29TH INTERNATIONAL WIRE AND CABLE SYMPOSIUM
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A review of the properties of perfluoroalkoxy fluorocarbon resin as they pertain to the electrical and electronics industry is presented.

Thermal exposure of wire insulation of perfluoroalkoxy fluorocarbon resin (PFA) at 285° C (545° F) for 20,000 hours in air produced no deterioration in the electrical, physical, or mechanical properties measured.

This unusual behavior, at temperatures only 15°C below the melt temperature of the resin, could not be adapted to the usual Arrhenius relationship commonly used to determine a temperature rating for the continuous use of such materials.

In light of the test data presented, it is proposed that Teflon® perfluoroalkoxy fluorocarbon resin insulations can be used continuously at 285° C and that the product be given such a rating for electrical uses.

Introduction

Teflon® PFA fluorocarbon resins represent a combination of mechanical, physical, and electrical properties over a range of temperatures that make them uniquely suitable for a wide variety of electrical and electronic applications. Typical physical and mechanical properties of the two grades of Teflon PFA resin produced for this application area are shown in Table I.

Teflon® 340 is a general purpose resin designed for melt extrusion on wire and for injection molding where maximum melt flow is required. Teflon® 350 is designed for use in extremes of chemical and thermal environments where maximum resistance to stress is required.

This paper describes those properties which are useful to the engineer in designing components for the electrical and electronic industry. Applications for this material include extruded coatings for hook-up wire, heater cables, heavy wall conduit, jacketing for multiconductor cable, geophysical cables, jacketing for fiber optics, and insulation for aircraft engine wires. It has also been injection molded into electrical switch components, connector inserts, insulating bushings and standoff insulators.

The Dielectric Constant

The dielectric constant of Teflon PFA fluorocarbon resins is approximately 2 over a wide range of frequencies, temperatures and densities. The minor changes which occur with changes in these conditions are shown in Figure 1. The values for density of Teflon PFA vary only slightly, 2.13-2.17, and the dielectric constant varies about 0.03 units over this range, among the lowest of all solid materials. There is no measurable effect of humidity on the dielectric constant of PFA.

FIGURE I
Dielectric Constant of TEFLON PFA Fluorocarbon Resins at Various Frequencies and Temperatures (by ASTM D-150)

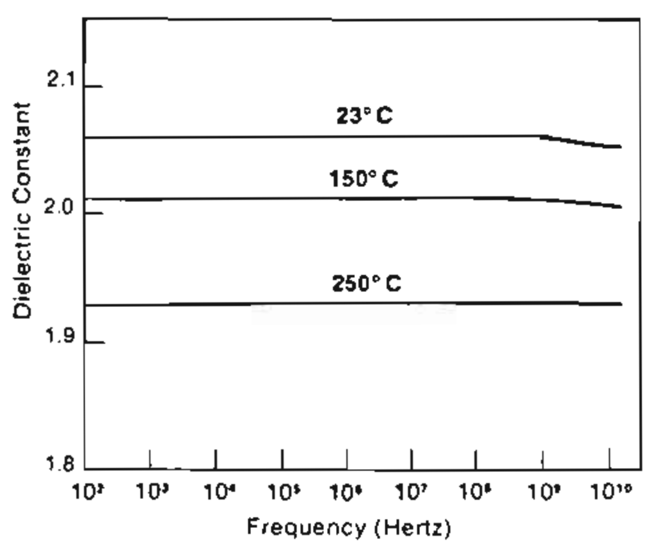


TABLE I

TYPICAL PROPERTIES OF TEFLON PFA

Property	ASTM Method	Teflon 340	Teflon 350
Nominal Melting Point, °C (°F)		302-306 (575-590°)	302-306 (575-590°)
Specific Gravity		2.13-2.16	2.13-2.16
Melt Flow Rate, Gms/10 min.	D-3307	11.0	2.0
Tensile Strength	D-1708		
Megapascals 23° C (73° F)		28	31
(lbs./sq. in.)		(4,000)	(4,500)
250° C (482° F)		12 (1,800)	14 (2,000)
Tensile Yield	D-1708		
Megapascals 23° C (73° F)		14	15
(lbs./sq. in.)		(2,000)	(2,200)
250° C (482° F)		3 (500)	4 (600)
Ultimate Elongation — %	D-1708		
23° C (73° F)		300	300
250° C (482° F)		480	500
Flexural Modulus	D-790		
Megapascals 23° C (73° F)		655	689
(lbs./sq. in.)		(95,000)	(100,000)
250° C (482° F)		58 (8,000)	70 (10,000)
Creep Resistance*	D-695		
Tensile Modulus			
Megapascals RT		276	276
(lbs./sq. in.)		(40,000)	(40,000)
250° C (482° F)		41 (6,000)	41 (6,000)
Hardness Durometer	D-2240	D-60	D-60
MIT Folding Endurance Cycles (7-8 mils)		50,000	500,000
Water Absorp., %	D-570	0.03	0.03
Coefficient of Linear Thermal Expansion	D-696		
M/M-Kelvin, 20° C-100° C (70° F-212° F)		1.2×10^{-5}	1.2×10^{-5}
(in./in./° F)		(6.7×10^{-5})	(6.7×10^{-5})
100° C-150° C (212° F-300° F)		1.7×10^{-5}	1.7×10^{-5}
(in./in./° F)		(9.4×10^{-5})	(9.4×10^{-5})
150° C-210° C (300° F-408° F)		2.0×10^{-5}	2.0×10^{-5}
(in./in./° F)		(11.1×10^{-5})	(11.1×10^{-5})

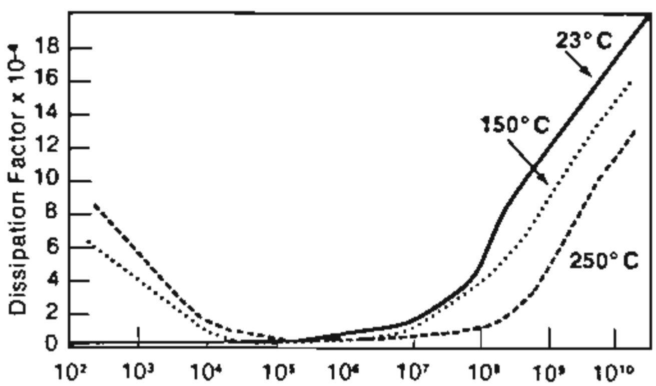
*10 hour apparent modulus modulus stress = 7 MPa (1,000 psi) at RT, .07 MPa (100 psi) at 250° C (482° F)

Dissipation Factor

The dissipation factor of PFA varies with frequency and temperature. This is shown in Figure 2.

The dissipation factor at low frequency (10^2-10^4 Hertz) increases at higher temperatures. It has been suggested that this observed increase is due ionic impurities present in the resin. Little difference is seen in dissipation factor with temperature in the range of 10^4-10^7 Hertz.) At higher frequencies to 10^{10} Hertz, there is a steady increase in dissipation factor with increasing frequency. Increases are greatest when measured at room temperature. There is also an indication that a maximum exists at about 3 x 10^9 Hertz. This higher dissipation factor with increasing frequency may preclude the use of this product as a core material for coaxial cable which operates at radar frequencies.

FIGURE 2
Dissipation Factor of Teflon PFA Fluorocarbon Resin at Various Frequencies and Temperatures (by ASTM D-150)



Electrical Resistivity of Teflon PFA

The volume and surface resistivities of fluorocarbon resins are high and are unaffected by time or temperature Measurements of the volume resistivity of Teflon PFA by the method outlined in ASTM D257 gave a value greater than 10^{18} ohm-cm. The surface resistivity was greater than 10^{16} ohm sq.

ARC Tracking

When Teflon PFA was tested by the method described in ASTM-D495 using stainless steel electrodes, no tracking was observed for the duration of the test—i.e. 180 seconds, indicating that the resin does not form a carbonized conducting path. Similar performance was observed when Teflon* FEP or TFE fluorocarbon resins were tested.

Performance In Fire Situations

Teflon PFA, like FEP and TFE fluorocarbon resin is among the safest of all plastics in fire situations. It passes the U/L83 vertical flame test and is classified 94VE-O according to U/L94. The OI (Oxygen Index) by ASTM-2863 is greater than 95% and the smoke density rating in the NBS smoke chamber is 4.

As in the case of other fluorocarbons, Teflon PFA contributes little in fuel value in case of exposure to fire. A comparison of fuel values of typical materials is shown below.

TABLE II

FUEL VALUES OF VARIOUS MATERIALS*

FUELS	HEAT CONTRIBUTED	
Fuel Oil	42MJ/kg	(18,000 BTU/lb.)
Coal	23-33MJ/kg	(10-14,000 BTU/lb.)
Wood	19-23MJ/kg	(8-10,000 BTU/lb.)
INSULATING MATERIALS		
Polyethylene	47MJ/kg	(20,000 BTU/lb.)
PVC	21-30MJ/kg	(9-13,000 BTU/lb.)
Rubber	23-33MJ/kg	(10-14,000 BTU/lb.)
Teflon	5MJ/kg	(2,200 BTU/lb.)

*Per ASTM D-240 and D-2015 heat of combustion

Performance on Prolonged Thermal Exposure

Long-term heat treatment of PFA plaques, tensile bars, and coated wires at 285° C (545° F) indicates that the resin can be used continuously at this temperature without deterioration of its mechanical or electrical properties.

In Figure 3, the change in the tensile strength of wire coatings as measured at room temperature is plotted versus hours of thermal treatments in air at 230° C and 285° C. The tensile strength measured at room temperature of coatings made from Teflon 340 resin show a gradual increase with time of about 15% after 20,000 hours at 285° C. Similar increases were observed when the tensile measurements were made at 200° C. The room temperature elongation of the tensile specimens increased about 25% with thermal treatment at 285° C as shown in Figure 4.

The increase in tensile properties is attributed to an increase in molecular weight as indicated by a decrease in melt flow as shown in Figure 5. The precise mechanism of the observed increase is not known at present. End-linking of the polymer chains appears to be the predominant reaction since there is no observable increase in melt elasticity as typified by cross-linking of polymer chains to establish a branched structure.

FIGURE 3
Tensile Strength of Teflon PFA Wire Coatings After Prolonged Thermal Treatment in Air

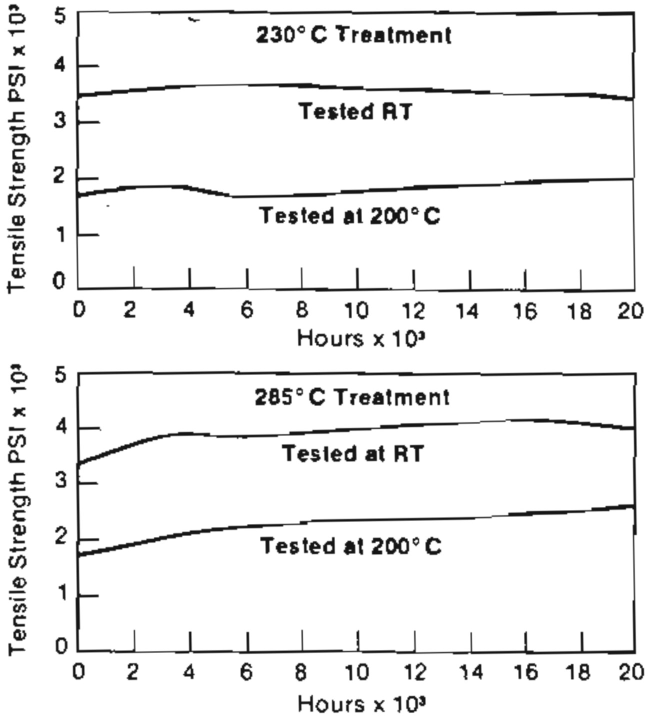


FIGURE 4
Tensile Elongation of Teflon PFA Wire Coatings After Prolonged Thermal Treatment in Air

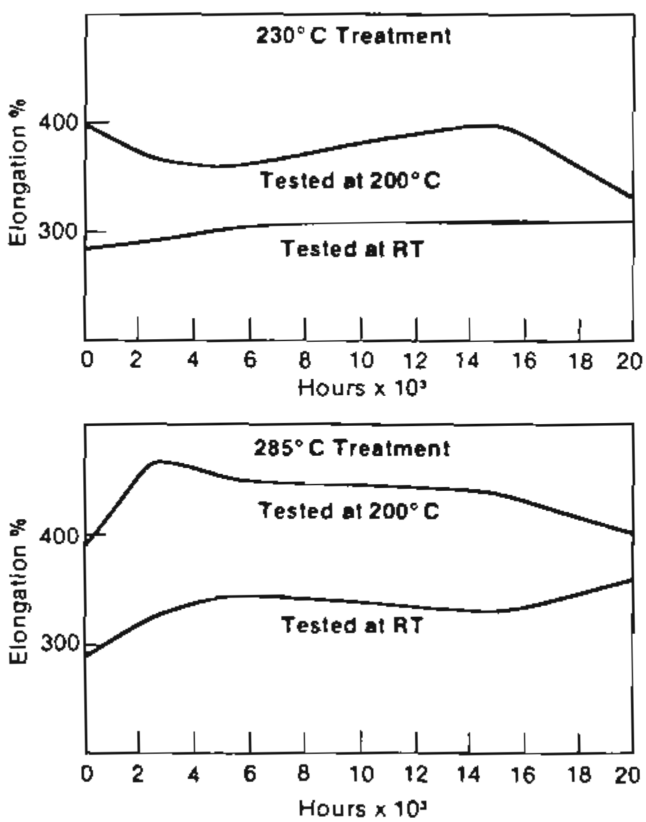
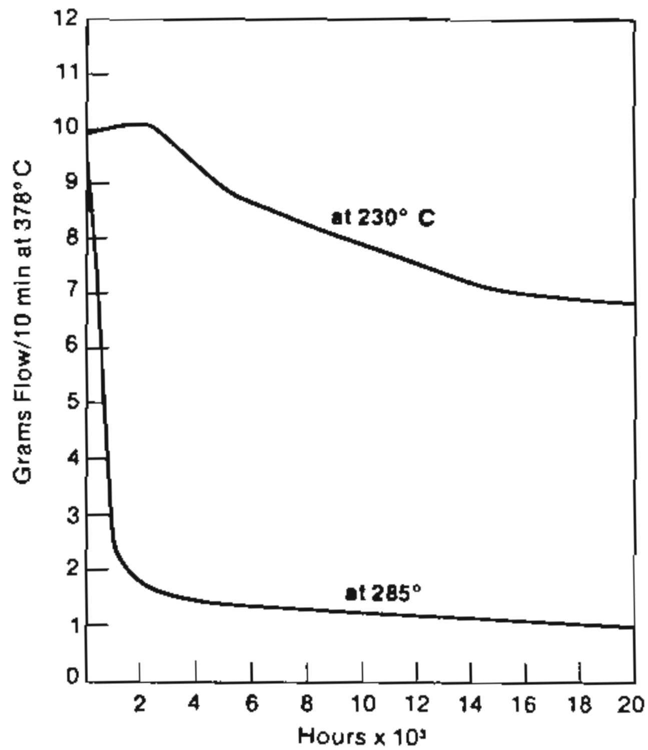


FIGURE 5
Change in Melt Flow During Prolonged Thermal Treatment of Teflon PFA Fluorocarbon Resins at 230° C and 285° C

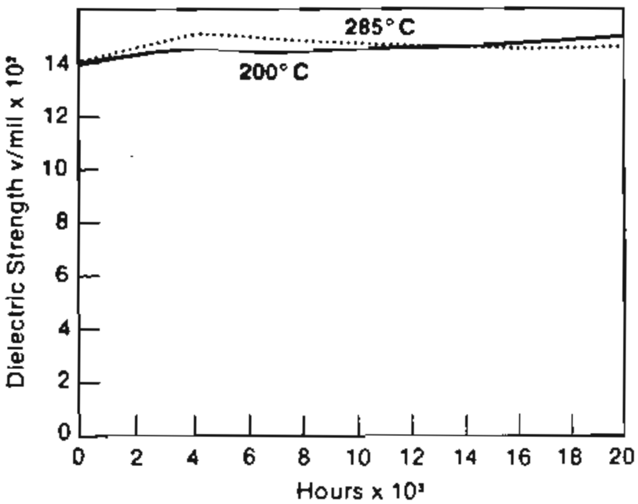


The intent of the thermal treatment was to establish a temperature rating for the continuous use of the resin in electrical applications. The method based upon the Arrhenius relationship following the IEEE standard No. 1 Underwriters' uses a temperature at which 50% of a given physical property is retained after 20,000 hours. (Polymeric Materials — Long Term — U/L-746B).

Temperatures of 230°C (440°F) and 285°C (545°F) were used in early exploratory tests to bracket the temperature range for study. The high temperature is only 15°C below the melting point listed for Teflon PFA (ASTM-3307-74). It became clear from this work that 285°C had to be the lowest of the four temperatures required for the study test. Since it is impossible, from a practical point of view, to select four test temperatures between 285°C and 302-306°, and considering the PFA is obviously improving in tensile properties at 285°C, this approach toward establishing a continuous use temperature rating was abandoned.

Further tests were performed to identify weaknesses which might preclude the use of this material at these temperatures. Changes in dielectric strength are plotted versus heating time at 285°C in Figure 6. No significant change in dielectric constant was observed. This again is typical of TFE and FEP fluorocarbon resins.

FIGURE 6
Change in Dielectric Strength of Teflon PFA on Prolonged Heating at 285°C and 230°C



The 1X Mandrel Wrap Test

A 1X mandrel wrap was employed to gain an insight into the mechanical performance of these wire constructions after prolonged thermal exposure. This severe treatment tests the ability of a wire to withstand bending abuse after prolonged heat exposure. The test is a slight modification of the wrapback test in MIL Specification 22759. A straight sample of wire is placed in an oven at a specified temperature for three hours; it is then removed and visually inspected for any cracks. If crack-free, the sample is wrapped on itself (1X) and replaced in the oven for three hours. The sample is removed and visually inspected for cracks. If crack-free, the wrapped sample is soaked in salt water for at least four hours and then tested dielectrically at 2.5 KV for five minutes. Those samples which survive are unwrapped and again dielectrically tested at 2.5KV for five minutes. The results of such tests are shown in Table III.

TABLE III

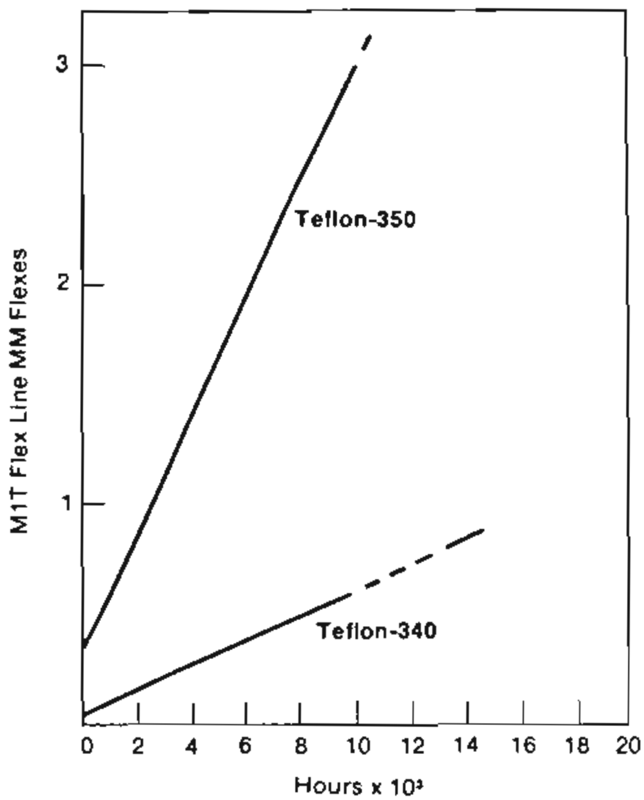
1X MANDREL WRAP TEST AFTER 3 HOURS AT 285°C

TIME IN HRS. THERMAL TREATMENT AT 285°C	NUMBER PASSING TEST WRAP	NUMBER PASSING TEST UNWRAP
0	3/3	0/3
2.500	3/3	2/3
10.000	3/3	3/3
20.000	3/3	3/3

Wire specimens passed the wrap portion of the 1X mandrel test at all thermal treatments. While the untreated samples could not pass the unwrap portion of the test, as the thermal treatment progressed, more and more of the specimens passed. This is consistent with the decrease in melt flow number observed, indicating an increase in molecular weight.

It parallels the improvement in flex life observed on thermal treatment shown in Figure 7.

FIGURE 7
Change in Flex Life of Teflon PFA on Long Term Thermal Treatment



The excellent performance of wires coated with Teflon PFA on heating at 285°C (15°C below melt temperature) in air for 20,000 hours led to the conclusion that wire constructions coated with this resin should be given a temperature rating of 285°C provided the conductor itself can withstand such thermal environments.

Performance of Pigmented Wire Coatings of Teflon PFA Under Prlonged Thermal Treatment

As a companion study, pigment-coated wire constructions using six common colors were also submitted to the prolonged heat treatment. The colors were blue, red, green, yellow, orange, and brown. The tensile properties, tensile strength, and elongation increased in a manner consistent with the unpigmented constructions described in Figures 1 and 2. The melt flow numbers decreased as expected. The dielectric strength values showed little difference in performance from the unpigmented samples, showing a decrease as heat treatment was prolonged. A modest improvement was noted in the 1X mandrel test as heat treatment progressed.

The most significant observation was a gradual color fading with time as the test continued. However, all colors were still recognizable after the 20,000 hour test at 285°C in air.

Summary and Conclusions

The electrical properties of Teflon PFA fluorocarbon resins are described in parameters useful to this general field of applications.

The dielectric constant (Ca 2), dielectric strength (2,000 v/mil), surface and volume resistivity ($> 10^{15}$ ohm), arc tracking ($>$ 180 sec) and flammability (94V-O) are typical of the fluorocarbon resins.

The dissipation factor at room temperature remains essentially constant at 0.00003 from 10^2-10^6 Hertz and increases gradually to 0.012 at 10^{10} Hertz. The dissipation factor varies at elevated temperatures in a similar manner. This may preclude its use as a primary insulation in stringent applications involving radar frequencies.

Thermal treatment at 285° C (545° C) for 20,000 hours caused no deleterious effects on the electrical properties. Indeed, improvements in the tensile properties, flex life, and "mandrel wrap" performance were observed. This was accompanied by an increase in the melt viscosity of the material. The resin did not follow the usual behavior adaptable to an Arrhenius plot. The tests indicate that Teflon PFA fluorocarbon resin can be used continuously at 285°C as wire insulation, as well as in other electrical applications such as switch components, bushings, and stand-off insulators. Although it is noted that this is only 15°C below its melting point, this is the highest continuous use temperature proposed for any fluorocarbon resin. While the tests performed were prototype constructions, actual use of the resin under these conditions has not been observed in the industry to date.

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Mr. Reed received a BSEE and a MS degree from Virginia Polytechnic Institute. He joined the Du Pont Company in 1948 and has worked in various positions in manufacturing and technical operations He is a member of ASTM Subcommittee on Fluoroplastics and Chairman of the Fluoropolymers Section.

MANVILLE I. BRO

Dr. Bro received his PhD in Organic Chemistry from the State University of Iowa. He joined the Du Pont Company in 1951. He has worked in various technical positions supervising Research and Development of fluorocarbon polymers. His present position as Marketing Programs Manager of new fluoropolymer products involves the analysis of markets and introduction of new, high and low temperature, corrosion resistant polymers with superior electrical properties.

DONALD I. McCANE

Dr. McCane received his PhD in Organic Chemistry from the University of Michigan. He joined Du Pont in 1953. He has held various positions in Du Pont Research groups conducting and supervising experiments toward new fluorocarbon polymers. He holds a number of patents in these areas. At present, he is a consultant in Du Pont's Fluoropolymer Products Division providing technical support for their melt fabricable fluoropolymers.

DAVID B. ALLEN

Mr. Allen received his BS in chemistry from Georgetown University He joined Du Pont in 1954 and has been involved in various technical and marketing assignments. His present assignment involves development of new markets and uses for wire and cable made from fluoropolymers. Mr. Allen is a member of the Society of Automotive Engineers, NEMA Electronics Industry Association and the Underwriters Laboratories Ad Hoc Committee on Large Scale Fire Testing.