Appendix 1

Functions of PFAS, the uses and substitutions of Specialist Equipment

Appendix 1-1 The characteristics and functions of PFAS

This document is the appendix 1 of the general comment to the Restriction report on Per- and polyfluoroalkyl substances (PFAS) from

Japan Electric Measuring Instruments Manufacturers' Association (JEMIMA)

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The characteristics and functions of PFAS

Summary

PFASs have many functions. The characteristics and functions of PFAS which are mainly used in Specialist equipment are described in this section.

PFAS has excellent properties such as, chemical resistance, electric insulation, heat resistance, repellency from water and oil, non-adhesion, weatherability, and others. PFASs are used where multiple of these properties are required simultaneously. We recognize that the ability to provide these various properties in a single material is the most important property of PFAS, and at present we do not have information on any other substance with this function other than PFAS.

Chemical resistance

Fluoropolymers compared to other general-purpose resins

	ETFE	FEP/TFE/FPA	FLPE	FLPP	HDPE	LDPE	PC	PETG	PP	PVC	TPE***
Acids, Dilute or Weak	E	E	E	E	E	E	E	G	E	E	G
Acids, **Strong/Concentrated	E	E	G	G	G	G	G	N	G	G	F
Alcohols, Aliphatic	E	E	E	E	E	E	G	G	E	G	E
Aldehydes	E	E	G	G	G	G	G	G	G	G	G
Bases/Alkali	E	E	F	E	E	E	N	N	E	E	F
Esters	G	E	G	G	G	G	N	G	G	N	N
Hydrocarbons, Aliphatic	E	E	E	G	G	F	G	G	G	G	E
Hydrocarbons, Aromatic	G	E	E	N	N	N	N	N	N	N	N
Hydrocarbons, Halogenated	G	E	G	F	N	N	N	N	N	N	F
Ketones, Aromatic	G	E	G	G	N	N	N	N	N	F	N
Oxidizing Agents, Strong	E	E	F	F	F	F	F	F	F	G	N

*Not for tubing chemical resistance (except PVC) **Except for oxidizing acids (See oxidizing agents, strong) ***TPE gaskets

Table 1 Classes of Substances at 20° C, Chemical Compatibility Chart - LDPE, HDPE, PP, Teflon Resistance (calpaclab.com)

* Not for tubing chemical resistance (except PVC) ** Except for oxidizing acids (See oxidizing agents, strong) *** TPE gaskets

Excellent: 30 days of constant exposure causes no damage. Plastic may tolerate for 30 years.
Good: Little or no damage after 30 days of constant exposure for the regent
Fair: Some effect after 7 days of constant exposure to the reagent. The effect may be crazing, cracking, loss of strength or discoloration.
Not recommended: Immediate damage may occur. Depending on the plastic, the effect may be severe crazing, cracking, loss of strength or dis coloration, deformation, dissolution or permeation loss.

Type / Properties	Fluoroelastomer	Silicon rubber	Acrylic rubber	Nitrile rubber	Ethylene propylene rubber
	FKM	MQ, VMQ	ACM	NBR	EPDM
Specific gravity	1.8～2.0	1.0	1.0	1.0	0.9
Heat resistance	◎	◎	○	△	○
Low temperature resistance	[illegible]	◎	○	◎	◎
Electrical properties	○	○	△	△	◎
Solvent resistance	◎	◎	○	△	○
Flame resistance	◎	○	▲	▲	▲
Ozone resistance	◎	◎	◎	×	◎
Steam resistance	◎	○	×	△	○
Acid resistance	◎	○	△	○	◎
Alkaline resistance	◎	◎	△	○	◎
Oil resistance	◎	△	○	○	×
Permeability resistance	◎	▲	○	○	△

Table 2 Property Comparison of Fluoro elastomers (FKM) with Other Rubbers[1]

◎ : Excellent ○ : Good △ : Fair ▲ : Marginal × : Poor

"Cleanliness" is defined as the fact that fluoropolymers are not easily eluted by acids, alkalis, or solvents (chemical resistance), do not contain other materials such as plasticizers in the molding process, and do not contain products that would thermally decompose during the material molding process.

Ozone resistance

Ozone is known to degrade plastic materials in two ways:

A: Substances with double bonds (C=C) in their structures (such as natural rubber, chloroprene rubber, butadiene rubber, etc.) undergo decomposition in which ozone reacts with the double bonds to produce ketones, when they come into contact with ozone.

B: When ozone exists in water, peroxy radicals are generated. Non-fluorine materials (eg polyethylene, polypropylene, etc.) deteriorate even if they do not have double bonds.

Fluoropolymers does not have decomposition pathways such as A and B even if it comes into contact with ozone, so it can be used for a long time without deterioration.

[1] https://www.daikinchemicals.com/library/pb_common/pdf/catalog/RC-1L.pdf translated from the document in Japanese. Last accessed on 14 July, 2023

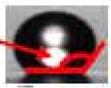
Thermoplastic resin		Ozon Resistance
Soft vinyl chloride	PVC	○
Rigid vinyl chloride	PVC	○
Vinylidene chloride resin	PVdC	◎
ABS	ABS	△
Polyethylene	PE	△
Nylon	N	×
Acrylic resin	PMMA	△
Fluoropolymer resin	PTFE	◎
Phenolic resin	PF	△
Melamine resin	PVC	○
Furan resin	FF	○
Epoxy resin	EP	△
Unsaturated polyester resin	UP	×

Table 3 Comparison of ozone resistance properties of plastics

Repellency from water and oil / non-adhesion

Since the fluoropolymers have a small polarizability, the intermolecular force is small. Because of its characteristics, fluoropolymers have repellency and non-adhere properties on the surface. In general, the repellency from various liquids is evaluated by the contact angle, and the larger the contact angle, the higher the repellency.

Contact angle θ



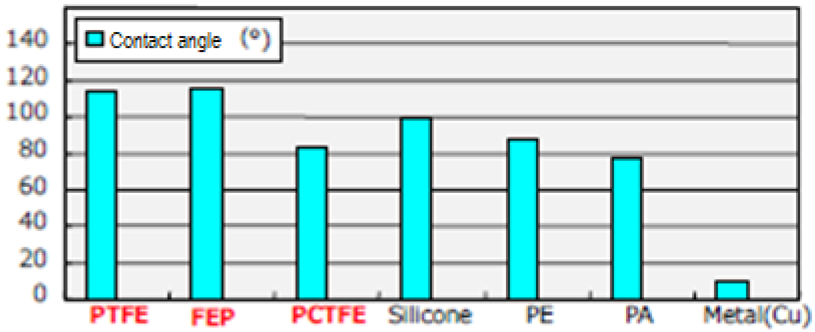


Figure 1 Contact angles with water

Adhesion energy refers to the amount of work required to pull a liquid contacting a solid away from the solid. The larger the contact angle, the smaller the adhesion energy. It means that a liquid in contact with a small adhesion energy solid easy to separate from the solid.[2]

Material name	Contact angle with water (°)	Adhesion energy (dyn/cm)
PTFE	114	43.1
FEP	115	42.0
Silicone resin	90~110	47.8~72.7
Paraffin	105~106	52.7~53.8
PE	88	75.2
PCTFE	83	-
PA	77	97.7
Phenolic resin	60	109.0
Copper(electropolishing)	9.6	144.2
Aluminium(electropolishing)	4.6	145.0

Table 4 Surface properties of various plastics and metals

This characteristic is sometimes called "mold releasability". It can also be expressed as antifouling because it does not easy to adhere.

Heat resistance

Fluoropolymers have high heat resistance as follows. They have higher heat resistance compared to other general-use resins

	Fluoropolymers						Other general-use resins	
Heat resistance : maximum operating temperature (C)	PTFE	PFA	FEP	ETFE	PCTFA	PVdF	PP	PVC
	260	260	205	150	120	120	100	60

Table 5 The heat resistance of Fluoropolymer [3]

Electric insulation

When the dielectric constant is low, the insulation in electrical components can be made thinner, leading to downsizing and weight reduction of the equipment. In applications where downsizing and weight reduction are necessary, it is an essential feature

[2] Japan Fluoropolymers Industry Association(2020), ふっ素樹脂ハンドブック, 14th edition. Page 34 Translated from Japanese.

[3] DAIKIN INDUSTRIES, LTD. (2009) ダイキン フッ素樹脂ハンドブック，Page 4

	Fluoropolymer				Fluorine rubber	
	PTFE	FEP	PFA	ETFE	FKM	FEPM
Dielectric constant	◎ 2.1			○ 2.3～2.8	△ 3～4	△～○ 2.5～3.5
	Non-fluoropolymer				Non-fluorine rubber	
	PVC	PEEK	TPI (Thermoplastic Polyimide)	Polyolefin	Silicone rubber	EPDM
Dielectric constant	△ 4～6	△ 3.2～4.5	△ 2.8～3.2	△～○ 2.3～4	△ 3.2～10	△ 2.5～3.5

Table 6 The dielectric constants of various resins

Low friction, self lubrication

Friction coefficient of fluorine resin is lower than that of other resins. It is because polarizability (Mobility of electrons in an electric field) of C-F bonding is low (0.68) and the intermolecular force is weak. (Reference: polarizability of C-Cl bonding is 2.59) [4]

Types of plastic	Plastic / Plastic	Plastic / Steel	Steel / Plastic
PTFE	0.04	0.04	0.10
PE	0.10	0.15	0.20
PS	0.50 *)	0.30	0.35
PMMA	0.80 *)	0.50 *)	0.45 *)

*) indicates occurrence of stick-slip motion.
Measurement condition: Bowden-Laden type measurement equipment, load: 9.8-39.2N, sliding speed: 0.01cm/s
Plastic/Steel indicates sample material/pin material
PE: polyethylene PS: polystyrene PMMA: polymethylmethacrylate

Table 7 Comparison of friction coefficient among PTFE and other materials[5]

As an example of low friction, Table8 shows friction coefficient of PTFE.

Type	ASTM test method	Measurement condition		Unit	PFA	PTEF	FEP
Coefficient of static friction	-	Against polished steel		-	0.05	0.02	0.05

Table 8 Comparison of static friction coefficient among PFA, PTFE and FEP[6]

One of the characteristics related to friction is “self lubrication”. The molecules of PTFE separate from molding of PTFE due to friction. The molecules in crystals of PTFE separate easily because intermolecular forces are weak. PTFE moves and attaches to the friction mating surface and generates friction between them. It lowers friction coefficient. [7]

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[4] Japan Fluoropolymers Industry Association(2020), ふっ素樹脂ハンドブック, 14th edition. Page 9 Translated from Japanese.

[5] Japan Fluoropolymers Industry Association(2020), ふっ素樹脂ハンドブック, 14th edition. Page 24 Translated from Japanese.

[6] DAIKIN INDUSTRIES, LTD. (2009) ダイキン フッ素樹脂ハンドブック，Page 53

[7] Japan Fluoropolymers Industry Association(2020), ふっ素樹脂ハンドブック, 14th edition. Page 24 Translated

Gas barrier properties/Gas permeation properties

Fluoropolymer film are less steam permeability.

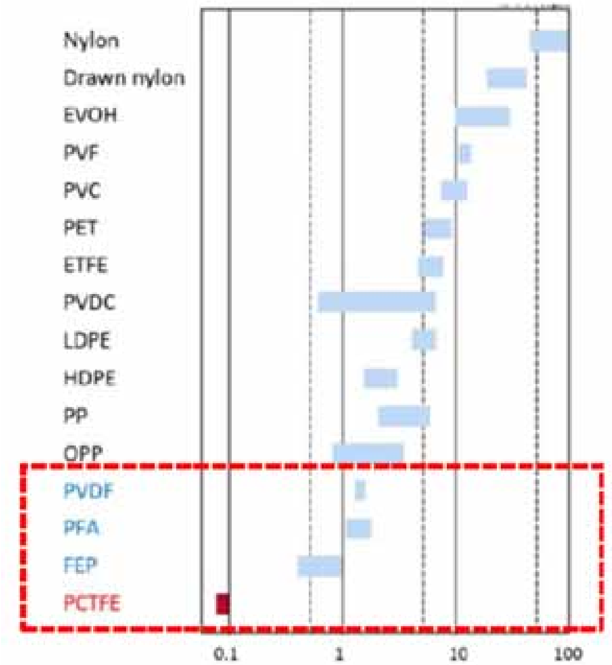


Figure 2 The degree of steam permeability [8]

steam permeability (g/m^2/d)

from Japanese.

[8] DAIKIN INDUSTRIES, LTD. (2009) Daikin Fluoropolymers Handbook，Page 109

Fluorine elastomers are less atmospheric (nitrogen, oxygen) permeability.

Material	Temperature degree Celsius	He	H_2	O_2	N_2	CO_2	CH_4	C_2H_2	C_3H_8
Vinyl methyl silicone rubber (VMQ)	25	N/A	400	400	200	1600	N/A	N/A	10000 or more
	50		570	500	280	1550			
Ethylene propylene rubber (EPDM)	25	N/A	N/A	16.5	5.90	79.2	N/A	N/A	91.2
	50			46.6	13.7	183			246
Perfluoro-elastomer (FFKM)	25	10.3	8.25	2.5	8.1	28.7	3.3	N/A	N/A
Styrene butadiene rubber (SBR)	25	17.5	30.5	13	4.8	94	N/A	N/A	N/A
	50	42	74	34.5	14.5	195			
Vinylidene fluoride fluororubber (binary FKM)	25	2.95	4.6	1.0	0.8	3.9	0.6	N/A	N/A
Vinylidene fluoride fluororubber (Ternary FKM)	25	2.64	4.13	1.7	0.7	1.6	0.4	N/A	N/A
Chloroprene Rubber (CR)	25	N/A	10.3	3.0	0.89	19.5	2.5	N/A	N/A
	50		28.5	10.1	3.55	56.5	9.8		
nitril-butadiene rubber (Mid-high NBR)	25	9.32	12.1	2.94	0.81	23.5	N/A	18.9	26.9
	50	23.4	33.7	10.5	3.58	67.9		68.3	78.3
nitril-butadiene rubber (High NBR)	25	5.2	5.42	0.73	0.18	5.67	N/A	8.25	11.2
	50	14.2	17.0	3.5	1.08	22.4		19.8	33.1
butyl rubber (IIR)	25	6.4	5.5	0.99	0.25	3.94	0.6	1.28	N/A
	50	17.3	17.2	4.03	1.27	14.3	3.2	5.82	

($\times 10^{-8}$ cc, cm/cm^2,sec,atm)

Table 9 Comparison of gas permeability of elastomer[9]

Property of Gas Permeability

Property			Standard Test method	Unit	FEP film
Gas Permeability	Gas permeability coefficient	N_2	ASTM D1434	cm³・cm/cm²・s・atm	120×10^{-10}
		O_2			370×10^{-10}
		H_2			$1{,}080\times10^{-10}$
		CO_2			970×10^{-10}
		CH_4			66×10^{-10}
		C_2H_4			44×10^{-10}
	Water-vapor permeability		JIS Z0208	g/m²・24h	1.6
	Water Absorption		ASTM D570	%・24h	<0.01

Table 10 Gas Permeability of FEP film[10]

9 DAIKIN INDUSTRIES, LTD. (2009) Daikin Fluoropolymers Handbook，Page 78

10 DAIKIN INDUSTRIES, LTD. (2009) Daikin Fluoropolymers Handbook，Page 78

Fluoropolymers permeate small molecular gases, such as oxygen and nitrogen, conversely, large molecular gases do not permeate. Fluoropolymer properties are used in permeate membranes for measurement and analysis.

Gas	Gas Permeability		
	FEP	PTFE	Low Density Polyethylene
N_2	1.2×10^{-8}	1.1×10^{-8}	0.74×10^{-8}
O_2	3.7×10^{-8}	3.2×10^{-8}	2.2×10^{-8}
CO_2	9.7×10^{-8}	8.9×10^{-8}	9.6×10^{-8}
CH_4	0.66×10^{-8}	—	2.2×10^{-8}
CH_3	0.66×10^{-8}	—	5.2×10^{-8}
C_3H_8	0.11×10^{-8}	—	7.2×10^{-8}
C_2H_4	0.48×10^{-8}	—	—

Temperature: 25 degree Celsius(77°F) Units: cm^3 (ST P) $cm/cm^2 \cdot atm$

Table 11 Comparison of gas permeability of various materials[11]

Low refractive index

Amorphous fluoropolymer resin has high transmittance. This is utilized for optical components and optical fibres.

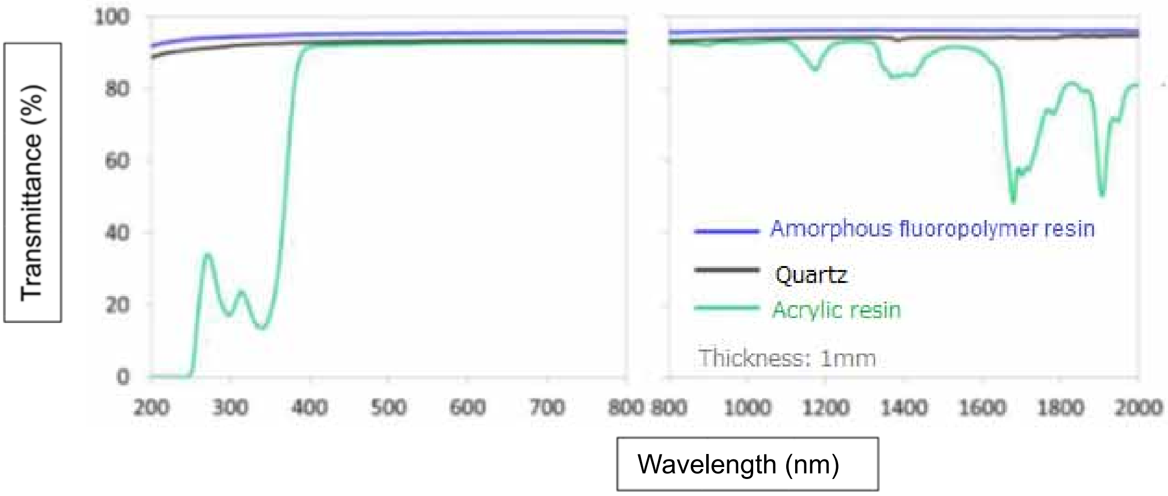


Figure 3 Comparison of transmittance

Weatherability

Fluoropolymer resin has high weatherability and can be used outdoors. It does not react to sunlight such as ultraviolet rays. It is not susceptible to oxidizing effects of atmospheric oxygen and other substances (see "chemical resistance"). It can be used in a wide temperature range from low to high (see "heat resistance"). It has high water repellency and does not absorb water, so it is not affected by humidity changes. It can be said that fluoropolymer resin has high weather resistance because it has the above points.

[11] DAIKIN INDUSTRIES, LTD. (2009) Daikin Fluoropolymers Handbook，Page 80

	Fluoropolymer resin						General resin	
	PTFE	PFA	FEP	ETFE	PCTFE	PVdF	PP	PVC
Weatherability	◎	◎	◎	◎	◎	◎	×	×

◎ Excellent, ○ Good △ Not very good ▲ Needs attention × Not good

Table 12 Fluoropolymer resin weatherability comparison [12]

Regarding the graph below, it can be seen from the accelerated weatherability test with the Sunshine Weather Meter that the gloss retention rate decreases by no more than 10% even after 4000 hours of exposure. [13]

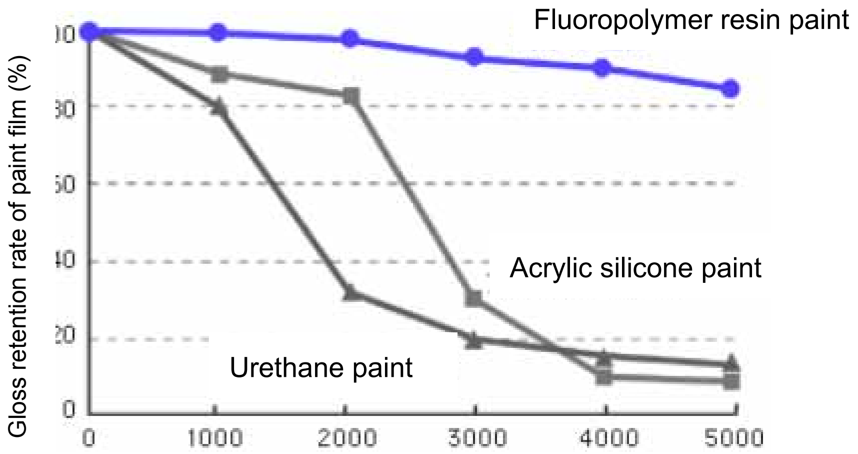
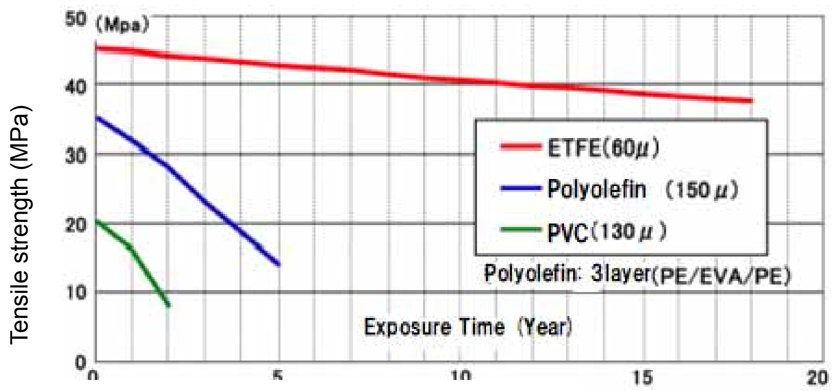


Figure 4 Accelerated weatherability test of paint



Exposure time by weather meter(h)

Figure 5 Outdoor exposure test Comparison of tensile strength between ETFE and other materials [14]

[12] DAIKIN INDUSTRIES, LTD. (2009) ダイキン フッ素樹脂ハンドブック, Page 4

[13] https://www.kyoeishoji.co.jp/business/chemical/fusso_toryo.html translated from the document in Japanese. Last accessed on 21 July, 2023

[14] https://www.taiyokogyo.co.jp/feature/etfe_film.html translated from the document in Japanese. Last accessed on 21 July, 2023

Durability

It means that it can be used for a long time. Due to its high chemical resistance and high weatherability, PFAS can achieve high durability.

Resistance to creep / Compression set

When a constant load is applied to a polymeric material, creep occurs, in which deformation progresses over time. Similarly, compression set occurs where the deformation does not recover when the force is removed. Both properties are known to be correlated. When rubber materials are used in elastic applications such as packings or diaphragms, it is required to minimize the effects of both properties.

Experimental examples of "30% creep time (Hour)" for major rubber materials are shown below. Creep is known to be worse at higher temperatures, Experiments have shown that FKM and silicon exhibit good properties.

	50 degree Celsius	70 degree Celsius	100 degree Celsius	120 degree Celsius	150 degree Celsius
NR	190	103	3.8	—	—
SBR	1250	203	14	—	—
CR	4200	550	45	7.4	—
NBR	3900	380	41	12.2	—
IIR	—	—	2.7	—	—
FKM	—	—	1650	305	180
Silicon	—	—	—	1550	190

Table 13

Quoted from the journal of “the Society of Rubber Science and Technology, Japan”, 1960(Vol33), P882-892, “Stress relaxation and creep properties of various vulcanized rubbers”.

Examples of compression set test results are shown below. In general, it is difficult to quantitatively compare materials because the measured values differ depending on the compounding and hardness of the rubber. Here, the compression set of the materials was compared by comparing the minimum value of each material in the database. FKM and silicon showed relatively good properties, showing the same tendency as creep.

	Compression set JISK6301 100 degree Celsius×70h
NR	—
SBR	Min 20%
CR	Min 23%
NBR	Min 9%
IIR	—
EPDM	Min 23%
FKM	Min 11%
Silicon	Min 6%

Table 14

The minimum value of each material was quoted from the data described in "Material Database / Organic Materials" (1989), The Nikkan Kogyo Shimbun”.