische Chemie*, **15**, 2, 1964, 64-73

[99] *Kirk-Othmer: Encyclopedia of Chemical Technology*, Vol 11, 3rd Ed., 11

[100] *Teflon® Mechanical Design Data, DuPont®* , Wilmington, Delaware, sec. IX, 1

[101] *Fluoropolymers Industrial*, Du Pont, Wilmington, Delaware, 4

[102] *Fluoropolymers Industrial*, Du Pont, Wilmington, Delaware, 5

[103] *Fluoropolymers Industrial*, Du Pont, Wilmington, Delaware, 5

[104] P.G. Konovolov & S.S. Vsesoyuz, "Structure of polymers and properties of films," Zaochmogo Politekh. Inst., Moscow, **23**, 1960, 92-102, Chem. Abstr., **55**, 1961, 20488b

6. CHEMICALLY INERT - continued

Gas Gases permeate PTFE at a significantly lower rate than most other polymers. Because it exhibits low permeability, PTFE finds extensive use in the chemical industry as an excellent barrier resin.[105]

Enzymes Further, it is inert to microbiological and enzymic attack because the pure PTFE polymer does not provide nourishment or porosity for these growths.[106]

Weather Remarkable resistance to heat, cold, ultraviolet light, permeation and corrosive attack results in PTFE that is virtually unaffected by weather. DuPont's "conclusive tests on samples exposed for fifteen years to practically all climactic conditions confirm these weather-resistant properties."[107]

Resilient Adding resilience, PTFE retains its properties after aging, even at high temperatures and in contact with solvents and oxidizing agents.[108]

Uses As a result, PTFE is well suited for the harsh environmental conditions encountered in chemical processing and other industries, as well as environmental pollutant exposure:

- Seals in turbine engines, alternators and rotary actuators utilize PTFE because of resistance to severe chemicals.[109]
- PTFE is utilized in "vertical take off and landing" (VTOL) aircraft bearing rings because of high corrosion resistance, which, in addition to low coefficient of friction, provides the ideal bearing surface for long life.[110]
- PTFE makes replacement of human arteries possible with no fear of rejection by the body.[111]

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105 *Kirk-Othmer: Encyclopedia of Chemical Technology*, Vol 11, 3rd Ed., 13
106 *Fluoropolymers Industrial*, Du Pont, Wilmington, Delaware, 4
107 *Teflon® Mechanical Design Data*, DuPont® , Wilmington, Delaware, sec. VIII, 1
108 *Fluoropolymers Industrial*, Du Pont, Wilmington, Delaware, 5
109 *Teflon® : the Discovery That Changed History*, Dupont, Wilmington, Delaware, 2
110 "PTFE Plays Role in Skyship Development," *Plast. South. Afr.*, **15**, 1, June 1985, 70
111 *Teflon® : the Discovery That Changed History*, Dupont, Wilmington, Delaware, 1

6. CHEMICALLY INERT - continued

- PTFE has proven well suited for oxygen-rich environments. It is safely used to contain liquid oxygen in Space Shuttle tanks as well as medical uses in hospital equipment, surgical instruments and implants.[112]
- In the Statue of Liberty restoration project, PTFE played a vital role as a galvanic corrosion isolator.[113]
- Soft packing applications are manufactured from PTFE resin dispersions, and hard packings are molded or machined from stocks and shapes made from granular resin.[114]
- Overbraided hose liners are made from fine powder PTFE by paste extrusion.
- Thread-sealant tapes are produced from fine powder PTFE by calendering.
- Fabricated gaskets are made from granular PTFE.
- Pipe liners are produced from fine powder PTFE resins.[115]
- Recently PTFE dispersions have been applied to heavy-duty glass fabric as a coating which protects the fabric strength and adds weather protection and resistance against chemical and microbial attack.[116]
- PTFE added to the lip of a shaft seal dramatically improves its ability to serve under pressure in heavily contaminated applications.[117]
- PTFE seals provide the solution to propellant valves that leak after numerous operations, leading to mandated use with highly reactive propellants.[118]

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[112] "Low-Flammability PTFE for High-Oxygen Environments," *NASA Tech Brief*, July/August 86/B86-10389/MFS-28127.

[113] *Fluoropolymers Industrial*, Du Pont, Wilmington, Delaware, 2

[114] U.S. Pat. 3,962,153 (June 8, 1976) R.W. Gore (to W.L. Gore & Assoc.)

[115] U.S. Pat. 3,962,153 (June 8, 1976) R.W. Gore (to W.L. Gore & Assoc.)

[116] *Kirk-Othmer: Encyclopedia of Chemical Technology*, Vol 11, 3rd Ed., 21

[117] "PTFE Liners Improve Radial Lip Shaft Seal Capability," *Automotive Engineering*, **87**, Feb. 2, 1979, 47-50

[118] "Zero-Leakage Valves," *NASA Tech Brief*, 1972, B72-10024.

7. ELECTRICAL

Non-polar As early as 1946 it was known that, because of its non-polar nature, PTFE contained ideal dielectric, or non-conducting, properties.[119/120] Excellent electrical properties combined with mechanical strength and chemical and thermal stability characterize PTFE as a very versatile electrical insulator. Since these PTFE resins do not absorb water, electrical resistance remains unchanged even after prolonged soaking.[121]

Flashover Arcing tests with other polymeric insulating materials show susceptibility to violent blazing flashover failure in wire bundles at high energy surge, a condition typical of Naval aircraft service. Tests revealed that PTFE insulation did not flashover, providing the answer to a critical problem.[122]

Wire PTFE wire produced in Great Britain in 1985 was shown to withstand temperatures from -94° F to +392° F (-70° C to +200° C), and was resistant to solder iron damage, adding a wide range of military aerospace and electronics applications.[123]

Data In an even wider range of temperatures, from -400° F to +500° F (-240° C to +260° C), PTFE maintains high dielectric strength and low dissipation factor, aiding high speed data processing.[124]

Uses This knowledge has lead to years of PTFE use in:

- Electrical tape, electrical components, and “spaghetti” tubing.[125]
- High performance wire and cable insulation applications.
- Wire used in electronic equipment in the military and aerospace industries.
- Coaxial wires using tapes made from fine powder PTFE and granular PTFE.
- Interconnecting wire applications, including airframes.

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119 *Physical properties of unfilled and filled polytetrafluoroethylene*, ICI, Herts, UK, 19

120 W.E. Hanford & R.M. Joyce, “Polytetrafluoroethylene,” J. Amer. Chem. Soc., **68**, 1946, 2082-2085

121 *Kirk-Othmer: Encyclopedia of Chemical Technology*, Vol 11, 3rd Ed., 13

122 F.J. Campbell, “Flashover Failures from Wet-Wire Arcing and Tracking,” Naval Research Lab Report, Washington, DC, Dec. 1984, 24.

123 “High-Performance PTFE Wire,” *Defence Material*, August 1985, **10**, 4, 138.

124 *Fluoropolymers Industrial*, Du Pont, Wilmington, Delaware, 5

125 *Kirk-Othmer: Encyclopedia of Chemical Technology*, Vol 11, 3rd Ed., 21

7. ELECTRICAL - continued

- Computer wire applications.[126]
- Semi-conductor computer chips that require high purity characteristics.[127]
- Circuit board substrates used in many military defense and commercial flight communication systems.[128]
- Microwave guides for satellite communications.[129]
- Microwave laser beams for defense systems.[130]
- Radar domes also benefit from the superior dielectric properties of PTFE.[131]

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[126] *Kirk-Othmer: Encyclopedia of Chemical Technology*, Vol 11, 3rd Ed., 21
[127] *Teflon® : the Discovery That Changed History*, Dupont, Wilmington, Delaware, 1
[128] *Fluoropolymers Industrial*, Du Pont, Wilmington, Delaware, 5
[129] *Fluoropolymers Industrial*, Du Pont, Wilmington, Delaware, 5
[130] *Fluoropolymers Industrial*, Du Pont, Wilmington, Delaware, 5
[131] *Fluoropolymers Industrial*, DuPont, Wilmington, Delaware, 5

8. FIBER

Tough PTFE fibers combine the qualities of chemical resistance and low coefficient of friction with the unique characteristic of high abrasion resistance and high strength to generate tough, durable fabric construction.[132]

Exploit Highly porous fabric structures, such as Gore-Tex® , that can be used as membranes for a variety of applications have been developed by exploiting the unique fibrillation capability of dispersion-polymerized PTFE resins.[133]

Abrasion PTFE also overcame a barrier to the use of glass fibers. Glass fibers have many benefits, but low resistance to abrasion prevented widespread use. Glass fibers twisted into a yarn and coated with dispersed PTFE resins provided essential resistance to abrasion and flammability.[134]

Uses PTFE fiber use has proven critical in space travel applications:

- The Apollo astronauts space suits contained two layers made of Teflon® .[135]
- Neil Armstrong was protected by PTFE when he set foot on moon.[136]
- Recently developed PTFE fibers provide a new class of high-strength fiber meeting rating standards for use on the Space Shuttle.[137]

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[132] M.E. Johnson, "Expanded PTFE Fibers - Extending the Limits of Textile Technology in Aerodynamic Decelerator Systems," Washington, DC, American Inst. of Aeronautics and Astronautics, 1989, 152-153.

[133] U.S. Pat. 3,962,153 (June 8, 1976) R.W. Gore (to W.L. Gore & Assoc.)

[134] "Nonflammable and Abrasion Resistant Coating Process for Glass Fibers," *NASA Tech Brief*, July 1972, B72-10445.

[135] *Teflon® : the Discovery That Changed History*, Dupont, Wilmington, Delaware, 2

[136] M.E. Johnson, "Expanded PTFE Fibers - Extending the Limits of Textile Technology in Aerodynamic Decelerator Systems," conference paper, AIAA Aerodynamic Decelerator Systems Technology Conference, Cocoa Beach, FL, April 18-20, 1989

[137] M.E. Johnson, "Expanded PTFE Fibers - Extending the Limits of Textile Technology in Aerodynamic Decelerator Systems," Washington, DC, American Inst. of Aeronautics and Astronautics, 1989, 152-153.

9. SAFETY

Years PTFE is chemically inert (not active or reactive). For over fifty years, thousands of tons of PTFE has been manufactured and placed in multitudes of potentially hazardous applications, including many that are above the rated use temperatures. There are no reported cases of injury, prolonged illness or death resulting from the handling of PTFE.[138]

Ingested PTFE is nonirritating to the skin.[139] It is also shown inert when ingested. In a ninety day experiment in which rats were given 25% fine PTFE resin powder in their daily feed, no symptoms of poisoning or disorders were observed.[140] The same findings were obtained in a seven month trial.[141]

Nonreactive Since PTFE resin polymers do not react with most chemicals, there is little possibility that toxic byproduct can be formed by chemical reaction.[142] PTFE absorbs no common acids or bases at temperatures as high as 390° F (200° C). The absorption of solvents is slight and has no substantial effect on bonding within the molecule, and should not be confused with degradation. It is a reversible physical process.[143]

Least flammable

Since PTFE does not propagate flame, normal fire rating tests have shown PTFE to be among the least flammable plastic materials. It has an Underwriter's Laboratories Rating of 94V-0.[144] While exposure of raw PTFE to direct flames will cause combustible gasses, combustion ceases when flames are removed.[145] Although little or no smoke is produced during combustion,[146] decomposition products are toxic to a greater or lesser extent and should not be inhaled.

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[138] *Kirk-Othmer: Encyclopedia of Chemical Technology*, Vol 11, 3rd Ed., 19-20
[139] *Kirk-Othmer: Encyclopedia of Chemical Technology*, Vol 11, 3rd Ed., 19
[140] J.A. Zapp, "Toxicity of plastics and resins." *Archives of Environmental Health*, **4**, no. **3**, 1962, 335
[141] D.K. Harris, *British Journal Industrial Medicine*, **16**, 1959, 221
[142] *Kirk-Othmer: Encyclopedia of Chemical Technology*, Vol 11, 3rd Ed., 19
[143] *Kirk-Othmer: Encyclopedia of Chemical Technology*, Vol 11, 3rd Ed., 11-12
[144] *Modern Plastics Encyclopedia*, (International), 1974-5
[145] J.A. Zapp, "Toxicity of plastics and resins," *Archives of Environmental Health*, **4**, no. **3**, 1962, 335
[146] J. R. Gaskill, "Smoke Development in polymers during pyrolysis or combustion," *Smoke and Products of Combustion*, **2**, 1973, 1-34

9. SAFETY - continued

When heated without direct flames, PTFE will not burn until a temperature of 1,065° F (575° C) is reached.[147] Above 1,275° F (690° C) the decomposition products burn, but they do not support combustion if the heat is removed. Combustion products primarily consist of carbon dioxide, carbon tetrafluoride and small quantities of hydrogen fluoride.[148]

Disposal All PTFE treatment disposal should follow local regulations for the disposal of liquid products of low toxicity.

[147] K.L. Paciorek, R.H. Kratzer and J. Kaufman, "Ocidative thermal Degradation of polytetrafluoroethylene," *Journal of Polymer Science* (Polymer Chemistry Edition), **2**, 1973, 1465-73

[148] *Kirk-Othmer: Encyclopedia of Chemical Technology,* Vol 11, 3rd Ed., 20

10. Q M I APPENDIX

The following appendix serves to highlight several items that have a direct bearing on QMI's PTFE resin treatments and their end-user benefits.

CHOICES

The importance of carefully choosing the PTFE manufacturer, as well as specific forms of PTFE resin, becomes obvious in light of the following references.

PTFE, page 10, indicates that "polymerization and processing of PTFE to achieve desired properties is very demanding, involving complex engineering problems."

Affect, page 11, refers to manners of fabrication that affect qualities of PTFE such as molecular weight, crystallinity, orientation and the presence of voids and interfaces. These influence other properties; notably tensile strength, elongation and dielectric strength. Also, molding and sintering conditions have an impact on mechanical, chemical and electrical properties of PTFE which affected sheer stress, flex life, permeability, stiffness, resiliency and impact strength.

Also reference **Forms**, pages 12 and 13. Note that the procedures described "produce distinctly different (forms of PTFE resins)."

When choosing the PTFE resin best suited for specific applications, QMI carefully balances the demands of the application against the capabilities of both PTFE type and method of fabrication. QMI has determined property and tolerance specifications necessary to achieve the utmost in PTFE resin treatment capabilities, and has gone to great length to secure the polymers most responsive to QMI's treatment demands.

PROPERTIES & BENEFITS

Many of the PTFE properties listed in previous pages bring unique benefits to the QMI treatment concept. Several are especially noteworthy:

Orientation Reference **Slide**, page 14, second paragraph; the 39% reduction in coefficient of friction achieved when PTFE resins slide along the chain as compared to sliding across the chain.

10. Q M I APPENDIX - continued

During the QMI treatment process, PTFE resins fuse into metal substrate while under pressure from opposing friction surfaces moving in consistent directional patterns. (Examples: constant same-direction movement of bearing surface against bearing surface, or back-and-forth movement of cylinder wall against piston ring, etc.)

This consistency in opposing surface movement aids in achieving the desired PTFE resin orientation. QMI PTFE resins fuse into surface pores under alignment forces that encourage the polymers to slide along the chain, rather than across the chain, maximizing low coefficient of friction and improving longevity.

Friction reduction

Reference **Increase = decrease**, page 14. With PTFE lubrication, as load increases, static friction decreases. This characteristic is a key to PTFE's remarkable success in high stress, high impact lubrication applications, especially when compared to failure patterns of alternative lubricants.

See documentation of this phenomenon in **Low**, page 14. The coefficient of friction was 0.04 under loads between 1 and 4 kg (2.2 and 8.8 lb.), but dropped to 0.01 under loads of 1,360 kg (3,000 lb.).

Oilless engine demonstration

To demonstrate QMI's outstanding ability to protect under extreme conditions, oil is drained from a small 4/cycle engine. The engine is then operated with no lubricant except previously applied QMI Engine Treatment with PTFE resins.

DuPont sheds light on the dynamics of this demonstration by stating, "(PTFE resins) outstanding wear resistance can be used to eliminate lubrication from many applications, and also to provide a safety factor in the event of lubricant failure."[149]

[149] *Teflon® Mechanical Design Data*, DuPont® , Wilmington, DE, sec. V, 1-4

10. Q M I APPENDIX - continued

DuPont continues, "Teflon® (PTFE) resins exhibit exceptionally low friction in nonlubricated applications, especially at low surface velocities and pressures higher than 5 psi. The coefficient of friction increases rapidly with sliding speeds up to about 100 ft./min. under all pressure conditions. This pattern of behavior prevents 'stick-slip' tendencies. Moreover, no 'squeaking' or noise occurs, even at the slowest speeds. Above 150 ft./min., sliding velocity has little effect at combinations of pressure and velocity below the composition's PV limit. (Figures indicate that) static friction of Teflon® resins decrease with increases in pressure."[150]

Oil drag reduced, cooling and cleaning enhanced

Reference **Oil**, page 14, which describes how that "when oil comes in contact with PTFE, oil slides easily because of the low surface energy."

Typically, oil enhances lubrication by clinging somewhat to friction surfaces. QMI's PTFE resin treatment displaces the need for this characteristic by providing a dry film lubricant "equivalent to wet ice on wet ice," fused into these surfaces. Hence, as lubricating oil is pumped over PTFE resin treated friction surfaces, the oil slides freely. This adds the benefits of reduced oil drag (improved performance and energy efficiency) and enhanced oil flow (improved cooling and cleaning capabilities).

Low and high temperatures

Reference **Hot** and **Cold**, page 19, for documentation of QMI PTFE resin treatment's ability to withstand temperatures extremes.

Each time an engine is started under normal temperature conditions, the equivalent of 500 miles of wear is lost before oil can circulate and lubricate adequately.[151] This start-up wear becomes more pronounced when oil's pumpability is reduced in very cold climates, cold storage locations, etc. QMI PTFE resin treatments, permanently fused with no regard to the presence of lubricating fluids, provides protection proven effective in the coldest of applications.

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[150] *Teflon® Mechanical Design Data*, DuPont® , Wilmington, DE, sec. V, 1-4
[151] R. Sikorsky, *Drive it Forever*, McGraw-Hill Pub. Co., 1983, 12

10. Q M I APPENDIX - continued

With extreme high temperatures encountered in upper cylinder areas, heat generated by internal combustion is absorbed into cylinder walls that act as supporting substrate for the PTFE resin treatment. The cylinder walls, cooled by coolant or air flow, moderate the temperature of the treatment to within functional limits.

Corrosion induced wear reduction

Reference **CHEMICALLY INERT**, pages 21 through 23.

A little known but significant cause of wear in internal combustion engines is the attack of corrosives upon metal surfaces. Robert Sikorsky, in *Drive it Forever,* explains how 100 gallons of gasoline burned in an engine produces 1 to 5 pounds of nitrogen and sulfuric acid, including extremely corrosive hydrochloric hydrobromic acid. These acids attack metal surfaces, speeding deterioration. Weakened high points break off more readily, creating new peaks and accelerating wear. This acceleration is best seen in engines operating with depleted acid-inhibiting oil additive; before warming to acid dissipating temperatures, wear is increased six times (or by a factor of six).[152]

QMI treatments fuse chemically inert PTFE resins into friction surfaces (and "cocoon" non-friction surfaces), protecting from corrosive acid attack and thereby reducing deterioration and wear.

Rust induced wear reduction

Rust is also a contributor to engine wear. Engines collect water as temperature changes within the crankcase cause condensation. When subjected to frequent short trips, engines often do not reach temperatures sufficient to boil off water, resulting in moisture induced rust. Sikorsky lists rust as "one of four main causes of engine wear."[153]

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[152] R. Sikorsky, *Drive it Forever*, McGraw-Hill Pub. Co., 1983, 16

[153] R. Sikorsky, *Drive it Forever*, McGraw-Hill Pub. Co., 1983, 8

10. Q M I APPENDIX - continued

Water, page 21, tells how QMI Engine Treatment's PTFE resins serve as "an excellent barrier to water permeation," thereby reducing the rust wear factor.

Climate conditions and pollution

QMI Paint Sealant with Teflon® utilizes unique qualities of PTFE resins to protect automotive finishes and other surfaces. Reference **Shield**, **Inert**, **Transparent** and **Water** on page 21, and **Gas**, **Enzymes**, **Weather** and **Resilient** on page 22 for a clear picture of accumulative PTFE protection properties, and the potential for QMI Paint Sealant to promote longevity of brilliant finishes in increasingly polluted environments.

HANDLING QMI

Reference **SAFETY**, pages 27 and 28.

All QMI products are easy to store and apply, and are safe when used properly. QMI PTFE treatments utilize petroleum based carrier oils, and should be disposed of accordingly.

CLOSING

Thank you for allowing QMI to open this door into the fascinating world of PTFE.

It is our goal to provide the utmost in the benefits PTFE resins offer, thereby helping QMI customers maintain the value of expensive vehicles and equipment. We are at your service.

THE END