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This document presents the radiation durability of various polymeric materials applicable to a solid-polymer-electrolyte (SPE) water electrolyzer to be used in the tritium facility of fusion reactor. The SPE water electrolyzers are applied to the water detritiation system (WDS) of the ITER. In the ITER, an electrolyzer should keep its performance during two years operation in the tritiated water of 9TBq/kg, the design tritium concentration of the ITER. The tritium exposure of 9TBq/kg for two years is corresponding to the irradiation of no less than 530 kGy. In this study, the polymeric materials were irradiated with γ-rays or with electron beams at various conditions up to 1600 kGy at room temperature or at 343 K. The change in mechanical and functional properties were investigated by stress-strain measurement, thermogravimetric analysis (TGA), differential scanning calorimetry (DSC), X-ray photoelectron spectra (XPS), and so on. Our selection of polymeric materials for a SPE water electrolyzer used in a radiation environment was Pt + Ir applied Nafion® N117 ion exchange membrane, VITON® O-ring seal and polyimide insulator.

Keywords: Radiation, Durability, Polymer, SPE, Tritium

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核融合トリチウムプラントで使用される 固体高分子水電解システム内の各種高分子材料の放射線耐久性

日本原子力研究開発機構　核融合研究開発部門
核融合エネルギー工学研究開発ユニット
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本資料は核融合プラントのトリチウム施設内で使用を予定している固体高分子水電解装置に適用可能な各種高分子材料の放射線耐性について纏めたものである。固体高分子電解装置は国際熱核融合実験炉(ITER)のトリチウム水処理システムを構成している。ITERにおいて固体高分子電解装置は設計値として 9TBq/kg のトリチウム水を二年間連続的に電解処理する性能が求められている。これはトリチウムの線量として 530kGy に相当する。本研究では固体高分子水電解装置に適用可能な各種高分子材料を室温あるいは 343Ｋの条件にてγ線あるいは電子線を用いて 1600kGy まで様々な雰囲気条件下にて照射を実施した。高分子材料の機械特性及び機能の変化を、応力-ひずみ分析、熱重量分析(TGA)、示差走査熱量測定 (DSC)、X 線光電子分光測定(XPS)等にて精査した。核融合トリチウム施設で使用する固体高分子電解装置には NafionN117 イオン電解膜、VITON シール、ポリイミド電気絶縁膜の組み合わせが最適であるとの結論を得た。

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1. Introduction

Solid-polymer-electrolyte (SPE) water electrolysis [1)-3)] is attractive in the electrolytic process of radioactive liquid waste because it can electrolyze liquid waste directly without alkaline addition. The SPE water electrolyzers are planned to be used in the water detritiation system (WDS) [4)] of the ITER [5)], international thermonuclear experimental reactor. **Figure 1** shows a structure of the electrolysis cell, a unit of electrolyzer.[6)] The polymeric materials used in the commercial SPE water electrolyzer are an integrated ion exchange membrane, and a set of gaskets and electric insulators. Hence, the radiation durability of these polymers is a debatable point to use SPE water electrolyzers under radiation environment. In the tritium facility of the ITER, each electrolyzer is planed to be replaced every two years. Therefore, the electrolyzer should keep its performance during two years operation in tritiated water of 9TBq/kg that is the design value of tritium concentration in the SPE water electrolyzers of the ITER. The tritium exposure of 9TBq/kg for two years is corresponding to the irradiation dose of 530 kGy. Therefore, the effect of tritium exposure on polymeric materials used in the SPE water electrolyzers should be carefully investigated.

The practically used ion exchange membranes are polyperfluorosulfonic acid (PFSA) membrane such as Nafion® (du Pont de Nemours & Co. Inc) because of high proton conductivity, good chemical stability and high mechanical strength.[7)] The PFSA membrane consists of a polytetrafluoroethylene (PTFE) backbone with perfluoroalkylether (PFAE) side-chains terminating with $-SO_3^- M^+$ groups, where M^+ is an exchangeable cation.[8)] There were not systematic data, available for the design of the SPE electrolyzer applicable to radiation environment, on the radiation deterioration in the properties of the Nafion membrabe swelling in the water. Surprisingly, there has been relatively little published on this aspect. E.N. Balko and J.T. Chaklos examined the effect of electron β and ^{60}Co γ-rays radiations in air on the deterioration in the Nafion properties.[9)] They concluded that Nafion irradiated in air deteriorated by the single chain scission, and the deterioration rate was not affected by the hydration state or by the nature of the exchangeable cation. A matter for consideration is then a contribution of contained water to the deterioration. The structure model that polymeric ions and water contained in the Nafion membrane are clustered and separated from surrounding fluorocarbon matrix is generally accepted.[10)-11)] The clusters are connected by the short and narrow channels in the hydrated Nafion. T. Sakai et al.

examined the oxygen diffusivities for dry Nafion N117 (H form) and for hydrated Nafion (H form), and they compared the values with that for PTFE.[12)] The permeability coefficient in the 35 w/o hydrated Nafion was one order magnitude greater than that in the dried Nafion. The permeability coefficient in the dried Nafion was close to that in PTFE. The diffusion coefficient in the dried Nafion was close to that in PTFE, whereas that in the hydrated Nafion was 20 times greater than that in the dried Nafion. The produced radicals in the polymer by irradiation promptly react on oxygen molecules. They are probably principal reactions for the deterioration of an oxygen-diffusible polymer even swelling in the oxygen-saturated water. Hence, the contribution of oxygen-induced radical termination reactions to the deterioration in the swelling Nafion properties must be quantified.

PTFE has high electrical insulation as well as a heat resistance and high stability to any chemical solvent. Therefore, PTFE is widely applied for industrial use. There are a number of reports on the radiation deterioration in PTFE properties.[13)] PTFE has been classified as a typical fragile polymer under radiation environment since main chain scission is promoted by irradiation. It is well known that even a small dose up to a few hundreds kGy leads to the decrease in molecular weight of PTFE either in air or under vacuum.[14)] The decrease deteriorates the mechanical properties of PTFE. Hence, replacing PTFE insulators with high durability insulators such as polyimide insulators is necessary to use SPE water electrolyzers under radiation environment.

There are many kinds of rubbers available for gaskets. For the gaskets, stable mechanical strength, softness and the negligible organic elution against the exposure to the tritiated water are necessary. However, there were not systematic data on the deterioration in the properties of rubbery polymer swelling in the water under radiation environment. The rubbers will be structurally changed with the competition reactions of chain scission and crosslinking.

In this study, a series of irradiation tests of the candidate polymeric materials for a SPE water electrolyzer up to 1600 kGy using the ^{60}Co irradiation facility or the electron beam irradiation facility at the Takasaki Advanced Radiation Research Institute of Japan Atomic Energy Agency (JAEA) was conducted to research the radiation durability of the polymeric materials.

2. Experimental Procedures

The PFSA membranes tested in this study were Nafion NE117CS, Nafion N112, Nafion N115, Nafion NE1110, Nafion NE1135. Four kinds of materials candidate for electric insulators were tested which were PTFE, PFA, FEP and polyvinyl chloride. Six kinds of materials candidate for gasket were tested which were Viton, AFLAS, Neoprene, EPDM, Kalrez, and Butyl rubber. Denaturated polyphenylene ether was also tested which is the packing material for an electrolytic conductivity meter.

Some kinds of Nafion membrane in the base form were provided by E. I. du Pont de Nemours & Co. Inc. No pretreatment was carried out on the hydrated base form membrane prior to its use. The structure of the test stand for the irradiation with ^{60}Co γ-rays at room temperature is illustrated in **Fig. 2**. Nafion membrane was cut to dumb-bell shape (ASTM D-1822L) specimens for the stress-strain measurement. The direction for membrane section was decided as specimens had the largest tensile strength. A part of the specimens swelled in the oxygen-saturated distilled water. The authors judged the complete hydration of the Nafion specimens with the periodic measurements of their weights. It took more than 60 hours to reach the stable swelling of a Nafion specimen. Six specimens were orderly enclosed with the oxygen-saturated distilled water of 35.0±0.1g in a laminate film bag. Distilled water produced by Kyouei Pharmaceutical Co., Ltd. was used in the experiments. The concentration of dissolved oxygen was measured with a DO meter (OE-270AA, DKK-TOA Corp.). The authors brought specimens into contact with the water in the bag. They were then irradiated with ^{60}Co γ-rays at the dose rate of 10 kGy/h at room temperature using the ^{60}Co γ-ray irradiation No. 2 facility or the ^{60}Co facility for food irradiation in the Takasaki Advanced Radiation Research Institute of Japan Atomic Energy Agency (JAEA). After the specimens were taken out from a laminate film bag, a series of stress-strain measurements were carried out using PC-controlled Strograph VE5D (Toyoseiki Co. Ltd.). The chuck span and the cross head speed adopted were 38.0 mm and 20 mm/min during the experiment, respectively. The resolution for the observation of elongation was 0.01mm. The pH value, electrolytic conductivity, electrolytic resistivity, and quantity of dissolved fluorine in the distilled water were measured with a pH meter (GST-2729C, DKK-TOA Corp.), with an EC meter (CM-21PW, DKK-TOA Corp.) and with a fluoride ion meter (F-2021, DKK-TOA Corp.), respectively. Prior to the measurement of the quantity of dissolved fluorine in the distilled water with a fluoride ion meter, we added the ionic strength adjuster for fluoride (TISAB-11, DKK-TOA Corp.) into the sample solution at the capacity ratio of 10: 1. The ionic strength adjuster dissolves the complex with metallic ion and makes it ionized completely as fluoride ion. The ion exchange capacity was measured by titration as follows. A piece of sample was cut from the irradiated specimen, and was immersed into hydrochloric acid. By replacing the hydrochloric acid several times, a sulfonic acid group in the sample was changed from SO_3H to $SO_3^-H^+$ by hydrolyze. The sample was then washed with distilled water to remove hydrochloric acid. After the washing, the sample was immersed into a solution of NaCl. The ion H^+ was replaced to Na^+, and the H+ exuded from the sample to the solution. An amount of H^+ was measured by titration with NaOH. The ion exchange capacity was thus evaluated through the above procedures. The water content was then measured. The sample was washed with distilled water to remove chlorine ion. After the washing, the sample was wiped off and its weight was measured (W_0). The sample was then dehydrated at 473 K under vacuum. The authors measured the weight of samples dehydrated in desiccator (W_1). The water content is evaluated as $(W_0/ W_1 - 1)\times 100$. To investigate the effect of oxygen on the radiation deterioration in Nafion properties, several conditions are taken up for comparative purpose in addition to the irradiation in the oxygen-saturated distilled water. These are the irradiations under atmosphere, under vacuum, under swelling in 35.0 ± 0.1g of 10wt% Na_2SO_3 solution, under swelling in 35.0 ± 0.1g of about 30% H_2O_2 solution (S. S. Grade, Wako Pure Chemical Industries, Ltd.), under atmosphere with an oxygen absorbent (A-500HS, I.S.O. Corp.) and under swelling in 35.0 ± 0.1g of oxygen-free water. Na_2SO_3 played a role of the absorber for dissolved oxygen in the water. Oxygen adsorbing time using oxygen absorbent was taken for more than 24h before irradiation. Adsorption of oxygen was checked with an oxygen indicator. Oxygen-free water was produced by the procedure that 100cc of distilled water was supplied in a gas wash bottle, and then dissolved oxygen in the water was purged off with the 1000 Ncc/min of helium gas for more than 24h.

A test tube with the screw cap was adopted as the enclosure for the irradiation of Nafion specimens with ^{60}Co γ-rays at 343 K. The temperature of 343 K was determined with due consideration of actual operating condition of a SPE electrolyzer in a nuclear facility.[4] Six specimens were orderly enclosed with the oxygen-saturated distilled water in a test tube and the tube was preheated at 343 K for more than 2 hours.

The test tube was then installed in a PID temperature-controlled heater in the ^{60}Co irradiation room. They were irradiated with ^{60}Co γ-rays at the dose rate of 10 kGy/h. To investigate the effect of oxygen on the radiation deterioration in the Nafion properties at 343 K, different two conditions are taken up for comparative purpose in addition to the irradiation in oxygen-saturated distilled water. These are irradiations under vacuum and in the oxygen-free water.

The effect was also observed with electron beams at room temperature to consider whether there is a discrepancy in the deteriorations between ^{60}Co γ-rays irradiation and electron beams irradiation. The enclosure and its content are the same as those for the irradiation with ^{60}Co γ-rays at room temperature. They were irradiated with electron beams at equivalent dose rate to 250 kGy/h using the electron accelerator No.1 facility of the Cockcroft-Walton type in Takasaki Advanced Radiation Research Institute of JAEA under the conditions of the beam energy of 1.99 MeV and the beam current of 2.00 mA. A sufficient long interval for every 50 kGy irradiation was taken to prevent the temperature rising of the specimens.

As for the gas permeability through the Nafion membrane, the effect of dose on the gas permeability was evaluated using a GTR-20XF (GTR TEC) with the test procedure of JIS K 7126 B. The gas permeability was measured at 343K with two gas systems; H_2-H_2O or O_2-H_2O. The relative humidity was set at 90% in each gas system.

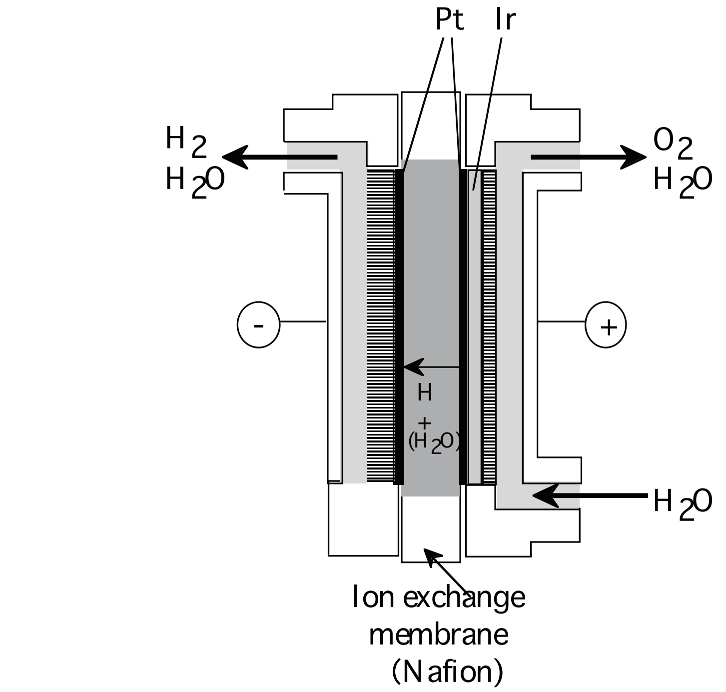
The effect of the dose rate on the deterioration was examined in addition to the dose rate of 10 kGy/h. The additional dose rates were 2.5 kGy/h and 0.5 kGy/h with due consideration of the previous observations that the effect of the dose rate on the radiation deterioration in the polymer properties is generally negligible at less than 1.0 kGy/h. The elongation at break and the ion exchange capacity for each dose rate were compared at the dose of 160 kGy.

Thermogravimetric analysis was carried out on a TG-DTA-2000S analyzer (Mac Science) under helium atmosphere to prevent a sample from oxidation and adsorption of moisture. An aluminum pan was used for all the samples, and it was flamed prior to each analysis. The continuous scan was carried out with a constant rate of 10K/min.

A DSC-3200 differential scanning calorimetry analyzer (Mac Science) was used to obtain DSC thermograms. Experiments were run from 80K to 893K with a heating rate of 5K/min on about 10- mg sample weight.

X-ray photoelectron spectra were obtained using a Kratos Axis Ultra electron spectrometer. Monochromatic AlK α photons (15kV, 10mA) were used for the measurement. The analyzer pass energy was set to 160 eV for surver scans and to 20 eV for high resolution narrow scans. An area of 300x700 micrometers of the sample surface was analyzed at the normal photoelectron take-off angle for all samples. The F(1s) peak set at 688.94 eV was used as the binding energy reference for all spectra.

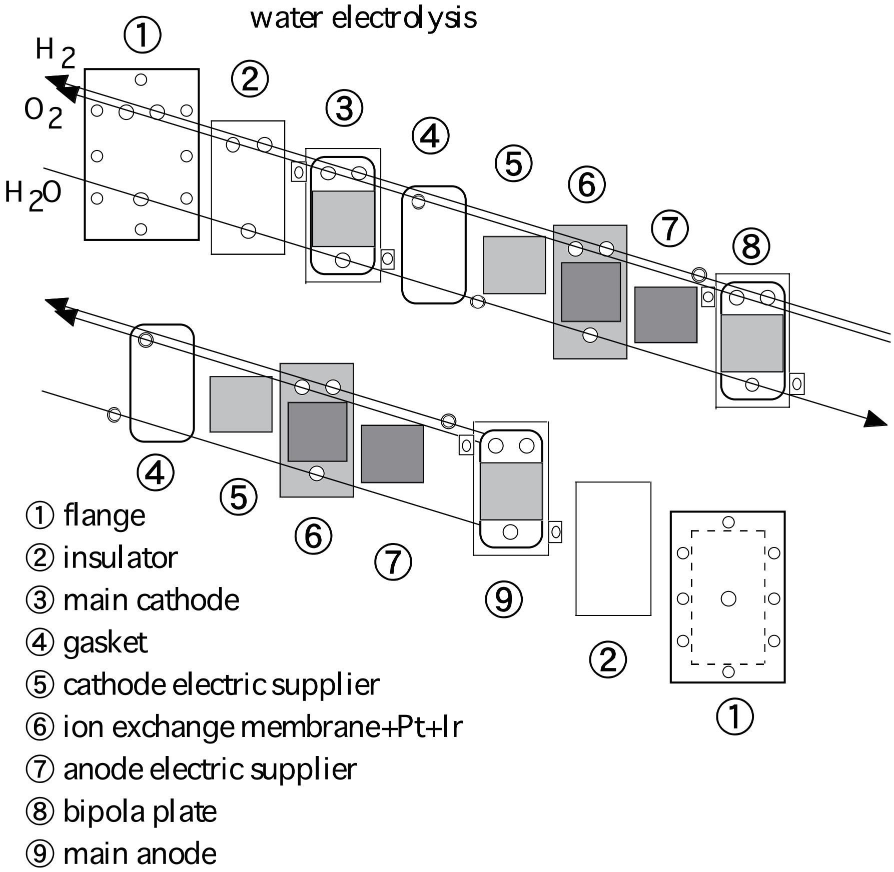
The test procedures to the Nafion membrane were applied to other porimeric materials.



Anode : $2H_2O \rightarrow 4H^+ + 4e + O_2$

Cathode: $4H^+ + 4e \rightarrow 2H_2$

(a) Principle of solid polymer electrolyte water electrolysis



(b) Exploded view of electrolyzer

Figure 1　　Structure of the SPE cell

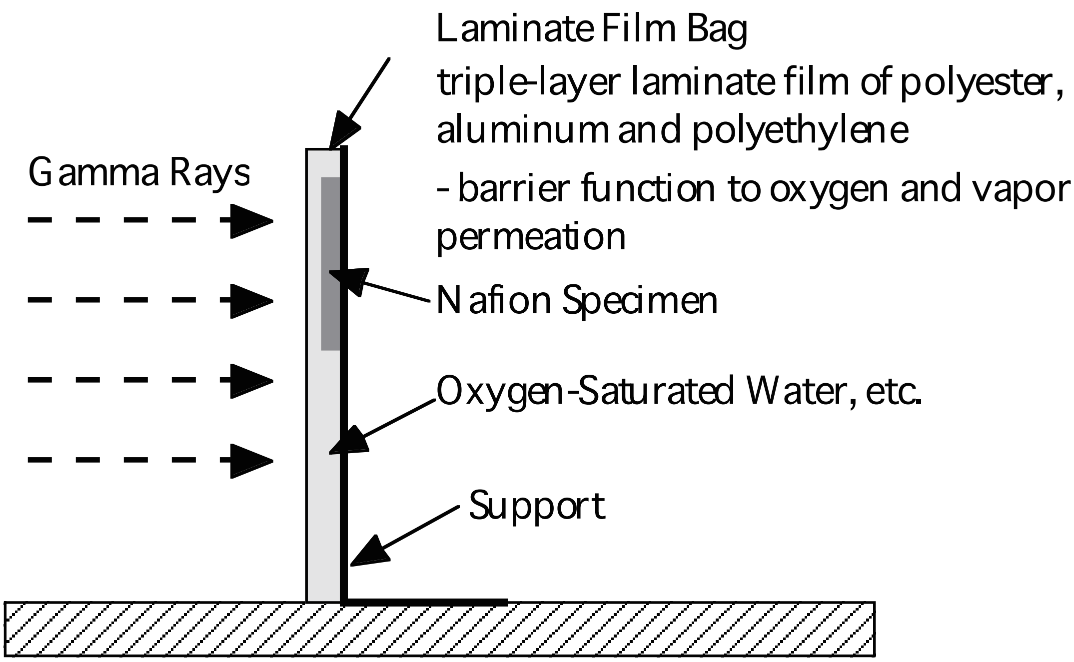


Figure 2 Structure of the TEST STAND for the gamma-rays irradiation

3. Data Tables on Radiation Durability of Various Polymeric Materials

3.1 Nafion N117CS [15)-19)]

Material	Nafion NE117CS (Du Pont de Nemours & Co. Inc)
Thickness	0.185 mm (as swelling in water)
Irradiation condition	^{60} Co γ-rays: 10kGy/h Room Temperature ■:Swelling in oxygen-satureted water Water: 35.0±0.1g ○:Atmosphere □ : Vacuum-packed ▲ : Swelling in 10wt% Na 2SO3 solution Solution: 35.0±0.1g ●: Swelling in about 30% H2O2 solution Solution: 35.0±0.1g △:Atmosphere with oxygen absorbent ▼:Swelling in oxygen-free water Water: 35.0±0.1g
Measurement	Stress-Strain Measurement Dumb-bell Shape: ASTM D-1822L Cross Head Speed: 20.0 mm/min Chuck Span: 38.0 mm Ion Exchange Capacity

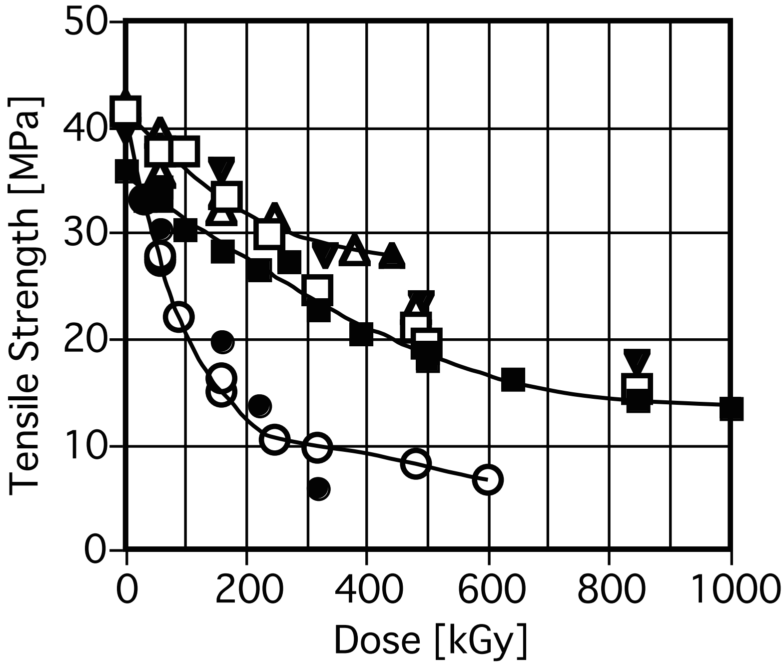


Figure 3.1-1　Tensile strength of γ-irradiated Nafion N117CS at room temperature

Material	Nafion NE117CS (Du Pont de Nemours & Co. Inc)
Thickness	0.185 mm (as swelling in water)
Irradiation condition	^{60}Co γ-rays 0.5kGy/h 2.5kGy/h 10kGy/h Room Temperature Swelling in Oxygen-Satureted Water Water: 35.0±0.1g
Measurement	Stress-Strain Measurement Dumb-bell Shape: ASTM D-1822L Cross Head Speed: 20.0 mm/min Chuck Span: 38.0 mm Ion Exchange Capacity

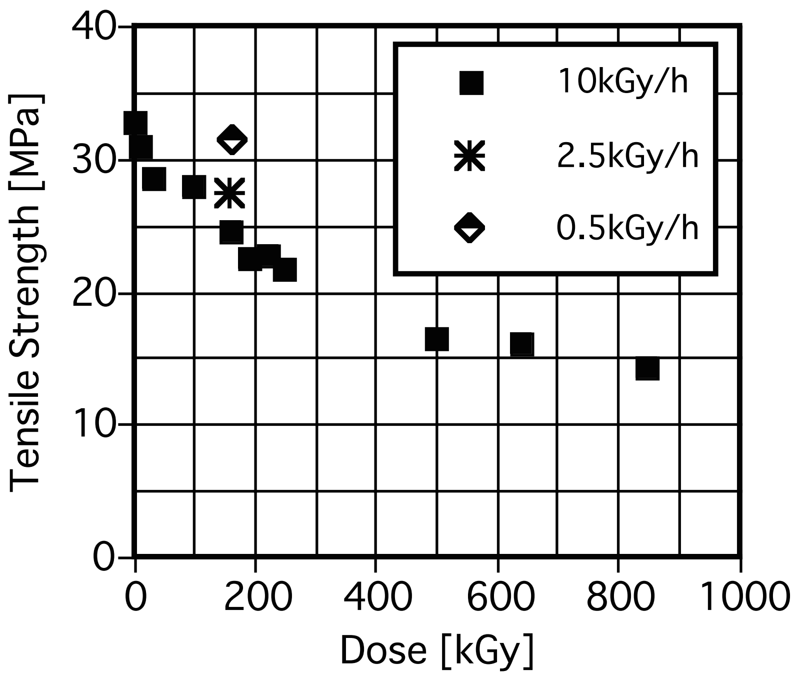


Figure 3.1-2 Effect of dose rate on deterioration in tensile strength

Material	Nafion NE117CS (Du Pont de Nemours & Co. Inc)
Thickness	0.185 mm (as swelling in water)
Irradiation condition	^{60}Co γ-rays: 10kGy/h 343K ■:Swelling in oxygen-satureted water Water: 35.0±0.1g □ : Vacuum-packed ▼:Swelling in oxygen-free water Water: 35.0±0.1g
Measurement	Stress-Strain Measurement Dumb-bell Shape: ASTM D-1822L Cross Head Speed: 20.0 mm/min Chuck Span: 38.0 mm Ion Exchange Capacity

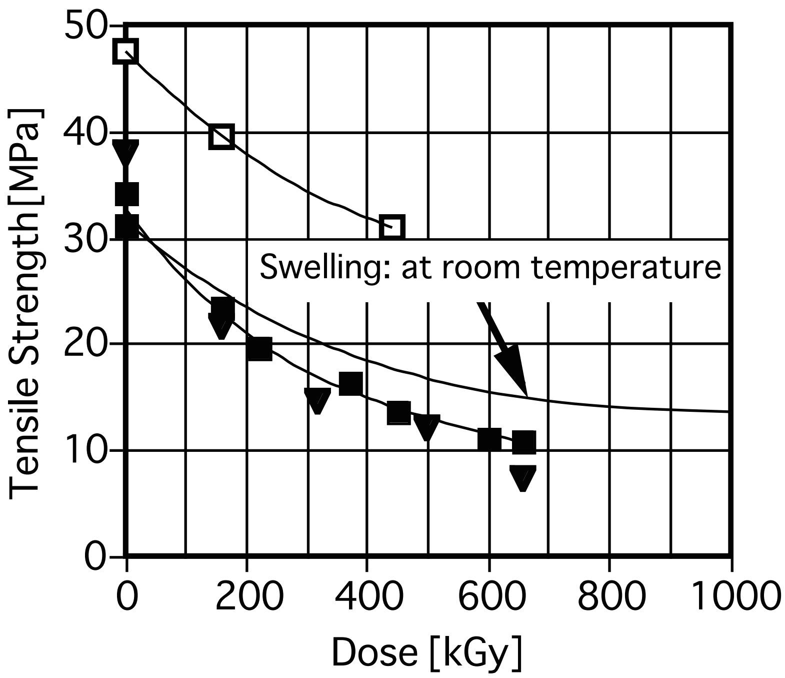


Figure 3.1-3 Tensile strength of γ-irradiated Nafion N117CS at 343K

Material	Nafion NE117CS (Du Pont de Nemours & Co. Inc)
Thickness	0.185 mm (as swelling in water)
Irradiation condition	^{60} Co γ-rays: 10kGy/h Room Temperature Swelling in oxygen-satureted water Water: 35.0±0.1g
Measurement	Permeability Coefficient GTR-20XF (GTR TEC) Humidity: 90%RH Temperature: 343K Permeation Area: 3.14cm2

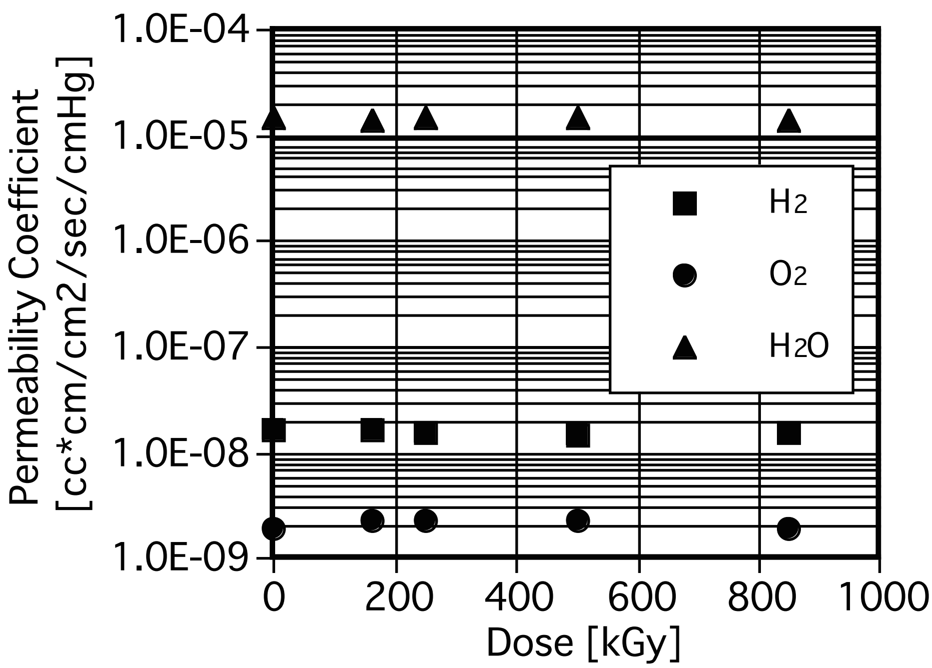


Figure 3.1-4 Permeability coefficient of γ-irradiated Nafion N117CS at room temperature

Material	Nafion NE117CS (Du Pont de Nemours & Co. Inc)
Thickness	0.185 mm (as swelling in water)
Irradiation condition	^{60}Co γ-rays: 10kGy/h Room Temperature Swelling in oxygen-satureted water Water: 35.0±0.1g
Measurement	Thermogravimetric analysis (TGA) TG-DTA-2000S (Mac Science) Sample*: 5mg *Cations were exchanged into Na+ before the TGA Temp. rate: 10K/min Purge gas: He, 50Ncc/min

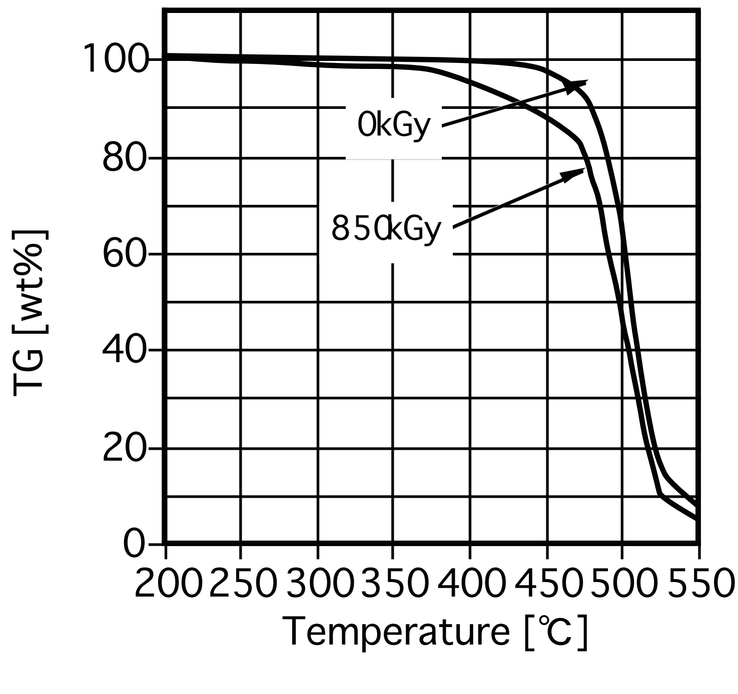


Figure 3.1-5 Weight loss curve *vs.* temperature of Na cation exchanged Nafion N117CS membrane under helium atmosphere

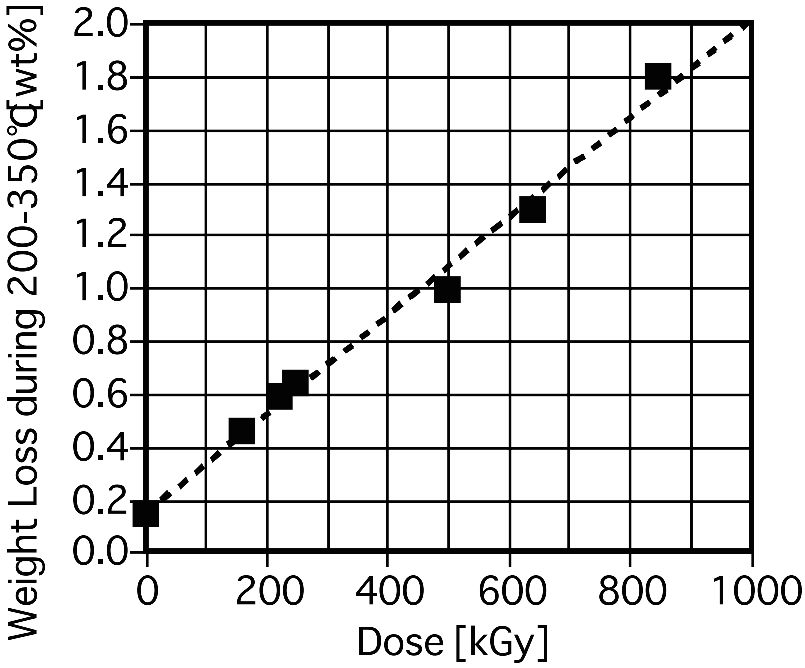


Figure 3.1-6 Weight loss of Na cation exchanged Nafion N117CS membrane between 473-623K under helium atmosphere

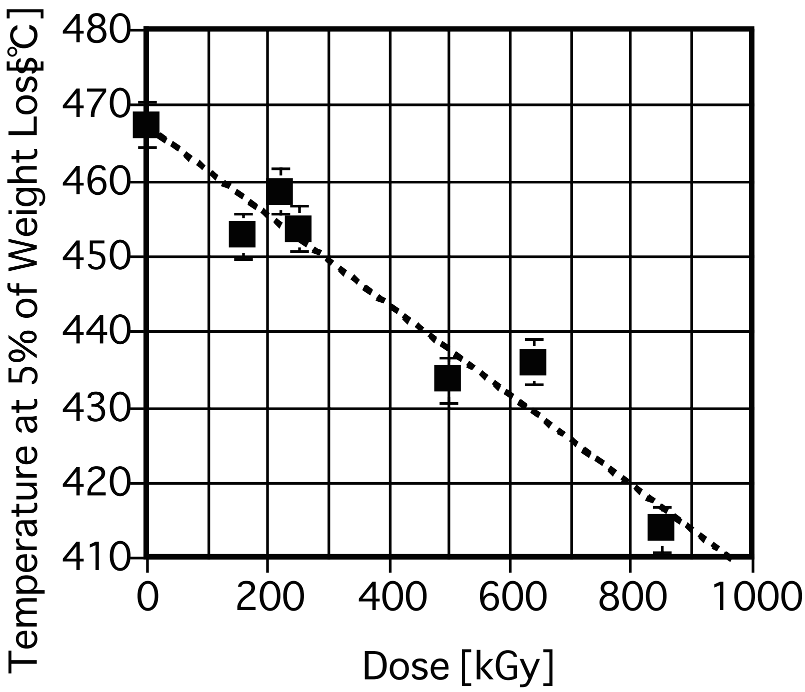


Figure 3.1-7 Temperature at 5% of weight loss of Na cation exchanged Nafion N117CS membrane under helium atmosphere

Material	Nafion NE117CS (Du Pont de Nemours & Co. Inc)
Thickness	0.185 mm (as swelling in water)
Irradiation condition	Electron beams: 10kGy/pass (250kGy/h) Room Temperature Vacuum-packed
Measurement	Differential scanning calorimetry (DSC) DSC-3200 (Mac Science) Sample: 10mg Temp. rate: 5K/min Purge gas: He, 50Ncc/min

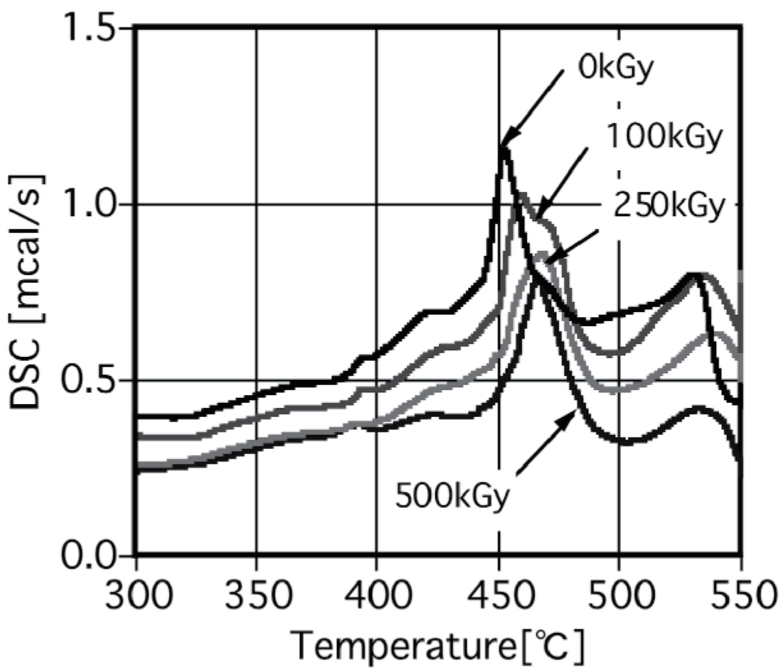


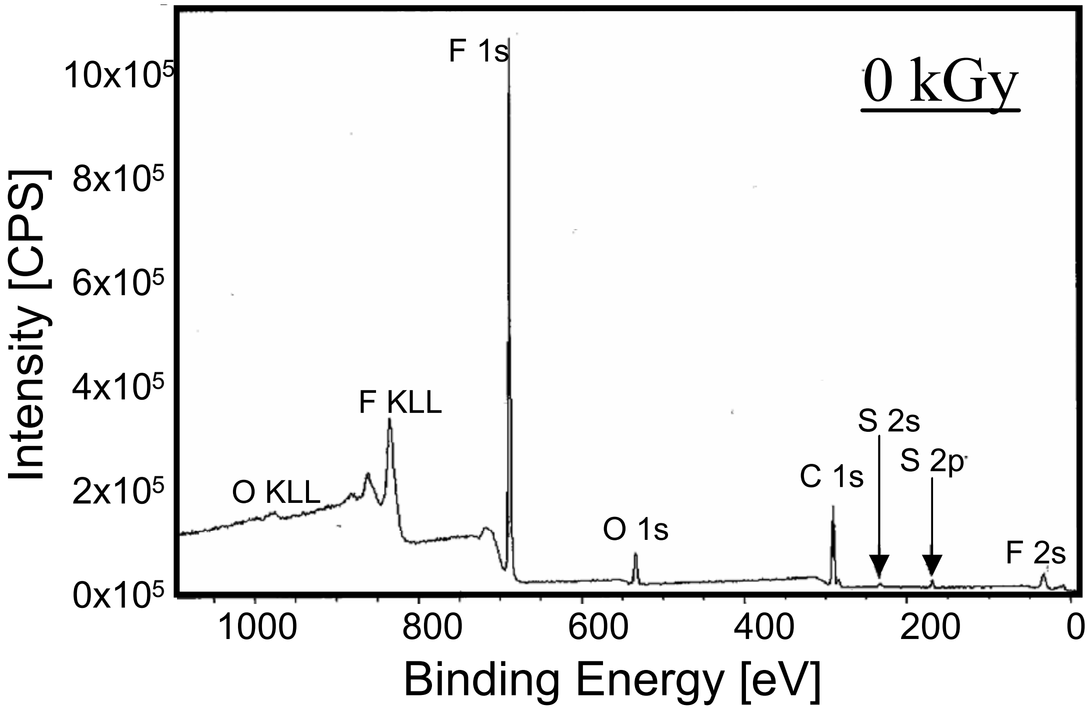
Figure 3.1-8 DSC curves of acid form Nafion N117CS membrane under helium atmosphere

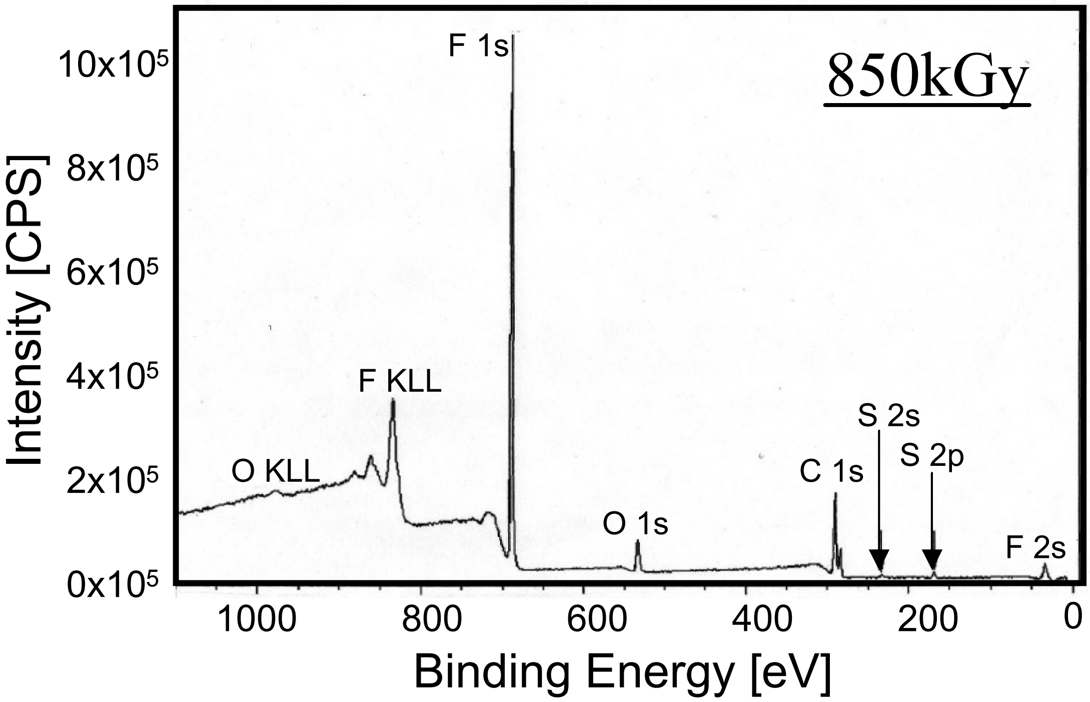
Material	Nafion NE117CS (Du Pont de Nemours & Co. Inc)
Thickness	0.185 mm (as swelling in water)
Irradiation condition	^{60}Co γ-rays: 10kGy/h Room Temperature 0kGy: Base form 850kGy: Under atmosphere with oxygen absorbent
Measurement	X-ray photoelectron spectra (XPS) Kratos Axis Ultra electron spectrometer (Kratos) Monochromatic AlKα photons (15kV, 10mA) Analyzer pass energy:160 eV for surver scans 20 eV for high resolution narrow scans Normal photoelectron take-off angle Binding energy reference:F(1s) peak at 688.94 eV Sampla area: 300x700 micrometers

Results

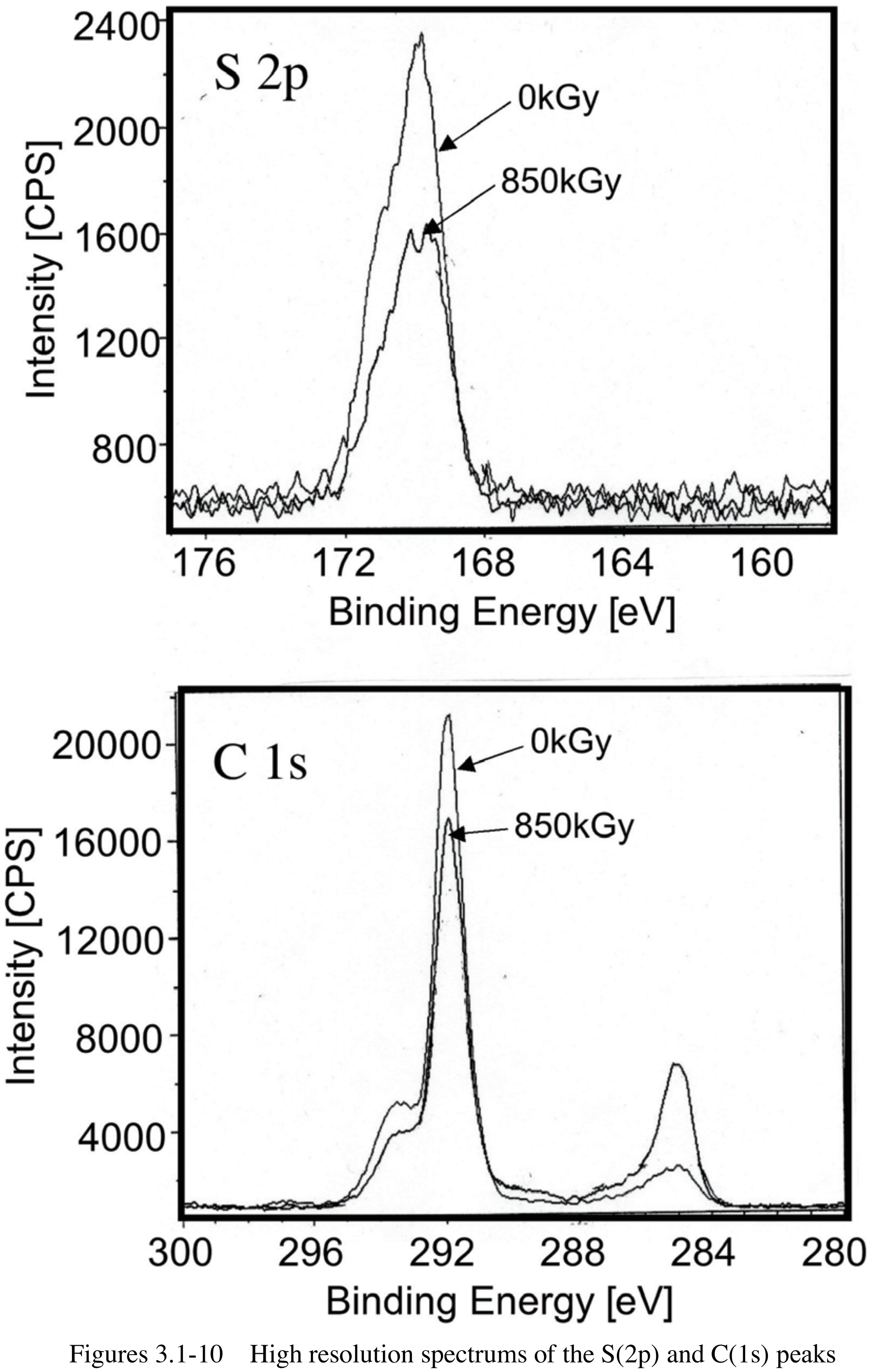
Table 3.1-1 Atomic percentage of Nafion N117CS membrane

Atomic %	S 2p	F 1s	C 1s	O 1s
0 kGy	1.35	59.81	31.77	7.07
850 kGy	1.08	55.75	36.55	6.62

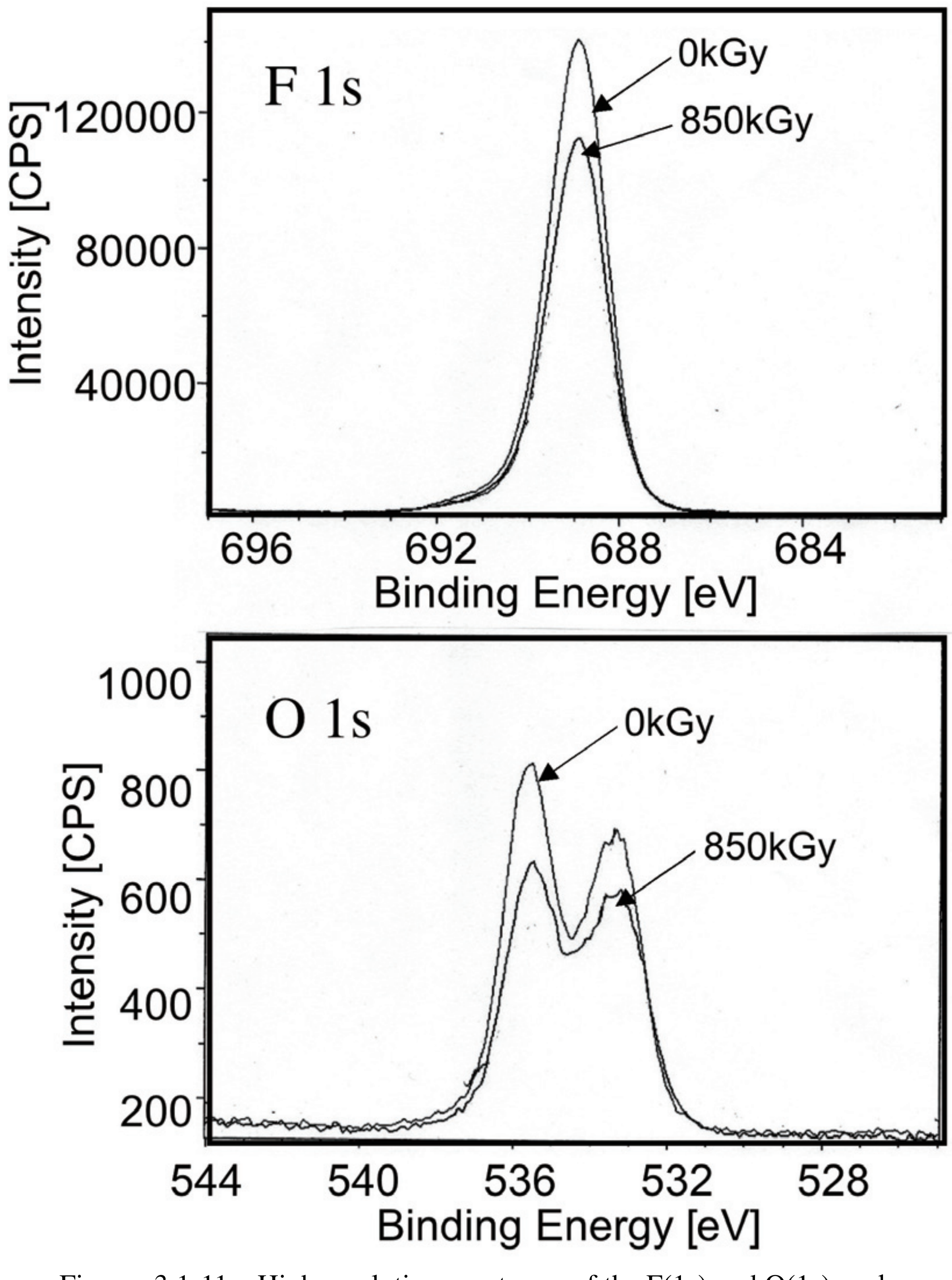




Figures 3.1-9 X-ray photoelectron spectrums of Nafion N117CS membrane



Figures 3.1-10　High resolution spectrums of the S(2p) and C(1s) peaks



Figures 3.1-11 High resolution spectrums of the F(1s) and O(1s) peaks

Table 3.1-2 S 2p: results of curve fitting

	sample	S2	S1
conc / %	0 kGy	100.00	0.00
	850 kGy	100.00	0.00
position / eV	0 kGy	169.793	
	850 kGy	169.652	
fwhm / eV	0 kGy	1.337	
	850 kGy	1.560	

Split span of $S2p_{3/2}$ and S $2p_{1/2}$ was set as 1.18 eV. Intensity ratio of of $S2p_{3/2}$ and $S2p_{1/2}$ was set as 2:1. Half width of $S2p_{3/2}$ and S $2p_{1/2}$ was set as same value.

O2: -SO3, O3: -OCF3

Table 3.1-3 O 1s: results of curve fitting

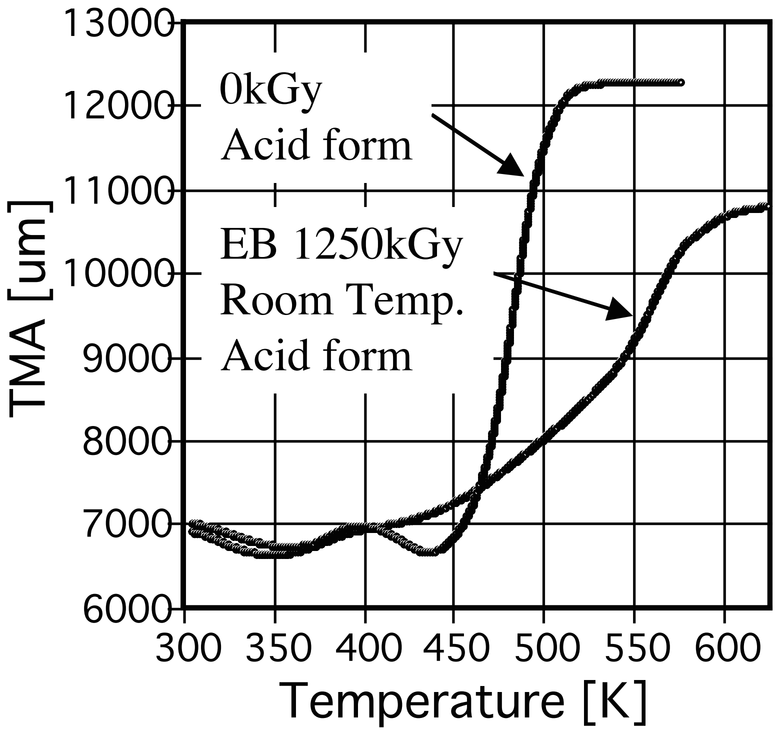
	sample	O4	O3	O2	O1
conc / %	0 kGy	2.09	50.11	47.80	0.00
	850 kGy	1.92	48.70	49.38	0.00
position / eV	0 kGy	537.493	535.662	533.448	
	850 kGy	537.496	535.523	533.358	
fwhm / eV	0 kGy	1.794	1.464	1.718	
	850 kGy	1.644	1.644	1.799	

Table 3.1-4 C 1s: results of curve fitting

	sample	C10	C9	C8	C7	C6
conc / %	0 kGy	1.40	9.27	11.47	64.92	2.07
	850 kGy	0.90	6.79	6.81	52.95	2.59
position / eV	0 kGy	296.616	293.911	293.210	291.850	290.548
	850 kGy	294.857	293.743	293.205	291.852	290.400
fwhm / eV	0 kGy	1.479	1.230	1.224	0.989	1.064
	850 kGy	1.486	1.230	1.168	1.033	1.064
	sample	C5	C4	C3	C2	C1
conc / %	0 kGy	0.60	0.66	0.79	2.63	6.19
	850 kGy	2.30	1.23	2.54	5.85	18.04
position / eV	0 kGy	289.249	287.889	286.779	286.006	285.000
	850 kGy	289.269	287.810	286.946	285.867	284.984
fwhm / eV	0 kGy	1.234	1.494	1.470	1.466	1.262
	850 kGy	1.209	1.319	1.374	1.373	1.026

C1: C-C, C2: C*-C-CF2, C3: O-C*-CF2, C4: C-F, C5: COO, C6: O-C-F, C7: CF2, C8: OCF2, C9: CF3, C10: OCF3

Material	Nafion NE117CS (Du Pont de Nemours & Co. Inc)
Irradiation condition	1) Acid Form, 0kGy 2) Irradiated with electron beams Dose: 1250kGy Dose rate: 10kGy/pass (250kGy/h) Room Temperature Swelling in Oxygen-Satureted Water Water: 35.0±0.1g
Thickness	1) 0.177mm (0kGy) 2) 0.180 mm (EB,1250kGy)
Measurement	Thermomechanical Analysis (TMA) TMA-60 (Shimadzu) Dumb-bell Shape: 5mmx12mm Load: 2.00g Temp. rate: 5K/min Chuck Span: 10.0 mm Purge gas: Nitrogen, 50cc/min



Figures 3.1-12 TMA curves of acid form Nafion N117CS membrane

3.2 Nafion N112 [18)]

Material	Nafion N112 (Du Pont de Nemours & Co. Inc)
Thickness	0.051 mm (as swelling in water)
Irradiation condition	^{60}Co γ-rays: 10kGy/h Room Temperature Swelling in Oxygen-Satureted Water Water: 35.0±0.1g
Measurement	Stress-Strain Measurement Dumb-bell Shape: ASTM D-1822L Cross Head Speed: 20.0 mm/min Chuck Span: 38.0 mm Amount of Dissolved Fluorine in the water Conductivity of the water Electrical Resistivity of the water

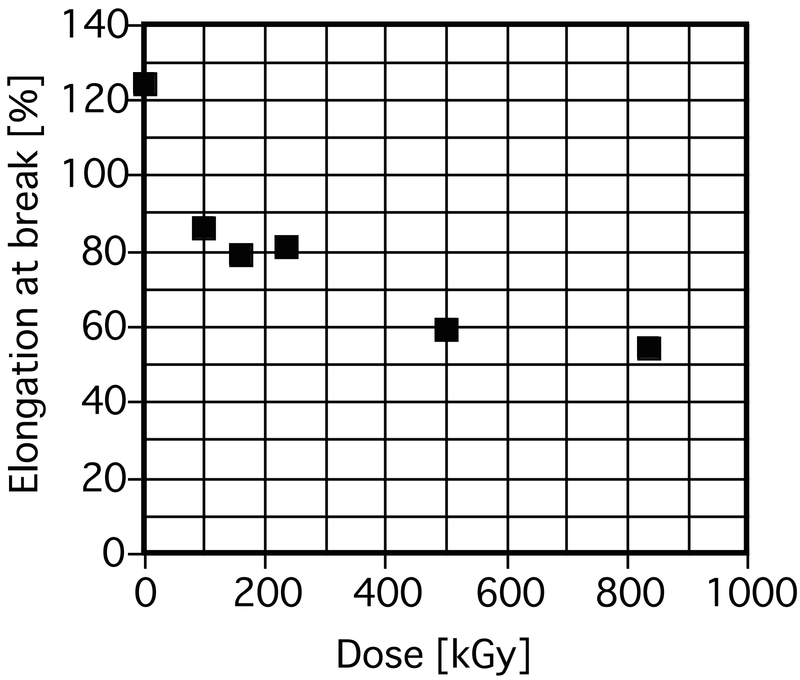


Figure 3.2-1 Elongation at break of γ-irradiated Nafion N112 at room temperature

3.3 Nafion N115 [18)]

Material	Nafion N115 (Du Pont de Nemours & Co. Inc)
Thickness	0.139 mm (as swelling in water)
Irradiation condition	^{60}Co γ-rays: 10kGy/h Room Temperature Swelling in Oxygen-Satureted Water Water: 35.0±0.1g
Measurement	Stress-Strain Measurement Dumb-bell Shape: ASTM D-1822L Cross Head Speed: 20.0 mm/min Chuck Span: 38.0 mm Amount of Dissolved Fluorine in the water Conductivity of the water Electrical Resistivity of the water

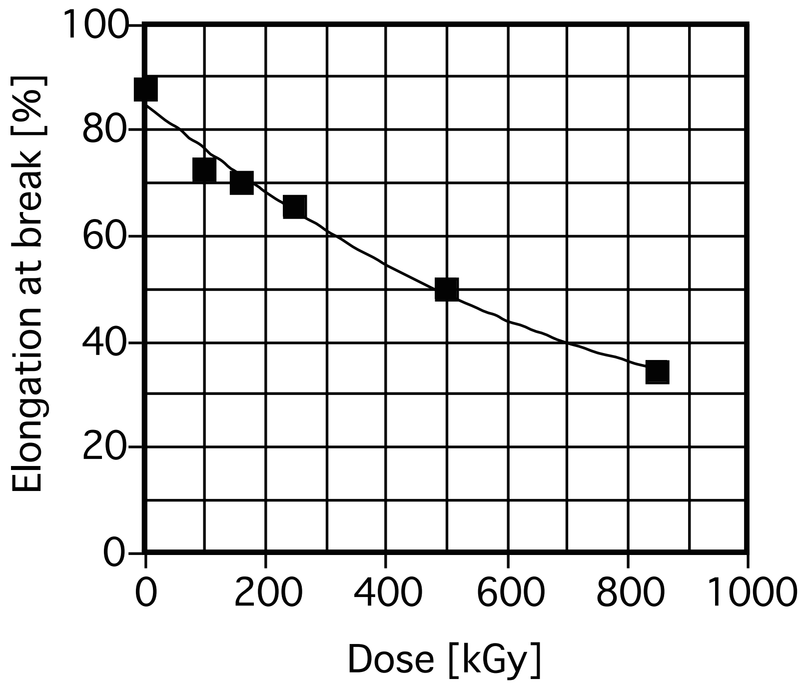


Figure 3.3-1 Elongation at break of γ-irradiated Nafion N115 at room temperature

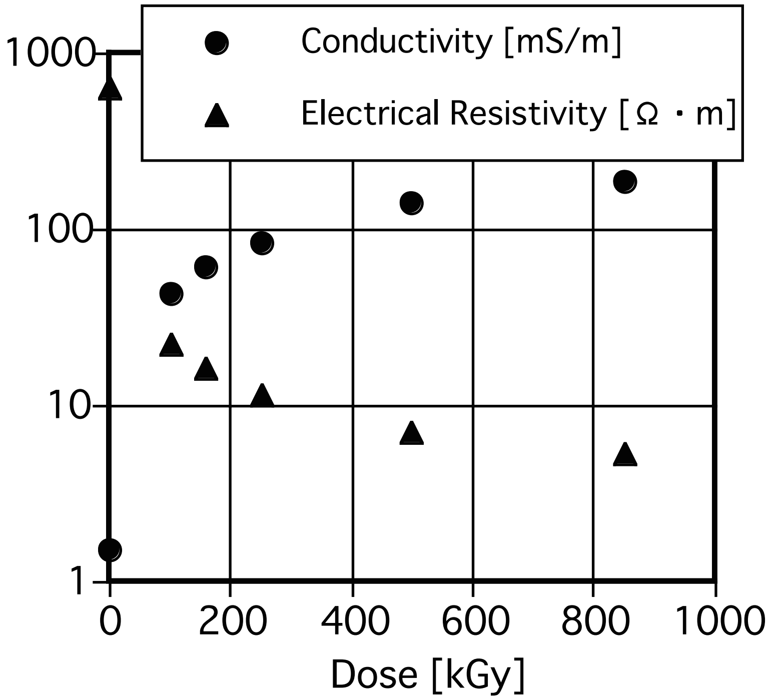


Figure 3.3-2 Conductivity and electrical resistivity of the water after irradiation

3.4 Nafion NE1110 [18)]

Material	Nafion NE1110 (Du Pont de Nemours & Co. Inc)
Thickness	0.291 mm (as swelling in water:■) 0.262 mm (as vacuum-packed: □)
Irradiation condition	^{60}Co γ-rays: 10kGy/h Room Temperature ■ : Swelling in Oxygen-Satureted Water Water: 35.0±0.1g □ : Vacuum-packed
Measurement	Stress-Strain Measurement Dumb-bell Shape: ASTM D-1822L Cross Head Speed: 20.0 mm/min Chuck Span: 38.0 mm Amount of Dissolved Fluorine in the water Conductivity of the water Electrical Resistivity of the water

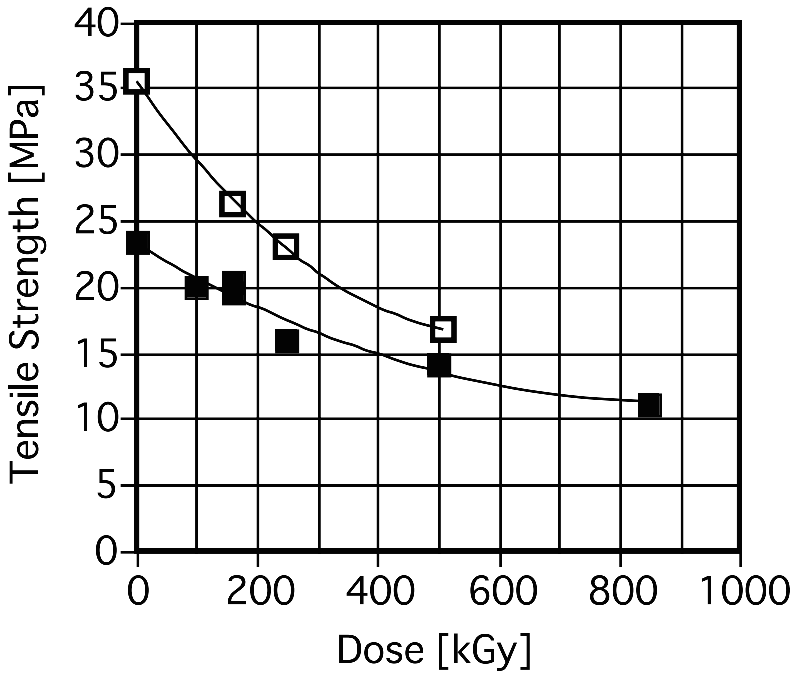


Figure 3.4-1　Tensile strength of γ-irradiated Nafion NE1110 at room temperature

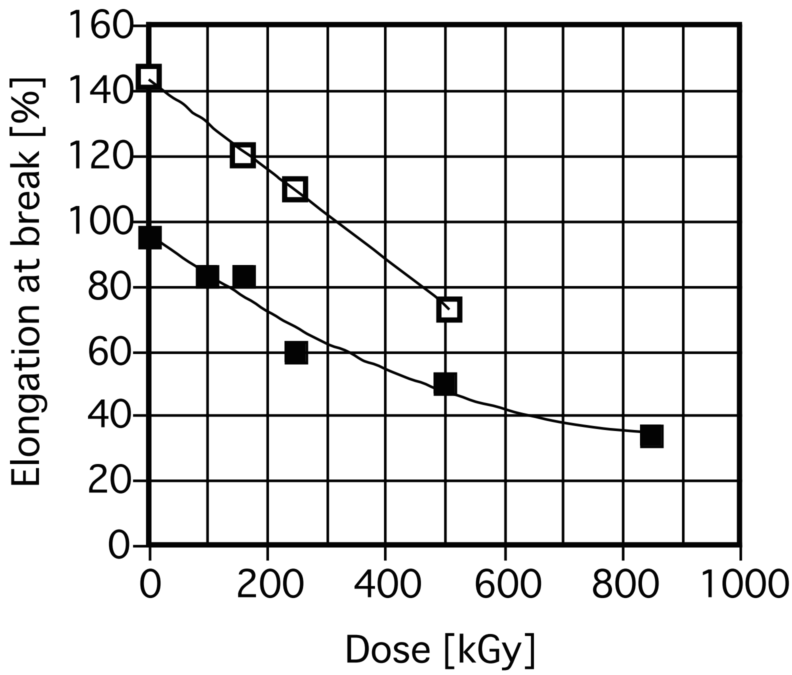


Figure 3.4-2　Elongation at break of γ-irradiated Nafion NE1110 at room temperature

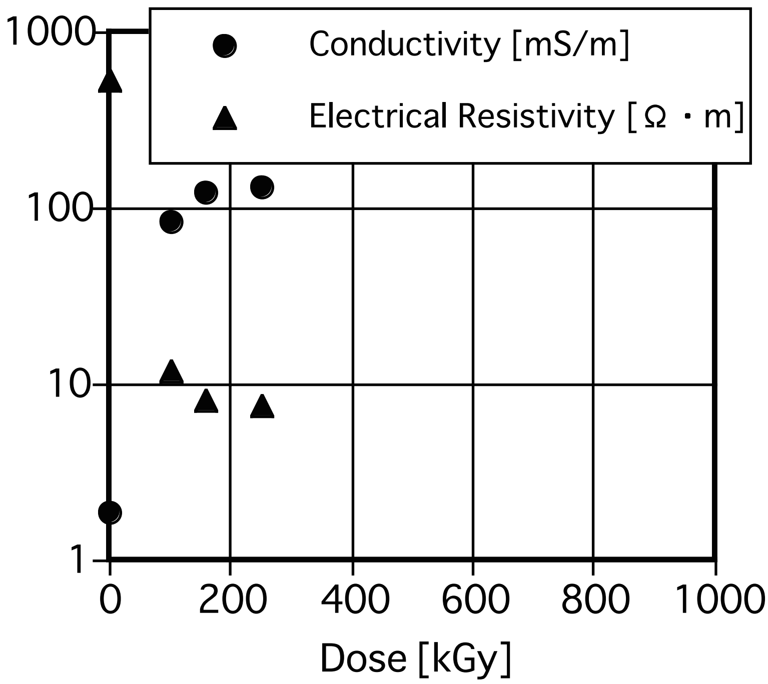


Figure 3.4-3　Conductivity and electrical resistivity of the water after irradiation

3.5 Nafion NE1135 [18)]

Material	Nafion NE1135 (Du Pont de Nemours & Co. Inc)
Thickness	0.083 mm (as swelling in water)
Irradiation condition	^{60}Co γ-rays: 10kGy/h Room Temperature Swelling in Oxygen-Satureted Water Water: 35.0±0.1g
Measurement	Stress-Strain Measurement Dumb-bell Shape: ASTM D-1822L Cross Head Speed: 20.0 mm/min Chuck Span: 38.0 mm Amount of Dissolved Fluorine in the water Conductivity of the water Electrical Resistivity of the water

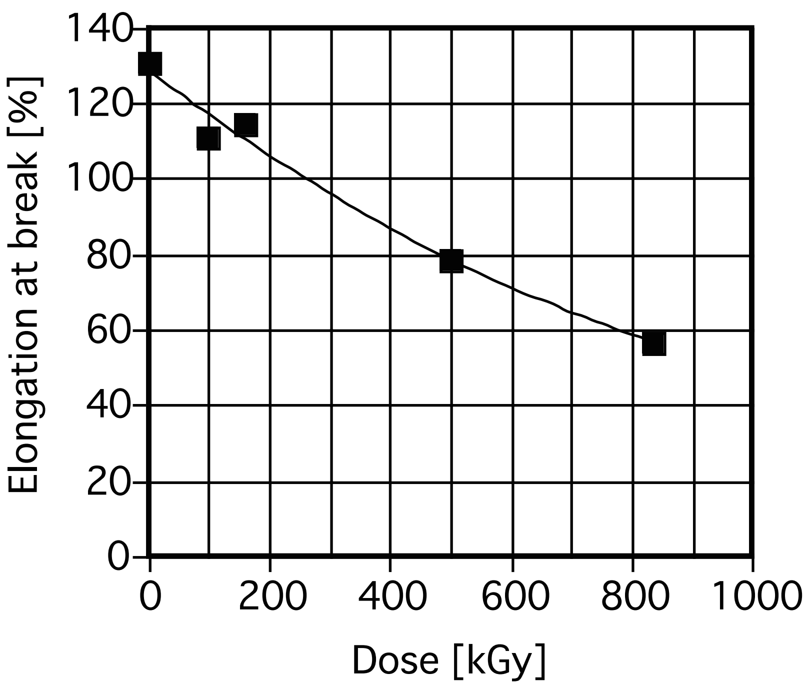


Figure 3.5-1 Elongation at break of γ-irradiated Nafion NE1135 at room temperature

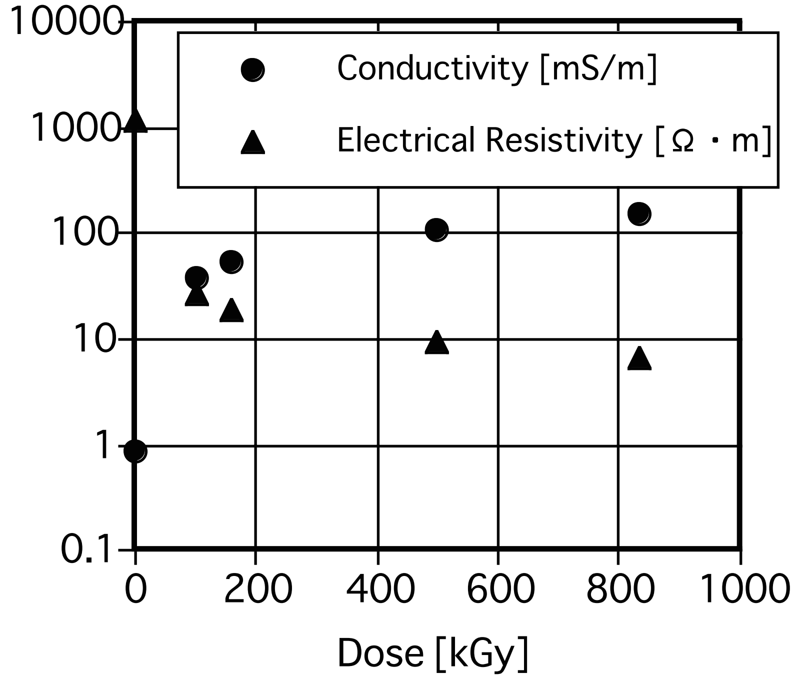


Figure 3.5-2 Conductivity and electrical resistivity of the water after irradiation

3.6 Polytetrafluoroethylene (PTFE)

Material	Polytetrafluoroethylene (PTFE) (SANPLATEC Corp.)
Thickness	0.205 mm
Irradiation condition	^{60}Co γ-rays: 10kGy/h Room Temperature □ : Vacuum-packed Electron beams: 10kGy/pass (250kGy/h) Room Temperature ○: Atmosphere △: Zero-oxygen atmosphere (with oxygen absorbent) ▽ : High vacuum lower than 10^{-3} torr
Measurement	Stress-Strain Measurement Dumb-bell Shape: ASTM D-1822L Cross Head Speed: 20.0 mm/min Chuck Span: 38.0 mm

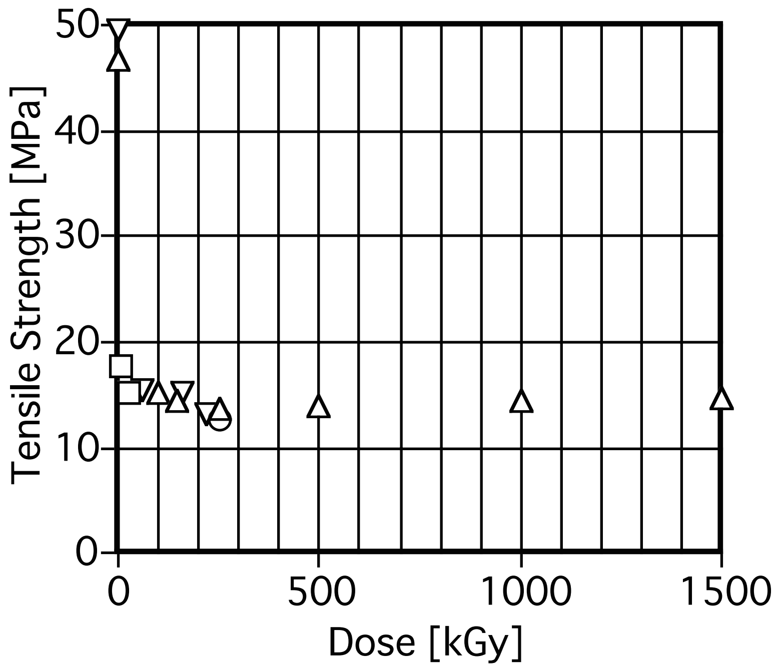


Figure 3.6-1 Tensile strength of γ-irradiated PTFE at room temperature

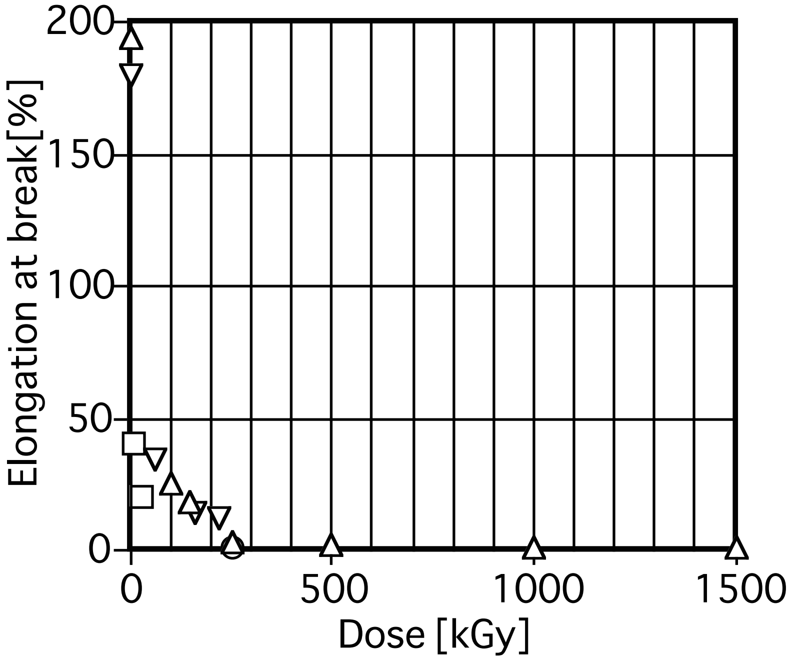


Figure 3.6-2 Elongation at break of γ-irradiated PTFE at room temperature

3.7 PFA 500LP [18)]

Material	PFA 500LP (Du Pont de Nemours & Co. Inc)
Thickness	0.127 mm
Irradiation condition	^{60}Co γ-rays: 10kGy/h Room Temperature ■ : Swelling in Oxygen-Satureted Water Water: 35.0±0.1g □ : Vacuum-packed △: Zero-oxygen atmosphere (with oxygen absorbent)
Measurement	Stress-Strain Measurement Dumb-bell Shape: ASTM D-1822L Cross Head Speed: 20.0 mm/min Chuck Span: 38.0 mm Amount of Dissolved Fluorine in the water Conductivity of the water Electrical Resistivity of the water

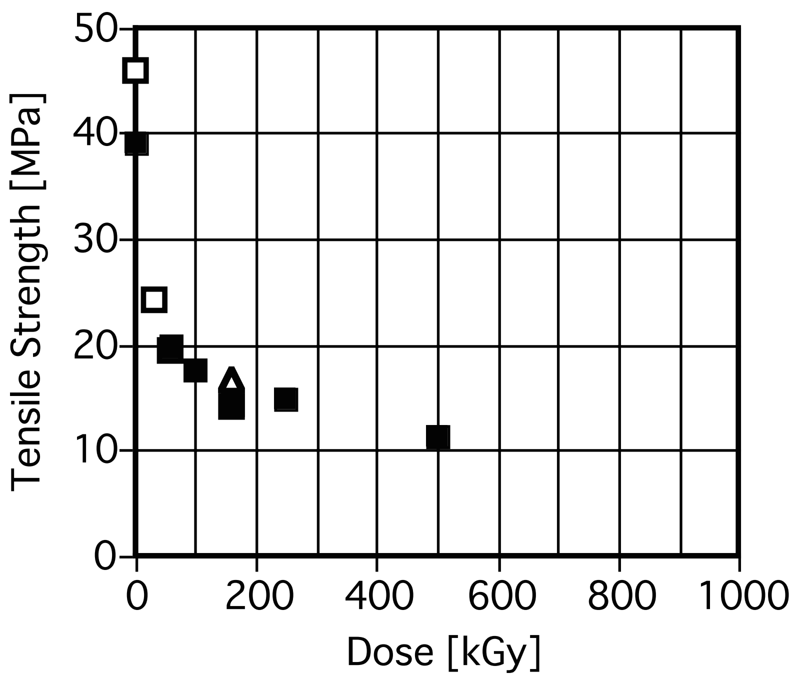


Figure 3.7-1 Tensile strength of γ-irradiated PFA 500LP at room temperature

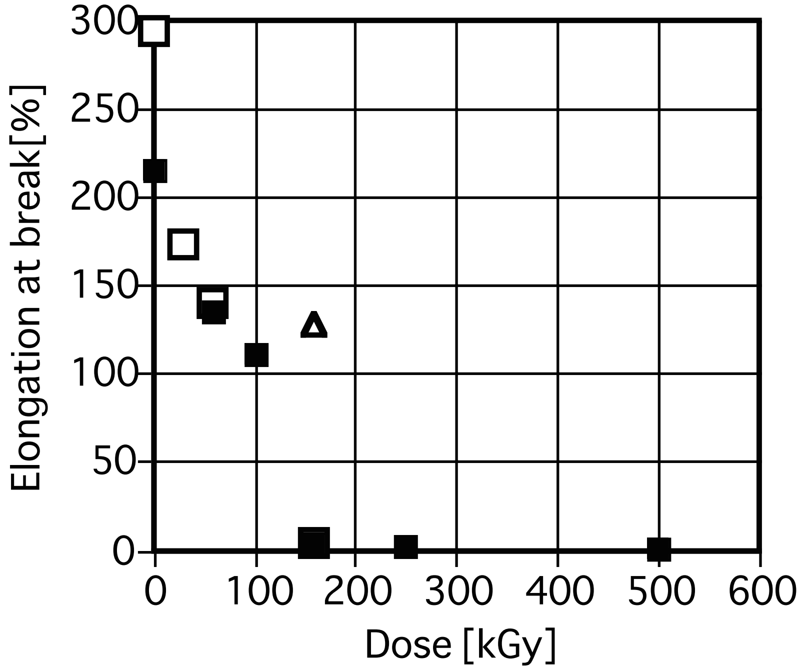


Figure 3.7-2　Elongation at break of γ-irradiated PFA 500LP at room temperature

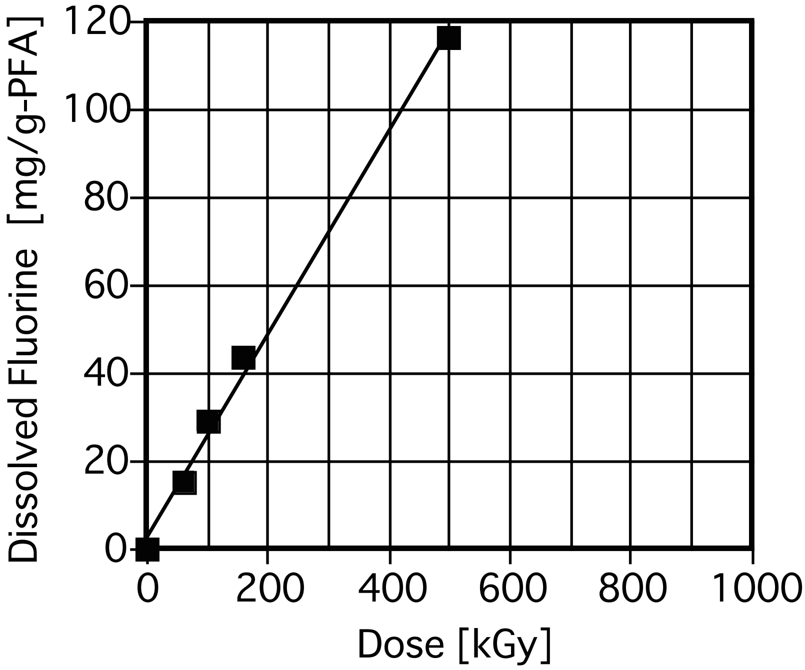


Figure 3.7-3　Quantity of dissolved fluorine *vs.* dose for PFA 500LP irradiated at room temperature

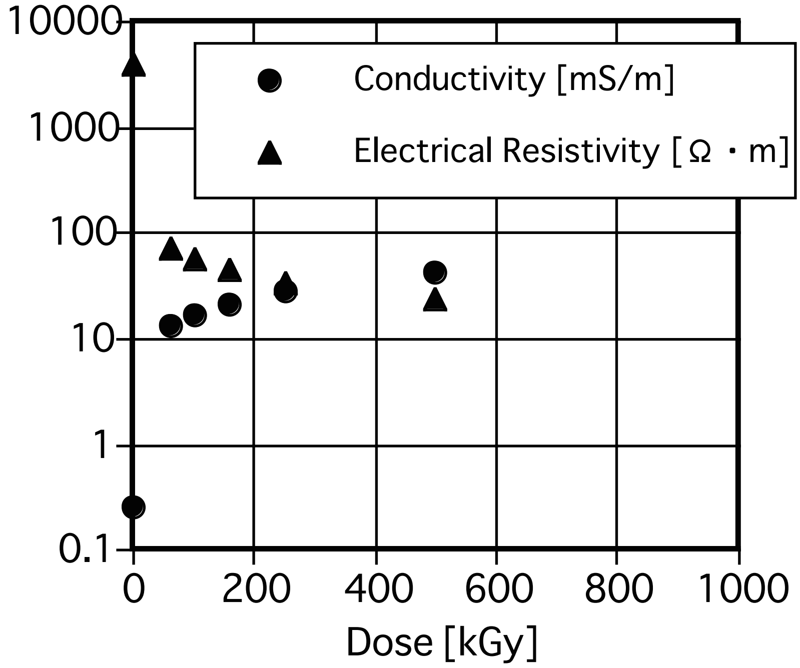


Figure 3.7-4　Conductivity and electrical resistivity of the water after irradiation

Material	PFA 500LP (Du Pont de Nemours & Co. Inc)
Thickness	0.127 mm
Irradiation condition	^{60}Co γ-rays: 10kGy/h Room Temperature Swelling in Oxygen-Satureted Water Water: 35.0±0.1g
Measurement	Differential scanning calorimetry (DSC) DSC-3200 (Mac Science) Sample: 10mg Temp. rate: 5K/min Purge gas: He, 50Ncc/min

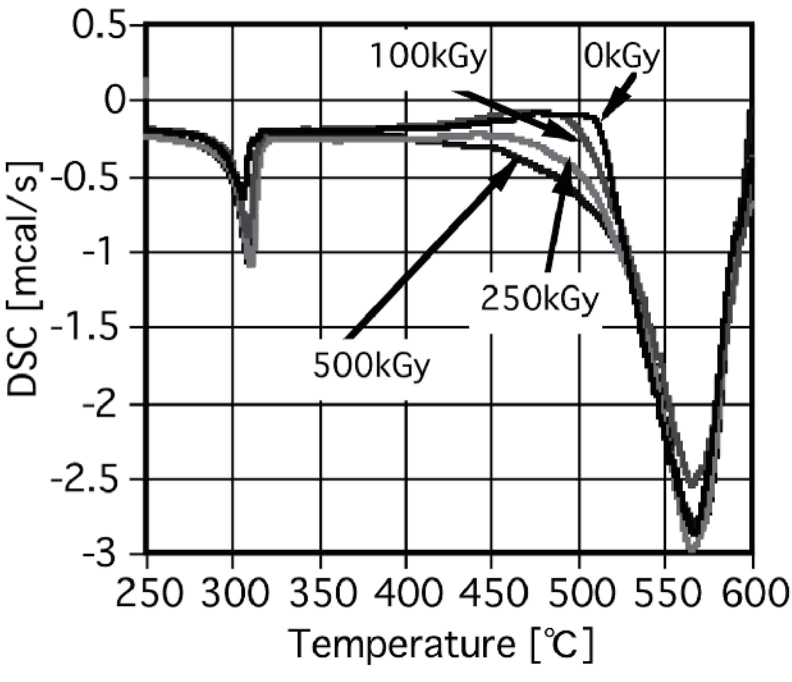


Figure 3.7-5 DSC curves of PFA 500LP under helium atmosphere

3.8 FEP 750A [18)]

Material	FEP 750A (Du Pont de Nemours & Co. Inc)
Thickness	0.190 mm
Irradiation condition	^{60}Co γ-rays: 10kGy/h Room Temperature Swelling in Oxygen-Satureted Water Water: 35.0±0.1g
Measurement	Stress-Strain Measurement Dumb-bell Shape: ASTM D-1822L Cross Head Speed: 20.0 mm/min Chuck Span: 38.0 mm Amount of Dissolved Fluorine in the water Conductivity of the water Electrical Resistivity of the water

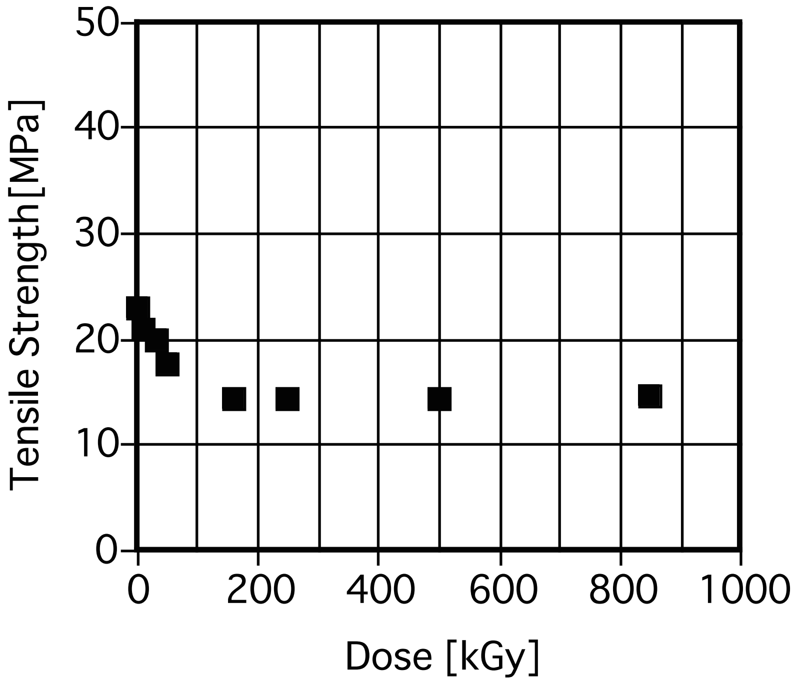


Figure 3.8-1 Tensile strength of γ-irradiated FEP 750A at room temperature

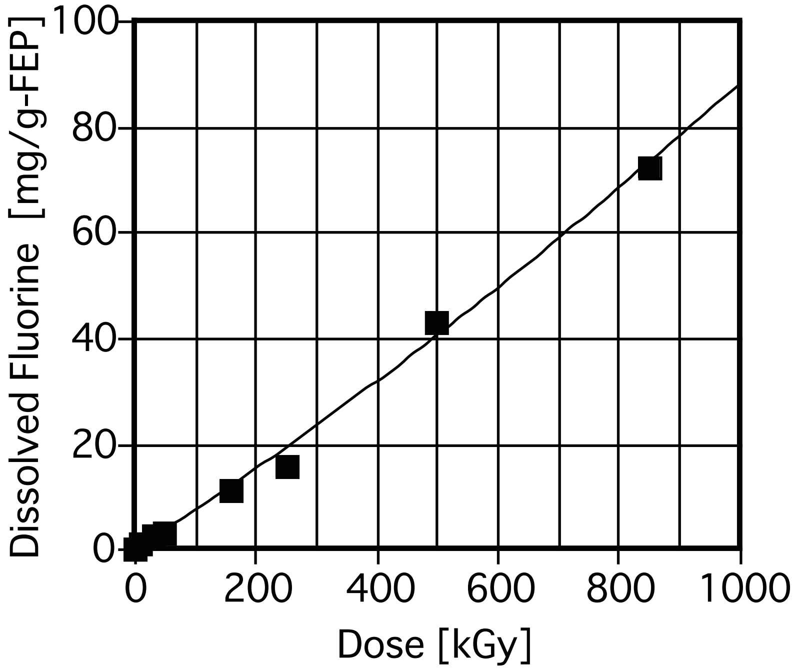


Figure 3.8-2 Quantity of dissolved fluorine *vs.* dose for FEP 750A irradiated at room temperature

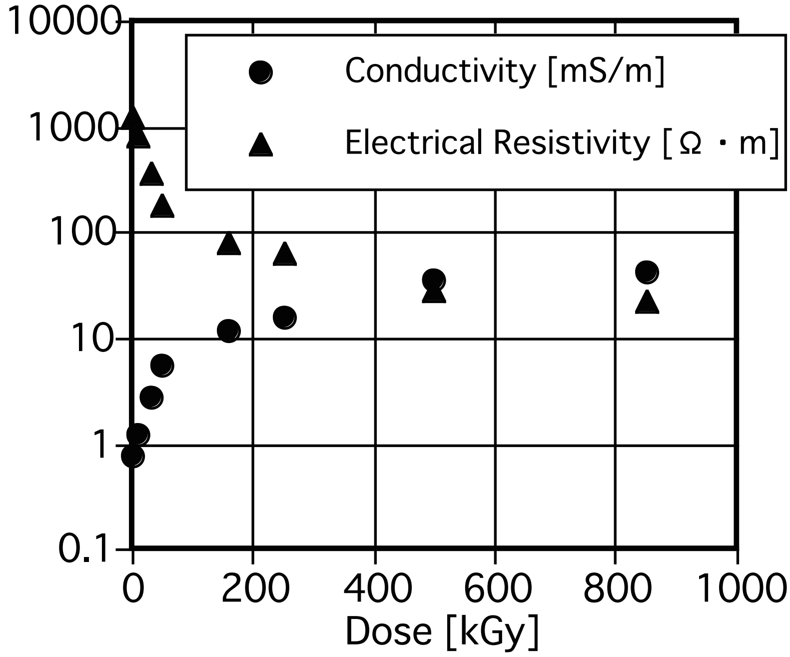


Figure 3.8-3 Conductivity and electrical resistivity of the water after irradiation

Material	FEP 750A (Du Pont de Nemours & Co. Inc)
Thickness	0.190 mm
Irradiation condition	^{60} Co γ-rays: 10kGy/h Room Temperature Swelling in Oxygen-Satureted Water Water: 35.0±0.1g
Measurement	Differential scanning calorimetry (DSC) DSC-3200 (Mac Science) Sample: 10mg Temp. rate: 5K/min Purge gas: He, 50Ncc/min

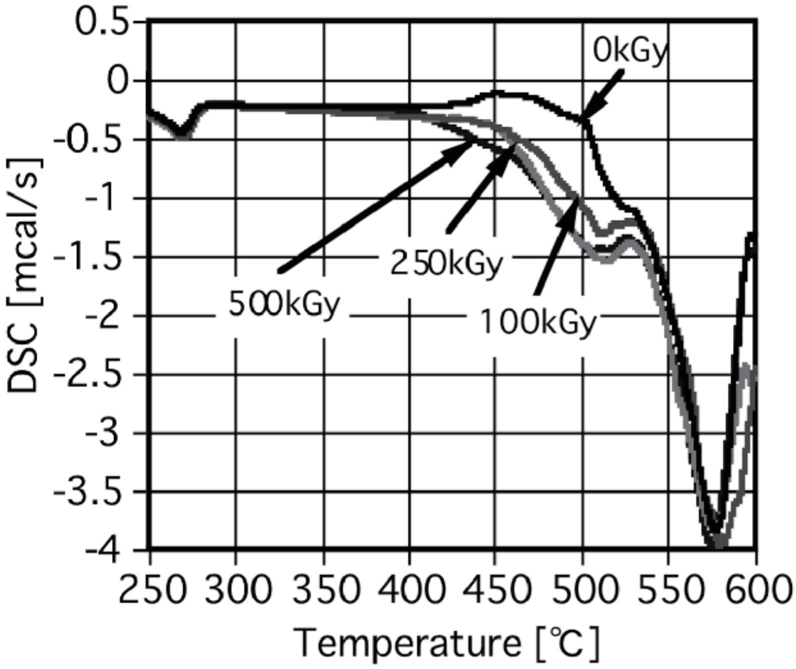


Figure 3.8-4 DSC curves of FEP 750A under helium atmosphere

3.9 Kapton 500H (Polyimide) [16)]

Material	Kapton 500H (Polyimide) (Du Pont de Nemours & Co. Inc)
Thickness	0.143 mm
Irradiation condition	^{60}Co γ-rays: 10kGy/h Room Temperature ■ : Swelling in Oxygen-Satureted Water Water: 35.0±0.1g ○ : Atmosphere 343K ◆ : Swelling in Oxygen-Satureted Water Water: 20.0±0.1g Electron beams: 10kGy/pass (250kGy/h) Room Temperature □ : Vacuum-packed ×: Atmosphere
Measurement	Stress-Strain Measurement Dumb-bell Shape: ASTM D-1822L Cross Head Speed: 20.0 mm/min Chuck Span: 38.0 mm Amount of Dissolved Fluorine in the water

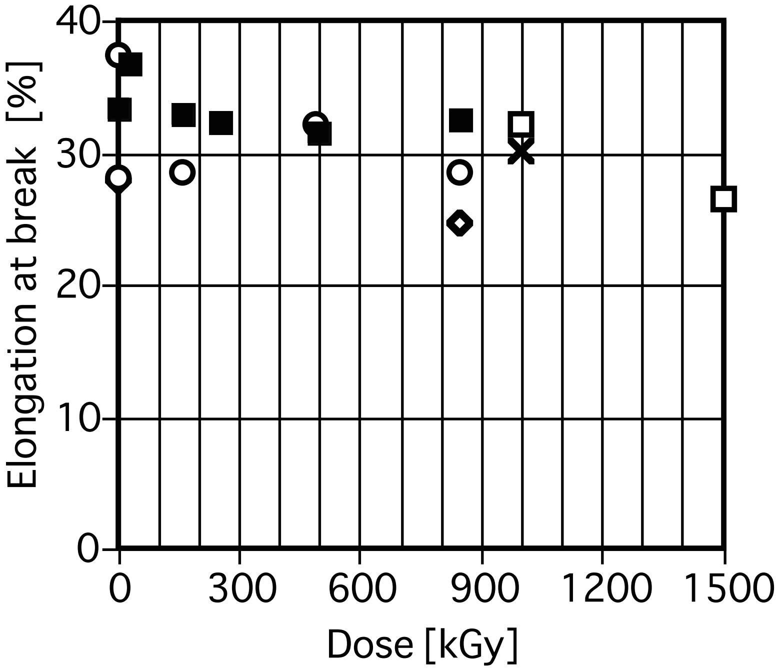


Figure 3.9-1 Elongation at break of Kapton 500H

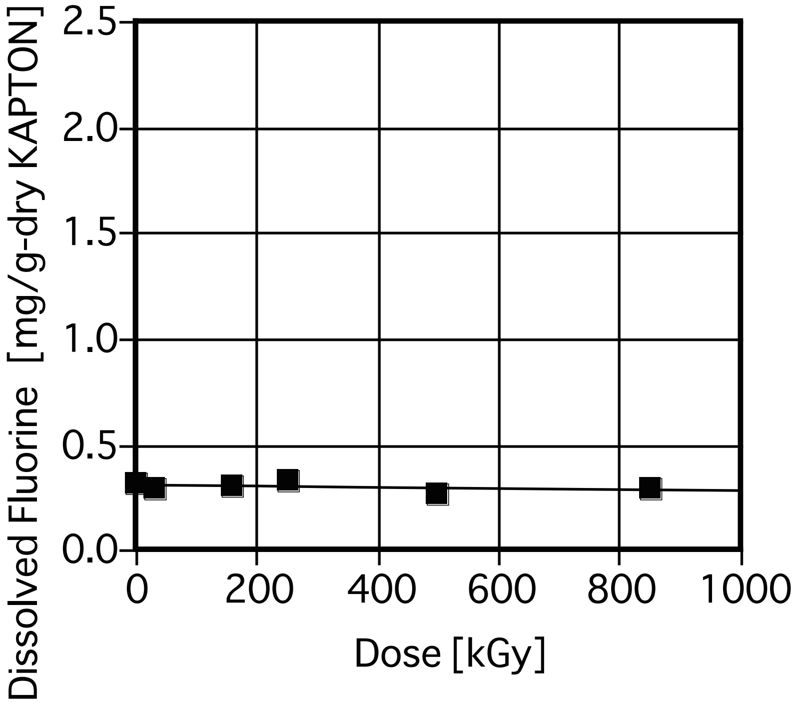


Figure 3.9-2 Quantity of dissolved fluorine *vs.* dose for Kapton 500H irradiated at room temperature

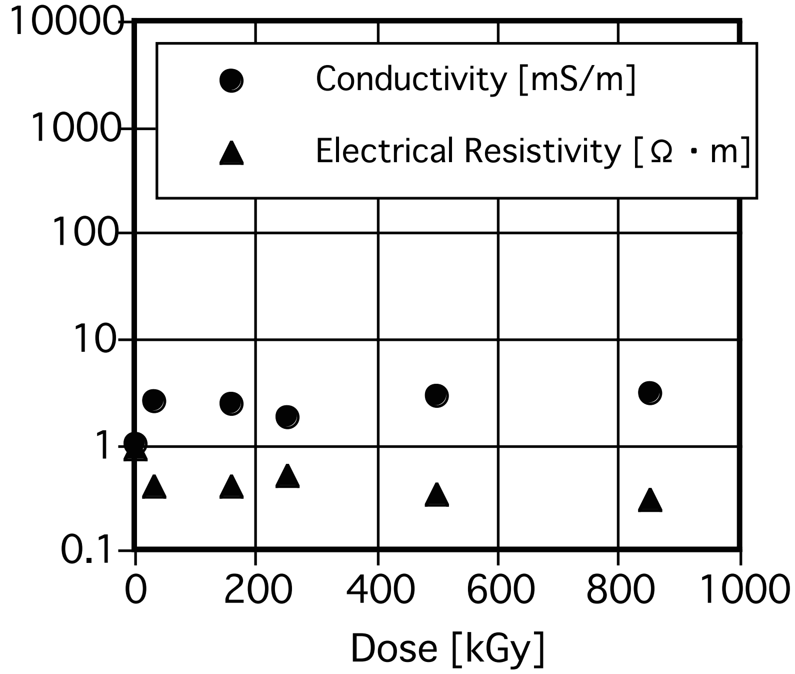


Figure 3.9-3 Conductivity and electrical resistivity of the water after irradiation

3.10 Polyvinyl Chloride HTGA5749

Material	Polyvinyl Chloride HTGA5749 (Achilles Corp.)
Thickness	0.924 mm
Irradiation condition	Electron beams: 10kGy/pass (250kGy/h) Room Temperature □ : Vacuum-packed ○: Atmosphere
Measurement	Stress-Strain Measurement Dumb-bell Shape: ASTM D-1822L Cross Head Speed: 20.0 mm/min Chuck Span: 38.0 mm

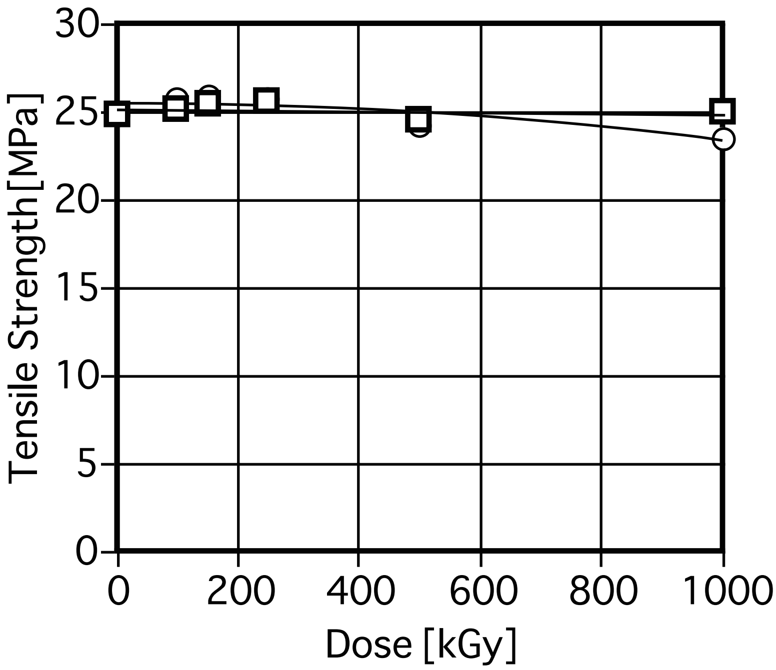


Figure 3.10-1 Tensile strength of EB-irradiated Polyvinyl Chloride HTGA5749 at room temperature

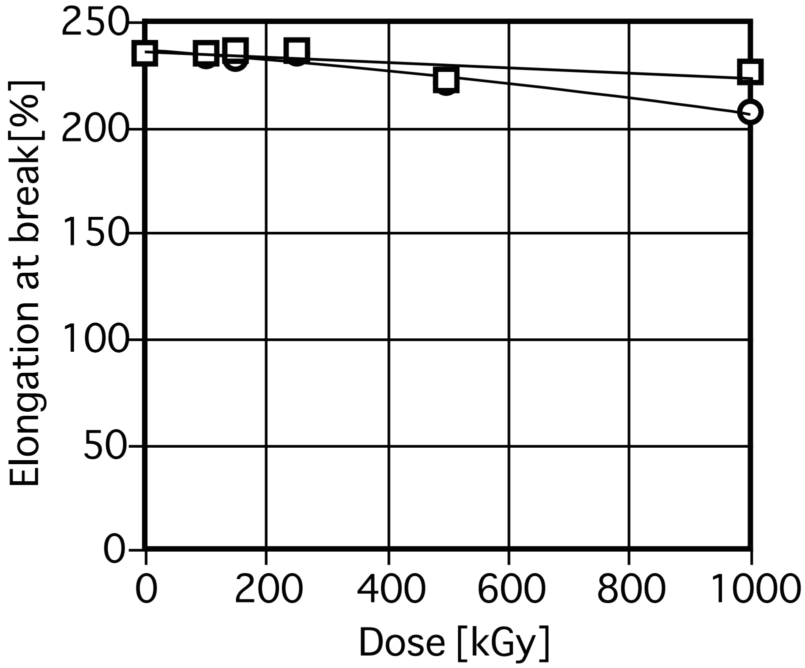


Figure 3.10-2　Elongation at break of EB-irradiated Polyvinyl Chloride HTGA5749 at room temperature

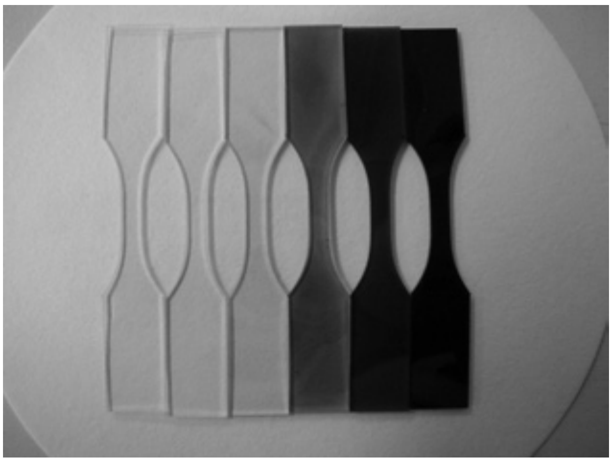


Figure 3.10-3　Coloring of EB-irradiated Polyvinyl Chloride HTGA5749 (0, 100, 160,250, 500, 1000 kGy, vacuum-packed)

3.11 VITON [16)-17)]

Material	VITON (Ebihara Rubber Corp.)
Thickness	0.975 mm
Irradiation condition	^{60} Co γ-rays: 10kGy/h Room Temperature ■ : Swelling in Oxygen-Satureted Water Water: 45.0±0.1g ○ : Atmosphere ● : Swelling in about 30% H2O2 solution Solution: 35.0±0.1g 343K ◆ : Swelling in Oxygen-Satureted Water Water: 20.0±0.1g Electron beams: 10kGy/pass (250kGy/h) Room Temperature □ : Vacuum-packed ×: Atmosphere
Measurement	Stress-Strain Measurement Dumb-bell Shape: ASTM D-1822L Cross Head Speed: 20.0 mm/min Chuck Span: 38.0 mm Amount of Dissolved Fluorine in the water

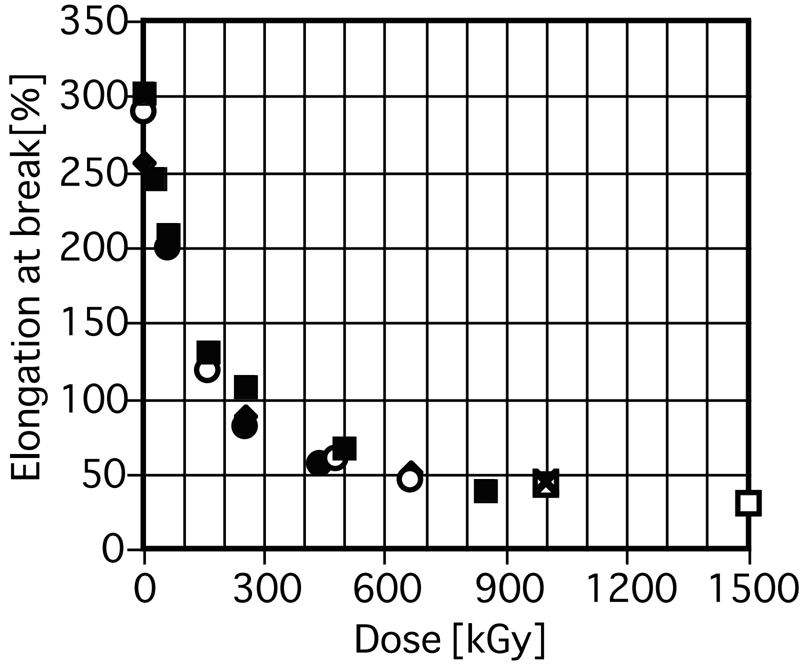


Figure 3.11-1　Elongation at break of VITON

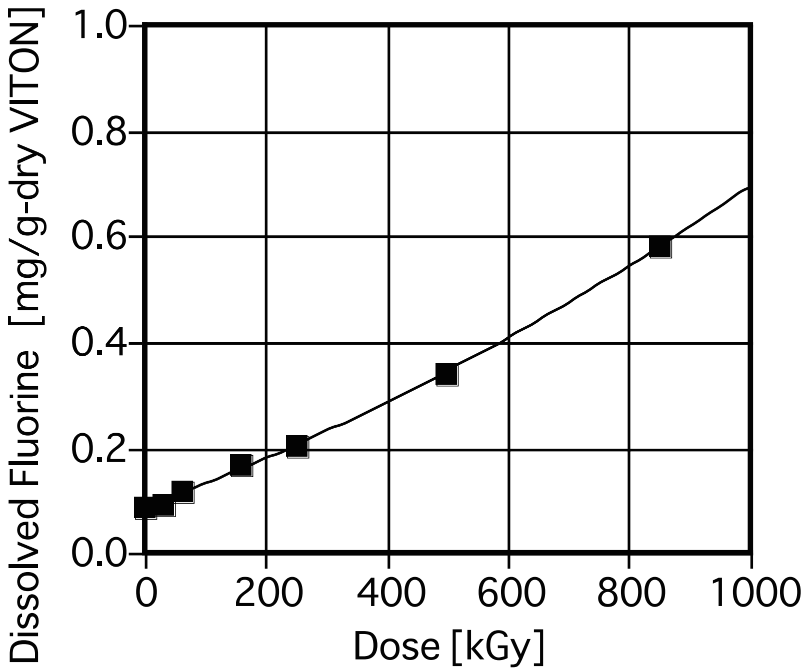


Figure 3.11-2　Quantity of dissolved fluorine *vs.* dose for VITON irradiated at room temperature

Material	VITON (Ebihara Rubber Corp.)
Thickness	0.975 mm
Irradiation condition	^{60} Co γ-rays: 10kGy/h Room Temperature Swelling in Oxygen-Satureted Water Water: 35.0±0.1g
Measurement	Differential scanning calorimetry (DSC) DSC-3200 (Mac Science) Sample: 10mg Temp. rate: 5K/min Purge gas: He, 50Ncc/min

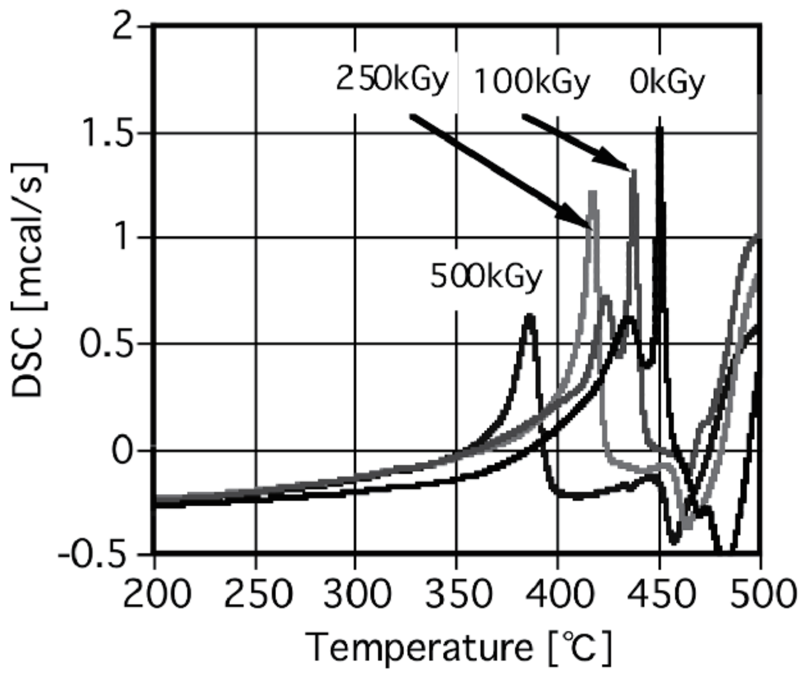


Figure 3.11-3 DSC curves of VITON under helium atmosphere

3.12 AFLAS SF [16) 17) 19)]

Material	AFLAS SF (IF900-AF) (JSR Corp.)
Thickness	1.155 mm
Irradiation condition	^{60}Co γ-rays: 10kGy/h Room Temperature ■ : Swelling in Oxygen-Satureted Water Water: 45.0±0.1g ○ : Atmosphere □ : Vacuum-packed ▲ : Swelling in 10wt% Na_2SO_3 solution Solution: 35.0±0.1g Electron beams: 10kGy/pass (250kGy/h) Room Temperature ＋ : Vacuum-packed ×: Atmosphere
Measurement	Stress-Strain Measurement Dumb-bell Shape: ASTM D-1822L Cross Head Speed: 20.0 mm/min Chuck Span: 38.0 mm Amount of Dissolved Fluorine in the water

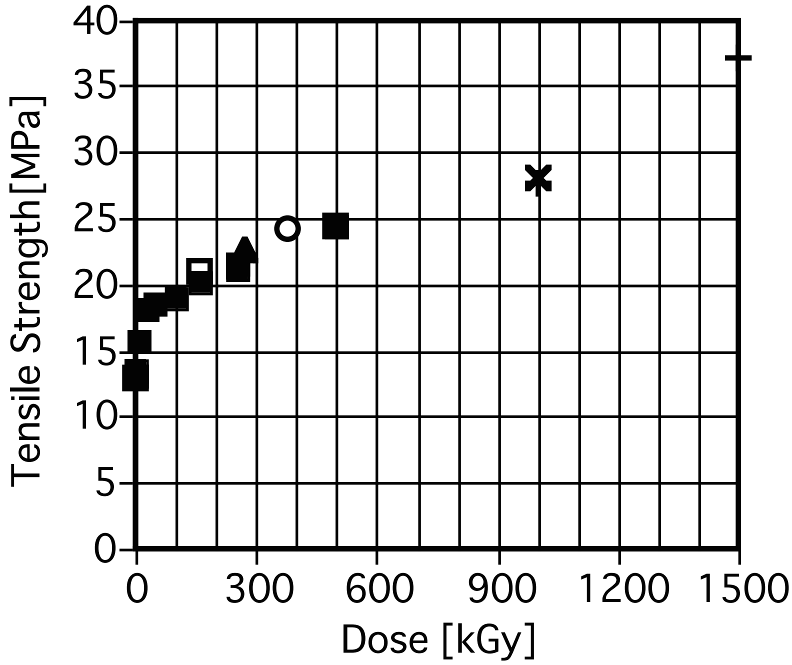


Figure 3.12-1 Tensile strength of AFLAS SF at room temperature

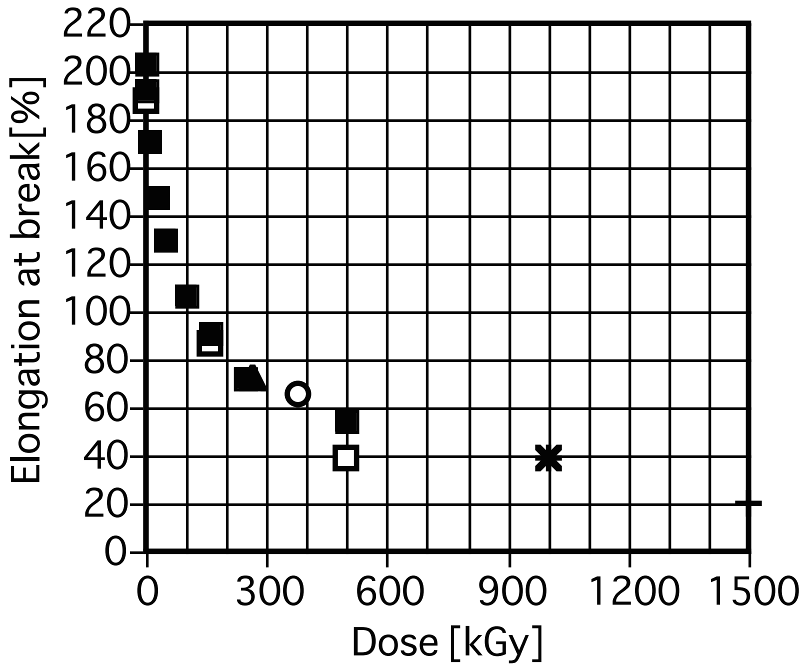


Figure 3.12-2 Elongation at break of AFLAS SF at room temperature

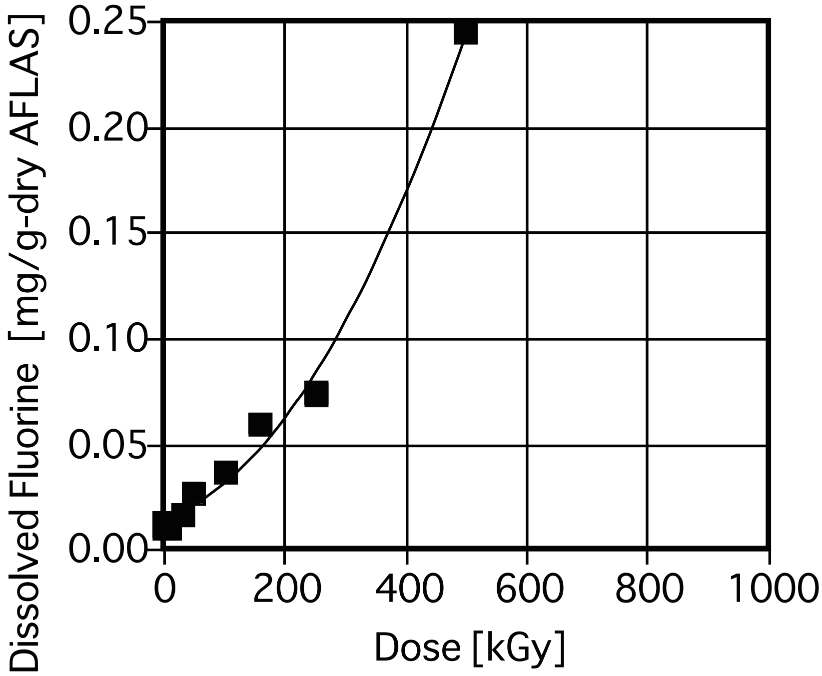


Figure 3.12-3 Quantity of dissolved fluorine *vs.* dose for AFLAS SF irradiated at room temperature

Material	AFLAS SF (IF900-AF) (JSR Corp.)
Thickness	1.155 mm
Irradiation condition	^{60} Co γ-rays: 10kGy/h Room Temperature ■ : Swelling in Oxygen-Satureted Water Water: 35.0±0.1g □ : Vacuum-packed
Measurement	Differential scanning calorimetry (DSC) DSC-3200 (Mac Science) Sample: 10mg Temp. rate: 5K/min Purge gas: He, 50Ncc/min

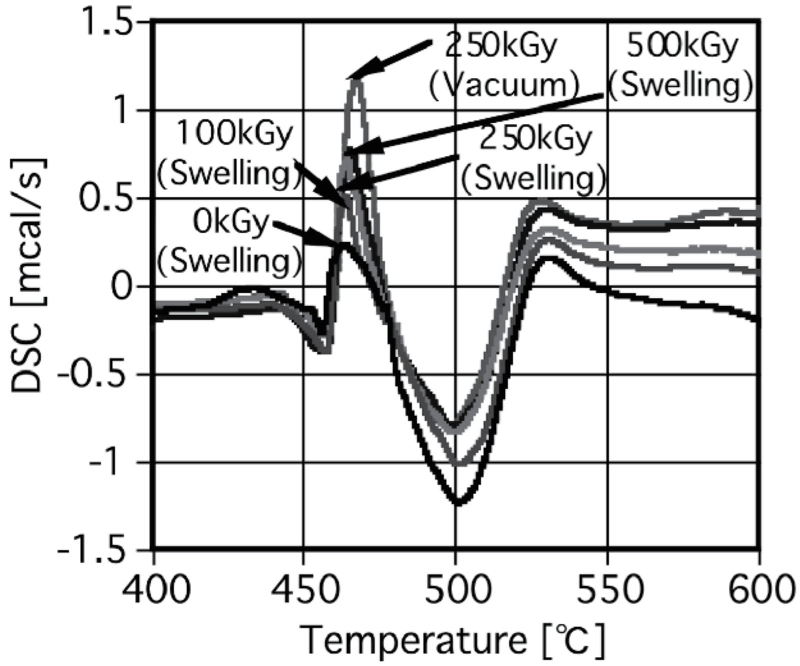


Figure 3.12-4 DSC curves of AFLAS SF under helium atmosphere

3.13 Neoprene [16)-17)]

Material	Neoprene (Ebihara Rubber Corp.)
Thickness	0.996 mm
Irradiation condition	^{60}Co γ-rays: 10kGy/h Room Temperature ■ : Swelling in Oxygen-Satureted Water Water: 45.0±0.1g ○ : Atmosphere ▲ : Swelling in 10wt% Na_2SO_3 solution Solution: 35.0±0.1g Electron beams: 10kGy/pass (250kGy/h) Room Temperature ＋ : Vacuum-packed ×: Atmosphere
Measurement	Stress-Strain Measurement Dumb-bell Shape: ASTM D-1822L Cross Head Speed: 20.0 mm/min Chuck Span: 38.0 mm

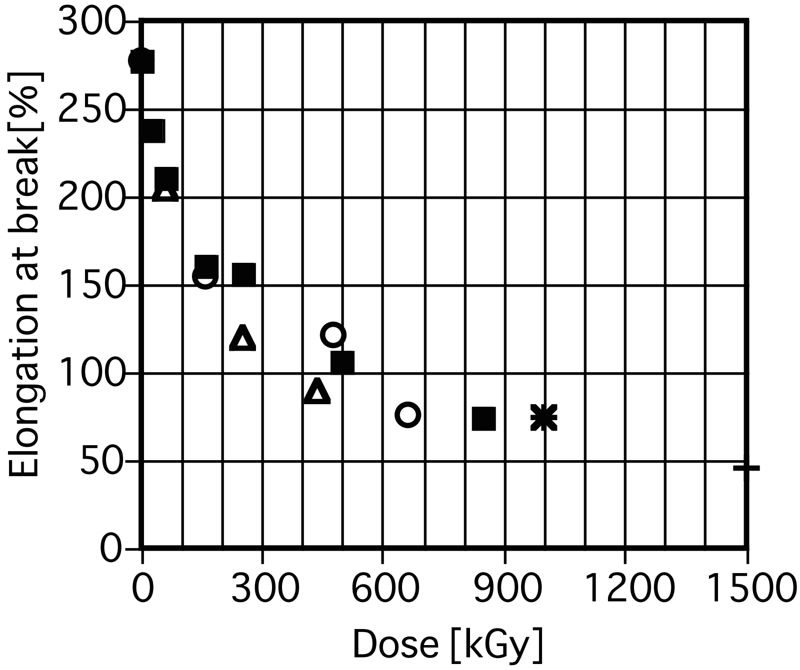


Figure 3.13-1 Elongation at break of Neoprene at room temperature

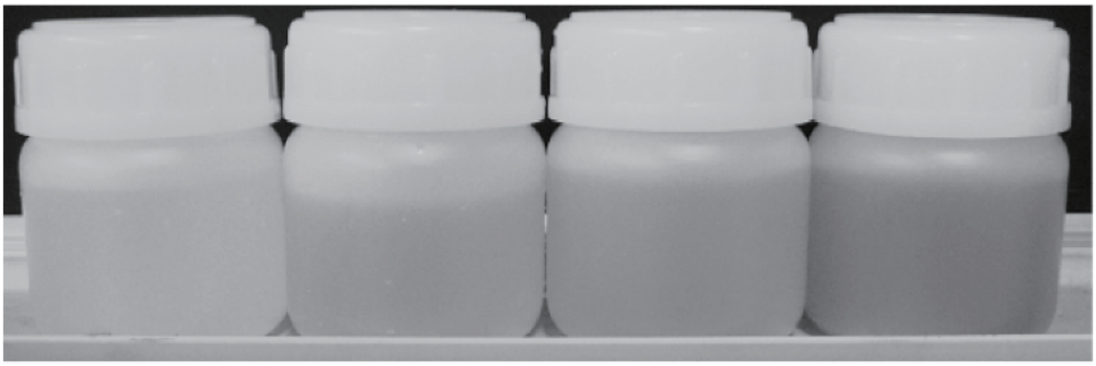


Figure 3.13-2 Coloring of the water after the irradiation of Neoprene with γ - rays
(0, 160, 500, 850 kGy)

Material	Neoprene (Ebihara Rubber Corp.)
Thickness	0.996 mm
Irradiation condition	^{60} Co γ-rays: 10kGy/h Room Temperature Swelling in Oxygen-Satureted Water Water: 35.0±0.1g
Measurement	Differential scanning calorimetry (DSC) DSC-3200 (Mac Science) Sample: 10mg Temp. rate: 5K/min Purge gas: He, 50Ncc/min

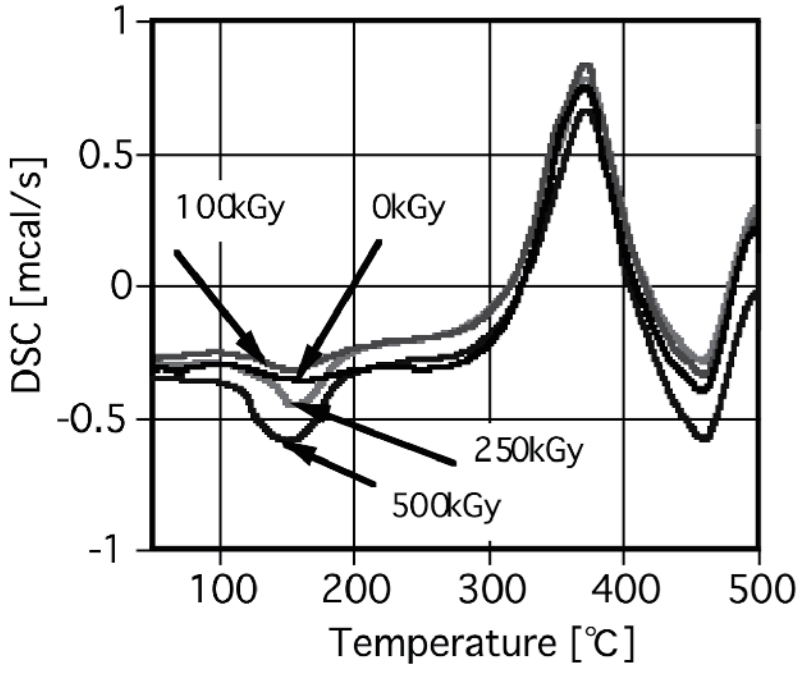


Figure 3.13-3　DSC curves of Neoprene under helium atmosphere

3.14 EPDM [16)]

Material	EPDM (Ebihara Rubber Corp.)
Thickness	0.850 mm
Irradiation condition	Electron beams: 10kGy/pass (250kGy/h) Room Temperature □ : Vacuum-packed
Measurement	Stress-Strain Measurement Dumb-bell Shape: ASTM D-1822L Cross Head Speed: 20.0 mm/min Chuck Span: 38.0 mm

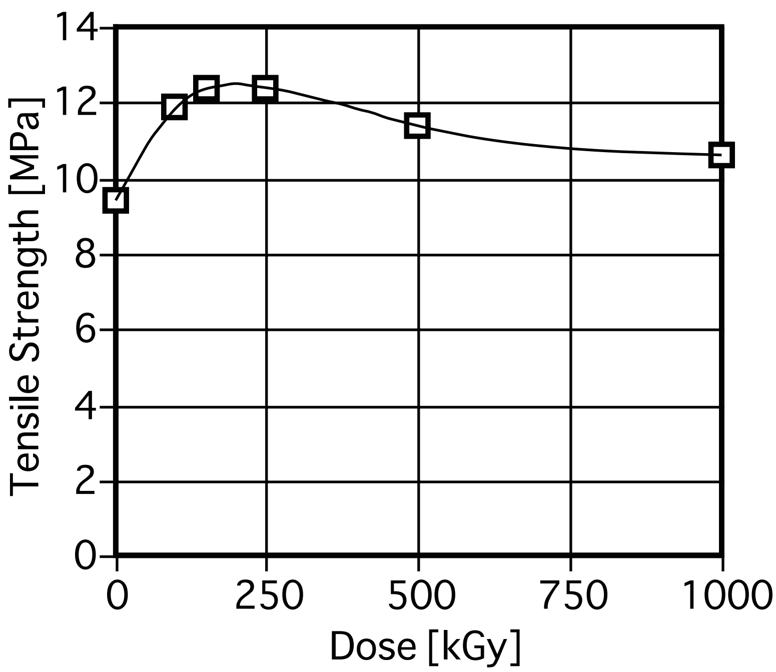


Figure 3.14-1 Tensile strength of EB-irradiated EPDM at room temperature

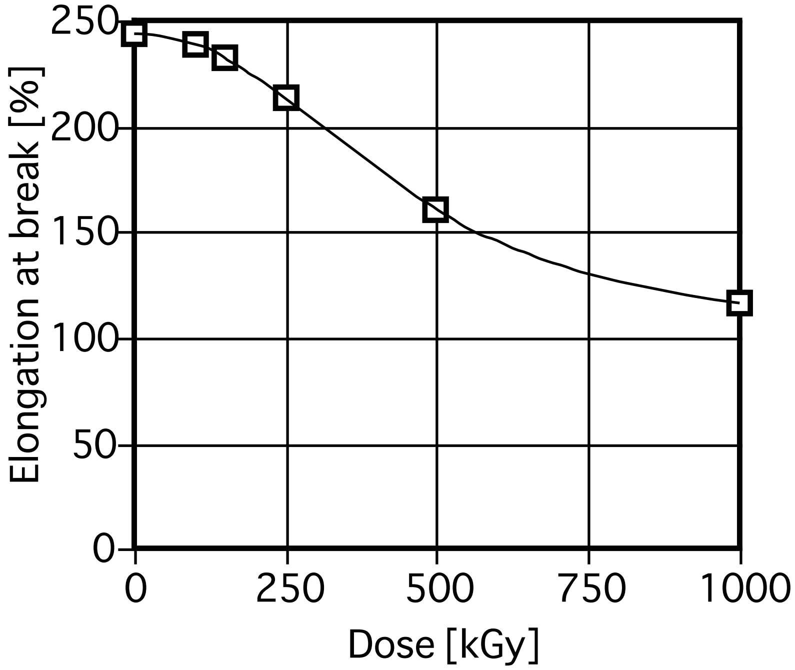


Figure 3.14-2 Elongation at break of EB-irradiated EPDM at room temperature

3.15 Kalrez

Material	Kalrez JIS P021, Compound: 4079 (Du Pont Performance Elastomers)
Nom	20.80mmφ X 2.40mm
Irradiation condition	^{60}Co γ-rays: 10kGy/h Room Temperature Swelling in Oxygen-Satureted Water Water: 35.0±0.1g
Measurement	Stress-Strain Measurement Dumb-bell Shape: (O-ring) Cross Head Speed: 20.0 mm/min Chuck Span: 38.0 mm Amount of Dissolved Fluorine in the water Conductivity of the water Electrical Resistivity of the water

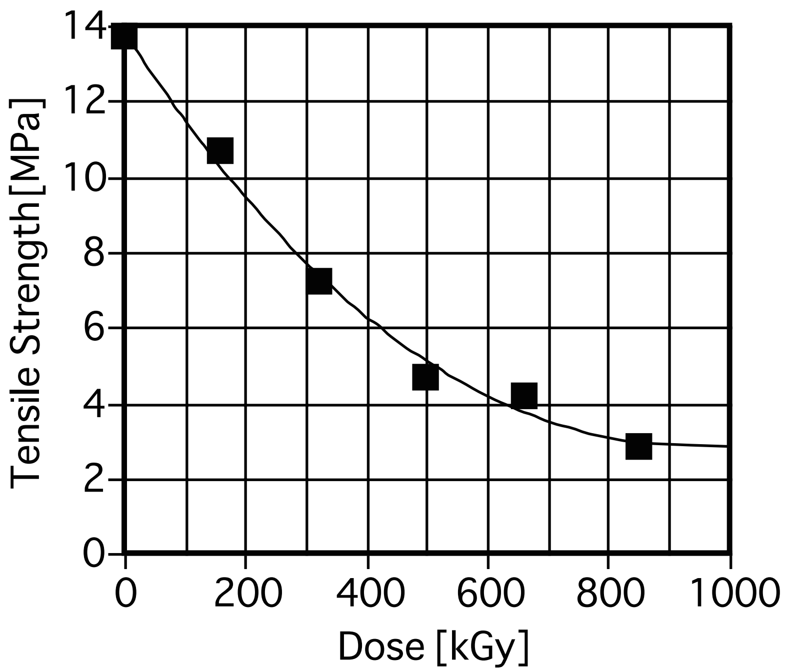


Figure 3.15-1 Tensile strength of γ-irradiated Kalrez at room temperature

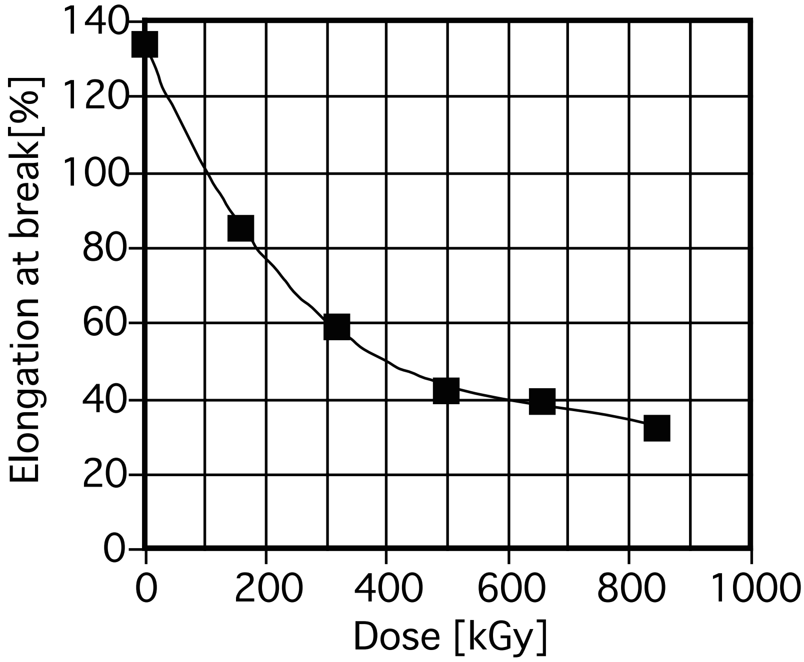


Figure 3.15-2 Elongation at break of γ-irradiated Kalrez at room temperature

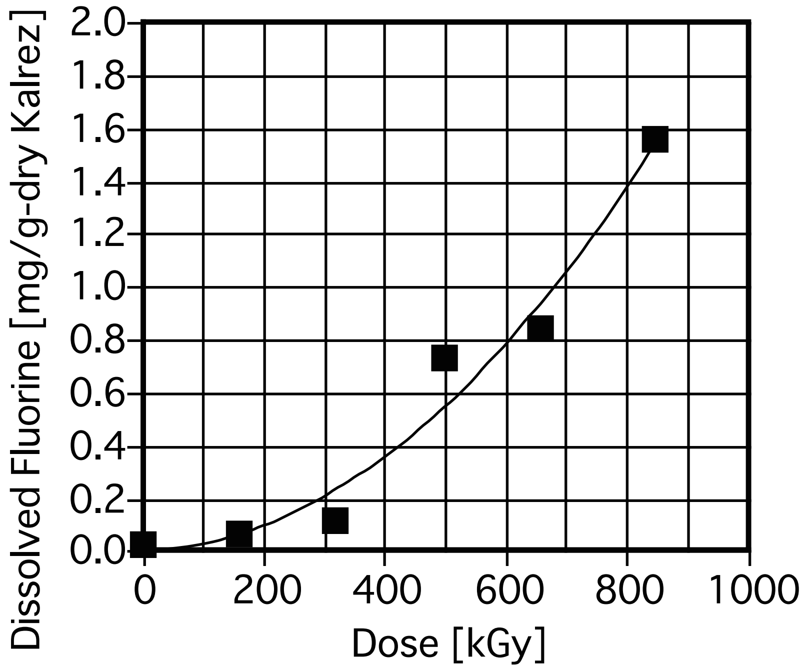


Figure 3.15-3 Quantity of dissolved fluorine *vs.* dose for Kalrez irradiated at room temperature

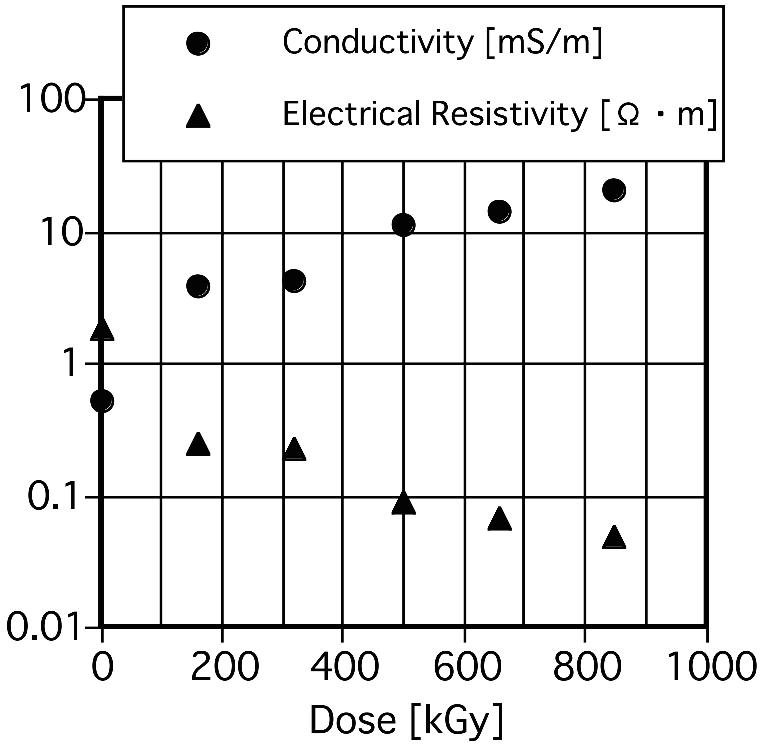


Figure 3.15-4 Conductivity and electrical resistivity of the water after irradiation

Material	Kalrez JIS P021, Compound: 4079 (Du Pont Performance Elastomers)
Nom	20.80mmϕ X 2.40mm
Irradiation condition	^{60} Co γ-rays: 10kGy/h Room Temperature Swelling in Oxygen-Satureted Water Water: 35.0±0.1g
Measurement	Thermogravimetric analysis (TGA) TG-DTA-2000S (Mac Science) Sample: 5mg Temp. rate: 10K/min Purge gas: He, 50Ncc/min

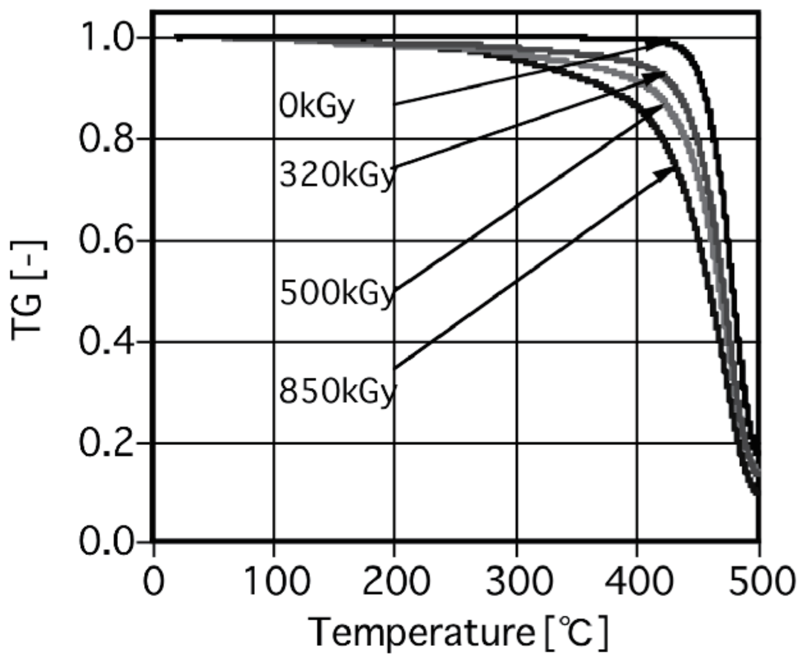


Figure 3.15-5 Weight loss curve *vs.* temperature of Kalrez under helium atmosphere

Material	Kalrez JIS P021, Compound: 4079 (Du Pont Performance Elastomers)
Nom	20.80mmϕ X 2.40mm
Irradiation condition	^{60} Co γ-rays: 10kGy/h Room Temperature Swelling in Oxygen-Satureted Water Water: 35.0±0.1g
Measurement	Differential scanning calorimetry (DSC) DSC-3200 (Mac Science) Sample: 10mg Temp. rate: 5K/min Purge gas: 0Ncc/min

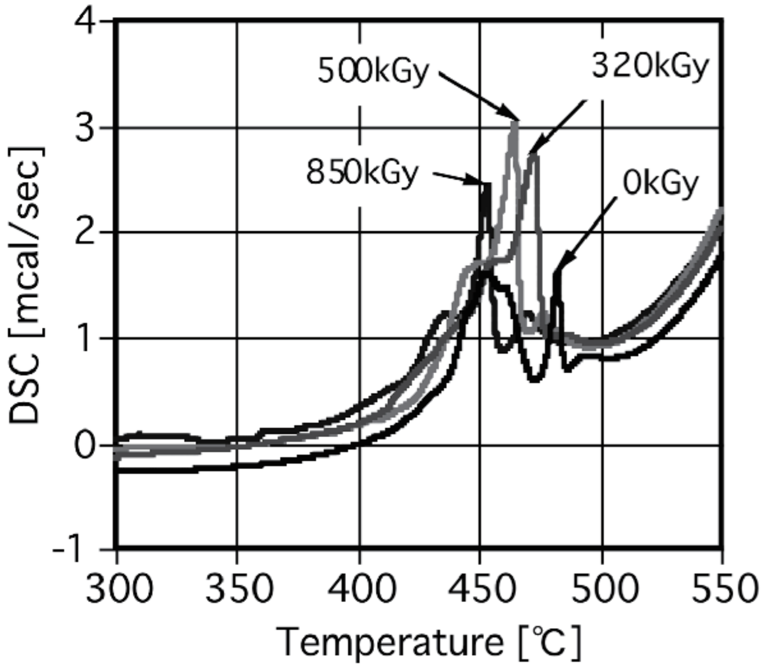


Figure 3.15-6 DSC curves of Kalrez

3.16 Butyl Rubber

Material	Butyl Rubber (Ebihara Rubber Corp.)
Thickness	1.001 mm
Irradiation condition	Electron beams: 10kGy/pass (250kGy/h) Room Temperature □ : Vacuum-packed
Measurement	Stress-Strain Measurement Dumb-bell Shape: ASTM D-1822L Cross Head Speed: 20.0 mm/min Chuck Span: 38.0 mm

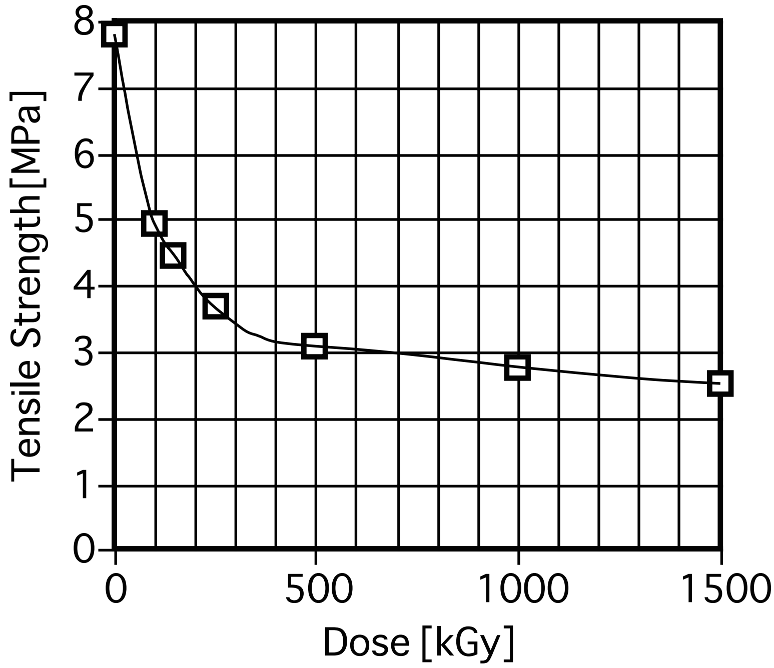


Figure 3.16-1 Tensile strength of EB-irradiated Butyl Rubber at room temperature

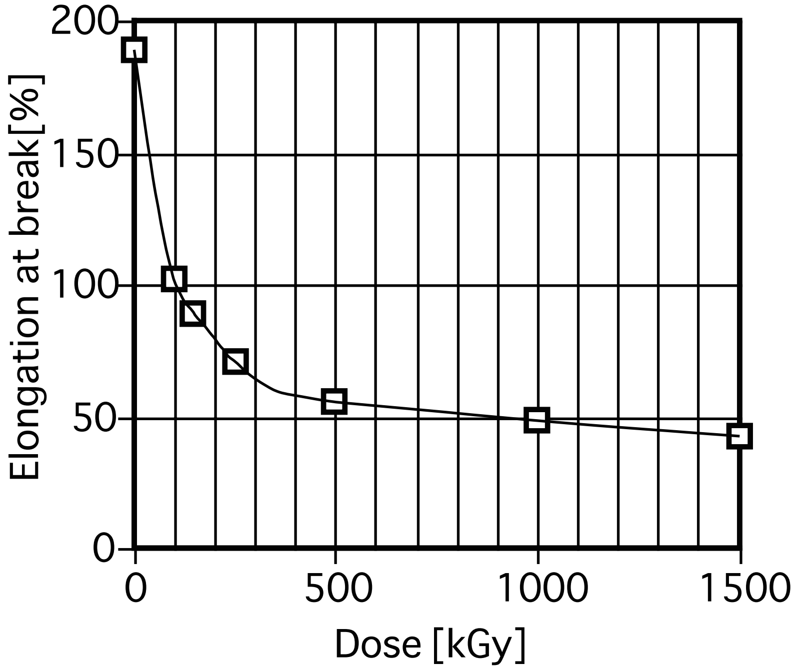


Figure 3.16-2 Elongation at break of EB-irradiated Butyl Rubber at room temperature

3.17 Denaturated Polyphenylene Ether

Material	Denaturated Polyphenylene Ether (Tsutui Plastic Corp.)
Thickness	0.491 mm
Irradiation condition	^{60}Co γ-rays: 10kGy/h Room Temperature ■ : Swelling in Oxygen-Satureted Water Water: 35.0±0.1g ○ : Atmosphere ▲ : Swelling in 10wt% Na_2SO_3 solution Solution: 35.0±0.1g Electron beams: 10kGy/pass (250kGy/h) Room Temperature + : Vacuum-packed ×: Atmosphere
Measurement	Stress-Strain Measurement Dumb-bell Shape: ASTM D-1822L Cross Head Speed: 20.0 mm/min Chuck Span: 38.0 mm

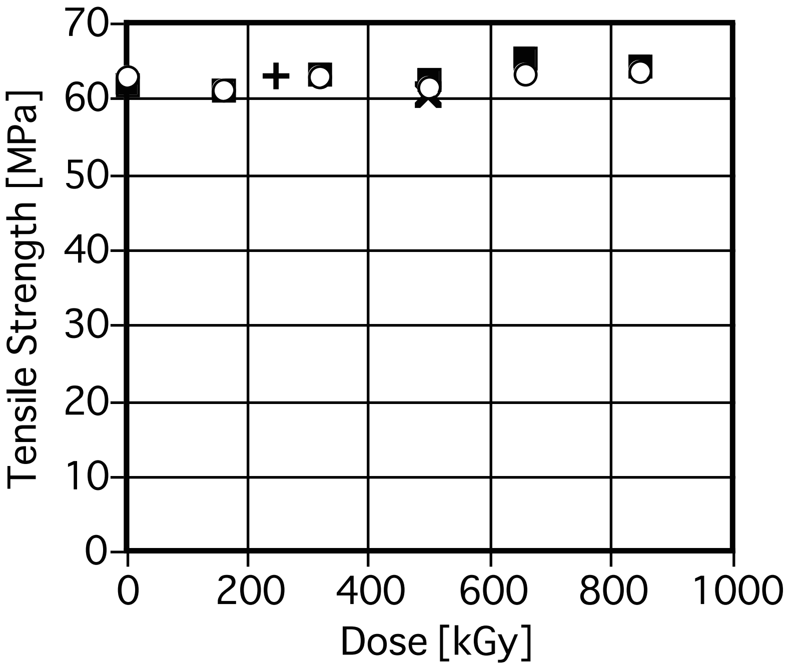


Figure 3.17-1 Tensile strength of Denaturated Polyphenylene Ether at room temperature

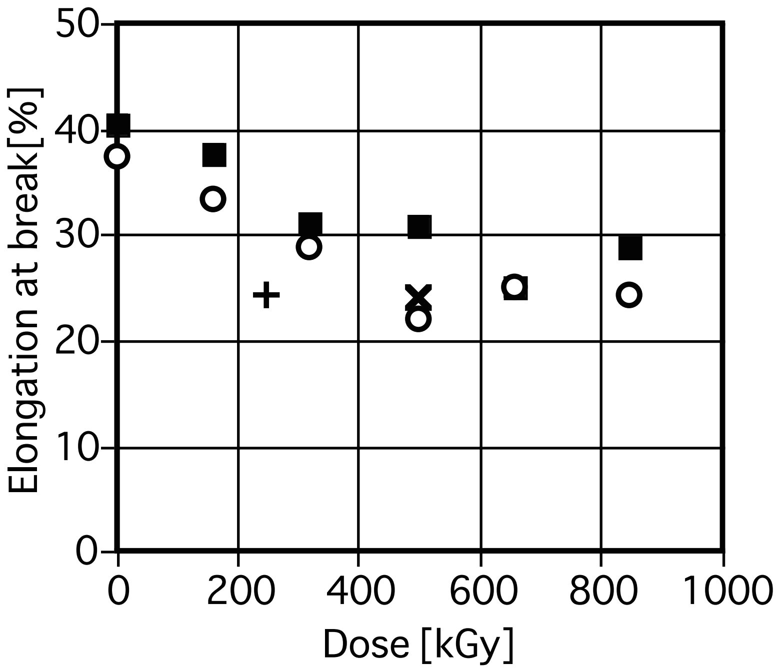


Figure 3.17-2 Elongation at break of Denaturated Polyphenylene Ether at room temperature

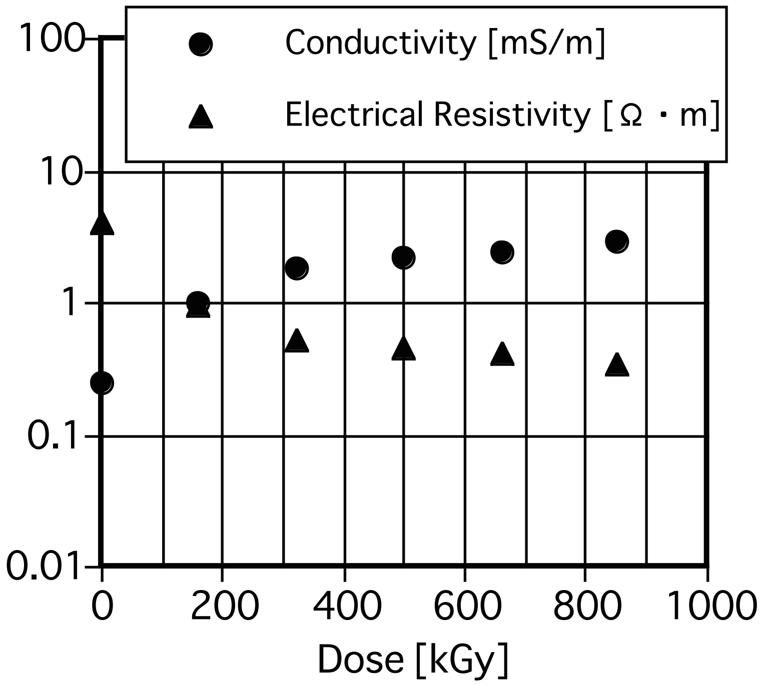


Figure 3.17-3 Conductivity and electrical resistivity of the water after irradiation

4. Conclusion

Solid-polymer-electrolyte (SPE) water electrolysis is attractive in the electrolytic process of the tritiated water in the Water Detritiation System (WDS) of a fusion reactor, whereas polymer durability in the electrolyzer under radiation is an important point. The radiation durability of the polymers was investigated from various viewpoints. The conclusions are summarized as follows.

1. A series of γ-ray irradiation tests of the Nafion® N117 ion exchange membrane beyond the ITER-WDS requirement (530kGy) indicated that the Nafion® N117 membrane had sufficient radiation durability up to 1600 kGy with regard to mechanical strength and ion exchange capacity.
2. To maintain the electrolysis function of the SPE cell up to 530 kGy, we suggest replacing the Teflon insulator with a polyimide insulator. Any serious degradation in the tensile strength of the Kapton polyimide up to 1500 kGy was not observed in a γ-ray irradiation test series.
3. Regarding the selection of rubber material for the O-ring seal, we observed that the VITON rubber swelling in the water maintained a constant tensile strength value up to 1500 kGy. Moreover, organic elution was not observed from VITON soaking. With regard to stable strength and negligible organic elution, VITON rubber is suitable for the O-ring seal.

The test for verifying the tolerability of the polymers to tritium exposure is planned using tritiated water. The test should determine whether there are any different damaging effects promoted by the decay of isotopically exchanged tritium within materials.

Acknowledgment

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国際単位系（SI）

表１．SI 基本単位

基本量	SI 基本単位	
	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd

表２．基本単位を用いて表されるSI組立単位の例

組立量	SI 基本単位	
	名称	記号
面積	平方メートル	m^{2}
体積	立法メートル	m^{3}
速さ，速度	メートル毎秒	m/s
加速度	メートル毎秒毎秒	m/s^{2}
波数	毎メートル	m^{-1}
密度，質量密度	キログラム毎立方メートル	kg/m^{3}
面積密度	キログラム毎平方メートル	kg/m^{2}
比体積	立方メートル毎キログラム	m^{3}/kg
電流密度	アンペア毎平方メートル	A/m^{2}
磁界の強さ	アンペア毎メートル	A/m
量濃度[(a)]，濃度	モル毎立方メートル	mol/m^{3}
質量濃度	キログラム毎立法メートル	kg/m^{3}
輝度	カンデラ毎平方メートル	cd/m^{2}
屈折率[(b)]	（数字の） 1	1
比透磁率[(b)]	（数字の） 1	1

(a) 量濃度（amount concentration）は臨床化学の分野では物質濃度（substance concentration）ともよばれる。
(b) これらは無次元量あるいは次元１をもつ量であるが、そのことを表す単位記号である数字の１は通常は表記しない。

表５．SI 接頭語

乗数	接頭語	記号	乗数	接頭語	記号
10^{24}	ヨタ	Y	10^{-1}	デシ	d
10^{21}	ゼタ	Z	10^{-2}	センチ	c
10^{18}	エクサ	E	10^{-3}	ミリ	m
10^{15}	ペタ	P	10^{-6}	マイクロ	µ
10^{12}	テラ	T	10^{-9}	ナノ	n
10^{9}	ギガ	G	10^{-12}	ピコ	p
10^{6}	メガ	M	10^{-15}	フェムト	f
10^{3}	キロ	k	10^{-18}	アト	a
10^{2}	ヘクト	h	10^{-21}	ゼプト	z
10^{1}	デカ	da	10^{-24}	ヨクト	y

表６．SIに属さないが、SIと併用される単位

名称	記号	SI 単位による値
分	min	1 min=60s
時	h	1h =60 min=3600 s
日	d	1 d=24 h=86 400 s
度	°	1°=(π/180) rad
分	’	1’=(1/60)°=(π/10800) rad
秒	”	1”=(1/60)’=(π/648000) rad
ヘクタール	ha	1ha=1hm^{2}=10^{4}m^{2}
リットル	L，l	1L=1l=1dm^{3}=10^{3}cm^{3}=10^{-3}m^{3}
トン	t	1t=10^{3} kg

表７．SIに属さないが、SIと併用される単位で、SI単位で表される数値が実験的に得られるもの

名称	記号	SI 単位で表される数値
電子ボルト	eV	1eV=1.602 176 53(14)×10^{-19}J
ダルトン	Da	1Da=1.660 538 86(28)×10^{-27}kg
統一原子質量単位	u	1u=1 Da
天文単位	ua	1ua=1.495 978 706 91(6)×10^{11}m

表３．固有の名称と記号で表されるSI組立単位

組立量	SI 組立単位			
	名称	記号	他のSI単位による表し方	SI基本単位による表し方
平面角	ラジアン[(b)]	rad	1[(b)]	m/m
立体角	ステラジアン[(b)]	sr[(c)]	1[(b)]	m^{2}/m^{2}
周波数	ヘルツ[(d)]	Hz		s^{-1}
力	ニュートン	N		m kg s^{-2}
圧力，応力	パスカル	Pa	N/m^{2}	m^{-1} kg s^{-2}
エネルギー，仕事，熱量	ジュール	J	N m	m^{2} kg s^{-2}
仕事率，工率，放射束	ワット	W	J/s	m^{2} kg s^{-3}
電荷，電気量	クーロン	C		s A
電位差（電圧），起電力	ボルト	V	W/A	m^{2} kg s^{-3} A^{-1}
静電容量	ファラド	F	C/V	m^{-2} kg^{-1} s^{4} A^{2}
電気抵抗	オーム	Ω	V/A	m^{2} kg s^{-3} A^{-2}
コンダクタンス	ジーメンス	S	A/V	m^{-2} kg^{-1} s^{3} A^{2}
磁束	ウエーバ	Wb	Vs	m^{2} kg s^{-2} A^{-1}
磁束密度	テスラ	T	Wb/m^{2}	kg s^{-2} A^{-1}
インダクタンス	ヘンリー	H	Wb/A	m^{2} kg s^{-2} A^{-2}
セルシウス温度	セルシウス度[(e)]	℃		K
光束	ルーメン	lm	cd sr[(c)]	cd
照度	ルクス	lx	lm/m^{2}	m^{-2} cd
放射性核種の放射能[(f)]	ベクレル[(d)]	Bq		s^{-1}
吸収線量, 比エネルギー分与, カーマ	グレイ	Gy	J/kg	m^{2} s^{-2}
線量当量, 周辺線量当量, 方向性線量当量, 個人線量当量	シーベルト[(g)]	Sv	J/kg	m^{2} s^{-2}
酸素活性	カタール	kat		s^{-1} mol

(a)SI接頭語は固有の名称と記号を持つ組立単位と組み合わせても使用できる。しかし接頭語を付した単位はもはやコヒーレントではない。
(b)ラジアンとステラジアンは数字の１に対する単位の特別な名称で、量についての情報をつたえるために使われる。実際には、使用する時には記号rad及びsrが用いられるが、習慣として組立単位としての記号である数字の１は明示されない。
(c)測光学ではステラジアンという名称と記号srを単位の表し方の中に、そのまま維持している。
(d)ヘルツは周期現象についてのみ、ベクレルは放射性核種の統計的過程についてのみ使用される。
(e)セルシウス度はケルビンの特別な名称で、セルシウス温度を表すために使用される。セルシウス度とケルビンの単位の大きさは同一である。したがって、温度差や温度間隔を表す数値はどちらの単位で表しても同じである。
(f)放射性核種の放射能（activity referred to a radionuclide）は、しばしば誤った用語で”radioactivity”と記される。
(g)単位シーベルト（PV,2002,70,205）についてはCIPM勧告2（CI-2002）を参照。

表８．SIに属さないが、SIと併用されるその他の単位

名称	記号	SI 単位で表される数値
バール	bar	1 bar=0.1MPa=100kPa=10^{5}Pa
水銀柱ミリメートル	mmHg	1mmHg=133.322Pa
オングストローム	Å	1 Å=0.1nm=100pm=10^{-10}m
海里	M	1 M=1852m
バーン	b	1 b=100fm^{2}=(10^{-12}cm)2=10^{-28}m^{2}
ノット	kn	1 kn=(1852/3600)m/s
ネーパ	Np	SI単位との数値的な関係は、対数量の定義に依存。
ベル	B	
デジベル	dB	

表９．固有の名称をもつCGS組立単位

名称	記号	SI 単位で表される数値
エルグ	erg	1 erg=10^{-7} J
ダイン	dyn	1 dyn=10^{-5}N
ポアズ	P	1 P=1 dyn s cm^{-2}=0.1Pa s
ストークス	St	1 St =1cm^{2} s^{-1}=10^{-4}m^{2} s^{-1}
スチルブ	sb	1 sb =1cd cm^{-2}=10^{4}cd m^{-2}
フォト	ph	1 ph=1cd sr cm^{-2} 10^{4}lx
ガル	Gal	1 Gal =1cm s^{-2}=10^{-2}ms^{-2}
マクスウェル	Mx	1 Mx = 1G cm^{2}=10^{-8}Wb
ガウス	G	1 G =1Mx cm^{-2} =10^{-4}T
エルステッド[(c)]	Oe	1 Oe (10^{3}/4π) A m^{-1}

(c) ３元系のCGS単位系とSIでは直接比較できないため、等号「　　」は対応関係を示すものである。

表４．単位の中に固有の名称と記号を含むSI組立単位の例

組立量	SI 組立単位		
	名称	記号	SI 基本単位による表し方
粘度	パスカル秒	Pa s	m^{-1} kg s^{-1}
力のモーメント	ニュートンメートル	N m	m^{2} kg s^{-2}
表面張力	ニュートン毎メートル	N/m	kg s^{-2}
角速度	ラジアン毎秒	rad/s	m m^{-1} s^{-1}=s^{-1}
角加速度	ラジアン毎秒毎秒	rad/s^{2}	m m^{-1} s^{-2}=s^{-2}
熱流密度，放射照度	ワット毎平方メートル	W/m^{2}	kg s^{-3}
熱容量，エントロピー	ジュール毎ケルビン	J/K	m^{2} kg s^{-2} K^{-1}
比熱容量，比エントロピー	ジュール毎キログラム毎ケルビン	J/(kg K)	m^{2} s^{-2} K^{-1}
比エネルギー	ジュール毎キログラム	J/kg	m^{2} s^{-2}
熱伝導率	ワット毎メートル毎ケルビン	W/(m K)	m kg s^{-3} K^{-1}
体積エネルギー	ジュール毎立方メートル	J/m^{3}	m^{-1} kg s^{-2}
電界の強さ	ボルト毎メートル	V/m	m kg s^{-3} A^{-1}
電荷密度	クーロン毎立方メートル	C/m^{3}	m^{-3} sA
表面電荷	クーロン毎平方メートル	C/m^{2}	m^{-2} sA
電束密度，電気変位	クーロン毎平方メートル	C/m^{2}	m^{-2} sA
誘電率	ファラド毎メートル	F/m	m^{-3} kg^{-1} s^{4} A^{2}
透磁率	ヘンリー毎メートル	H/m	m kg s^{-2} A^{-2}
モルエネルギー	ジュール毎モル	J/mol	m^{2} kg s^{-2} mol^{-1}
モルエントロピー, モル熱容量	ジュール毎モル毎ケルビン	J/(mol K)	m^{2} kg s^{-2} K^{-1} mol^{-1}
照射線量（Ｘ線及びγ線）	クーロン毎キログラム	C/kg	kg^{-1} sA
吸収線量率	グレイ毎秒	Gy/s	m^{2} s^{-3}
放射強度	ワット毎ステラジアン	W/sr	m^{4} m^{-2} kg s^{-3}=m^{2} kg s^{-3}
放射輝度	ワット毎平方メートル毎ステラジアン	W/(m^{2} sr)	m^{2} m^{-2} kg s^{-3}=kg s^{-3}
酵素活性濃度	カタール毎立方メートル	kat/m^{3}	m^{-3} s^{-1} mol

表10．SIに属さないその他の単位の例

名称	記号	SI 単位で表される数値
キュリー	Ci	1 Ci=3.7×10^{10}Bq
レントゲン	R	1 R = 2.58×10^{-4}C/kg
ラド	rad	1 rad=1cGy=10^{-2}Gy
レム	rem	1 rem=1 cSv=10^{-2}Sv
ガンマ	γ	1γ=1 nT=10-9T
フェルミ		1フェルミ=1 fm=10-15m
メートル系カラット		1メートル系カラット = 200 mg = 2×10-4kg
トル	Torr	1 Torr = (101 325/760) Pa
標準大気圧	atm	1 atm = 101 325 Pa
カロリー	cal	1cal=4.1858J（「15℃」カロリー），4.1868J（「IT」カロリー）4.184J（「熱化学」カロリー）
ミクロン	µ	1 µ =1µm=10^{-6}m

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